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SUSTAINABILITY IN INCREMENTAL SHEET FORMING PROCESSES

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Department of Mechanical, Energy and Management Engineering - DIMEG

PhD Thesis

SUSTAINABILITY IN INCFEMENTAL SHEET FORMING PROCESSES

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A mia madre e a mio padre

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INTRODUCTION

In the manufacturing field, the main objective is to find the right process to produce components in the best possible way. That means to do an optimization process able to calibrate a lot of control parameters. In the past three decades, many researchers have focused their work on improving manufacturing processes under several aspects, such as geometric requirements, shape quality. According to that aim, they have controlled some process variables: the required forces, the tool geometry and the material, the blank design, etc.. However, in the field of manufacturing processes, the sheet forming ones are often multi-objective optimization problems and no optimum solution exists when there are conflicting goals, whereas a set of compromise solutions can be available. As consequence of the optimization processes, in the last years the concern about environmentally friendly processes and products has continuously increased its importance in all industrial fields. This growing interest is also motivated by the increasing consumption of energy and raw materials as well as the general and prolonged indifference to the environment, which was made evident by the increasing trends in global emissions, as shown in the following chart (**Figure 1**). There are other factors that solicit a greater attention to the environment, such as the more and more numerous environmental laws that impose penalties, taxes and incentives. In the last years, the word “sustainability” has become very popular. Even if the necessity of more “sustainable” practices and behavior in industrial field has become more and more urgent, from an industry standpoint, “sustainability” aspects must meet both technical and financial requirements. Since it is commonly agreed that making sustainable choices imply higher costs and it is technically difficult to achieve, there is a sort of caution towards sustainability. The term “sustainable development” has been coined, already in the eighties, by the Brundtland Commission[1] which attributed to it the following

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[1] The Brundtland Commission is also known as the World Commission on Environment and Development. Its name originates from Gro Harlem Brundtland, the chairman of the commission, who was appointed in 1983 by the General Secretary of the United Nations. The Brundtland Commission’s reason for being is the heavy deterioration of natural resources and human environment. Its mission is to push countries to

well-known definition: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations World Commission on Environment and Development, 1987)". Since 1987, gradually, the awareness about what kind of problems could generate the pollution and the insane use of natural resources, has augmented. The problems related to the environment acquired a specific identity and an appropriate name: global warming, ozone depletion, acidification, eutrophication[2].

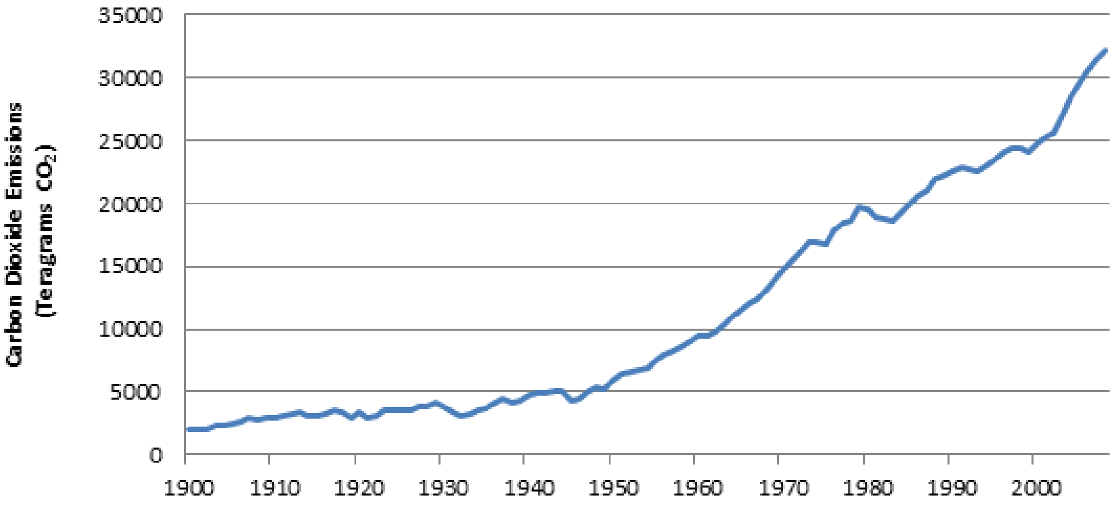

Figure 1. Global carbon dioxide emissions from fossil-fuels, during the years 1990-2008 (Boden et al., 2010).

The activity sectors responsible of the worldwide greenhouse gases emissions have been identified by the International Energy Agency (2011), as shown in **Figure 2**. The sector more pollutant is "heat and electricity". Consequently, efficiency in energy use and the research of new energy fonts have become priorities in all the industrial fields (Hermann

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pursue sustainable development all together. The Brundtland Commission, dissolved at the end of 1987, generated in the same year the report "Our Common Future". This report has been the result of interviews made by the team put together by Gro Harlem Brundtland. This team went around the world asking all types of people (farmers, school teachers, fishermen, homemakers, loggers, indigenous people and industry leaders) what environmental concerns were and how they should be addressed. In "Our common future" there are people reactions and reflections about their living conditions, education, health, resources consumption, population pressures. These wide interviews have highlighted that the environmental issues, the social and economic ones, are all interrelated (Sustainablemeasures, 2013).

[2] Eutrophication is the enrichment of bodies of fresh water by inorganic plant nutrients (e.g. nitrate, phosphate). It may occur naturally but can also be the result of human activity (cultural eutrophication from fertilizer runoff and sewage discharge) and is particularly evident in slow-moving rivers and shallow lakes. Increased sediment deposition can eventually raise the level of the lake or river bed, allowing land plants to colonize the edges, and eventually converting the area to dry land (Lawrence and Jackson, 1998).

and Thiede, 2009). This interest in sustainable methods for manufacturing led the researchers to establish some objectives: manufacturing processes have to be designed and then developed in order 1) to eliminate, or at least to reduce, or to recycle wastes; 2) to find and then use new sources of energy and new materials; 3) to avoid any risk to the environment or the human health (Veleva et al., 2001). Industries that choose environmental friendly strategies have learned to select less impactful materials, to minimize scraps and wastes, to reduce energy use or to use energy in a more clever way. One of the environmental strategies is the 6R approach, that suggests how to move towards more sustainable products: 6R stands for Recover, Reuse, Recycle, Redesign, Reduce and Remanufacture (Joshi et al., 2006). One other environmental strategy is LCA methodology, widely investigated by research labs and more utilized by industry.

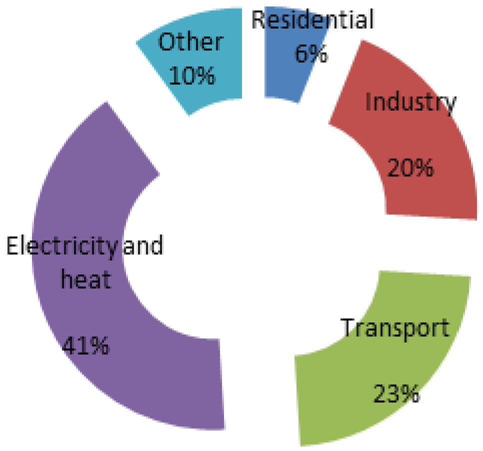

Figure 2. 2009 worldwide greenhouse gases emissions, divided by sectors (International Energy Agency, 2011).

In spite of progresses achieved about sustainable problems, improving manufacturing processes from a sustainability point of view is very complex: it means to take into account all the input/output flows (materials, lubricant, water, energy, wastes) and to be able to determine if tooling systems and technology are the most environmental friendly or, if not, to find out the better ones (Ingarao et al., 2011b). Thus, in literature, the analysis about forming processes impact is not yet well documented and there are a few attempts to model their input/output flows. Any process requires different and comprehensive approaches (Bare, 2002; Jolliet et al., 2003; ISO, 2006a; ISO, 2006b). For this reason, there is still a lack of knowledge on metal forming (in particular about the aspects related to environmental burden), that is still quite complex because of its process-dependency. On the other hand, regarding machining processes, a lot of quantitative models have been realized and a wide state of the art is already available (Gutowski, 2004; Gutowski et al., 2006; Pusavec et al., 2010a; Pusavec et al., 2010b; Vijayaraghavan and Dornfeld, 2010). Limiting the whole attention to sheet forming processes, Ingarao et al. (2011b) gave an interesting holistic vision that provides the general principles to find possible solutions to improve sustainability during the life cycle of formed components. In particular, sheet stamping processes large application contributes to the carbon emission reduction and that happens in several industrial areas. Especially the automotive sector (McAuley, 2003; Sutherland and Gunter, 2004) pushes to lightweight solutions and technologies for sheet stamping operations; actually, this can be justified because the use phase has the greatest impact throughout a typical vehicle life cycle. After measuring energy consumption during sheet stamping processes, Chee et al. (2011) identified some opportunities for carbon reduction. As adequate alternative to the conventional stamping (Jeswiet et al., 2005), among the others, Incremental Sheet Forming results suitable to process lightweight materials, since this technology has revealed to reach higher strains level and formability (Duflou et al., 2008). Bay et al. (2005) proposed some studies on the tribological technologies, enhancing how dry manufacturing or manufacturing with benign lubricants[3] can be an appropriate solution to sustainability problems. Talking of sheet stamping processes, lubrication and material efficiency (the last one related to die design and optimization of the initial blank shape) are indicated as the major aspects to be taken into account in order to reduce the environmental burden (Gantar et al., 2005). Furthermore, Petek et al. (2007) presented a method that measures efficiency in material use, lubrication and process energy. Speaking of energy, Rahimifard et al. (2010) invented a specific method that recognizes two types of energy: a direct energy, useful for manufacturing processes, and an indirect energy, necessary for the auxiliary activities, like lighting or heating.

Admitting that the knowledge is quite poor on sustainable techniques and on analysis in manufacturing fields, during these three years, the attention was focused massively in that direction. As specific manufacturing process, the Incremental Sheet Forming (ISF) was

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[3] The benign lubricants are the environmental friendly lubricants, such as products based on plant seed oil esters, made of animal fat and used cooking oil. Among the advantages that they present, there are their renewable source, their biological biodegradability and the lack of aromatic hydrocarbons (Hermann et al., 2007).

chosen. From a sustainable perspective, while maintaining or even improving the product and process quality, this manufacturing process must demonstrate (see **Figure 3**):

- a reduced environmental impact;
- an improved resources and energy use efficiency;
- to produce minimum wastes quantity;
- to guarantee operational safety;
- to pay attention to all manufacturing costs;
- to assure improved personal health (Jawahir et al., 2013).

The present research focused on three pillars out of six summarized in **Figure 3**, such as the environmental impact, the energy and resources efficiency.

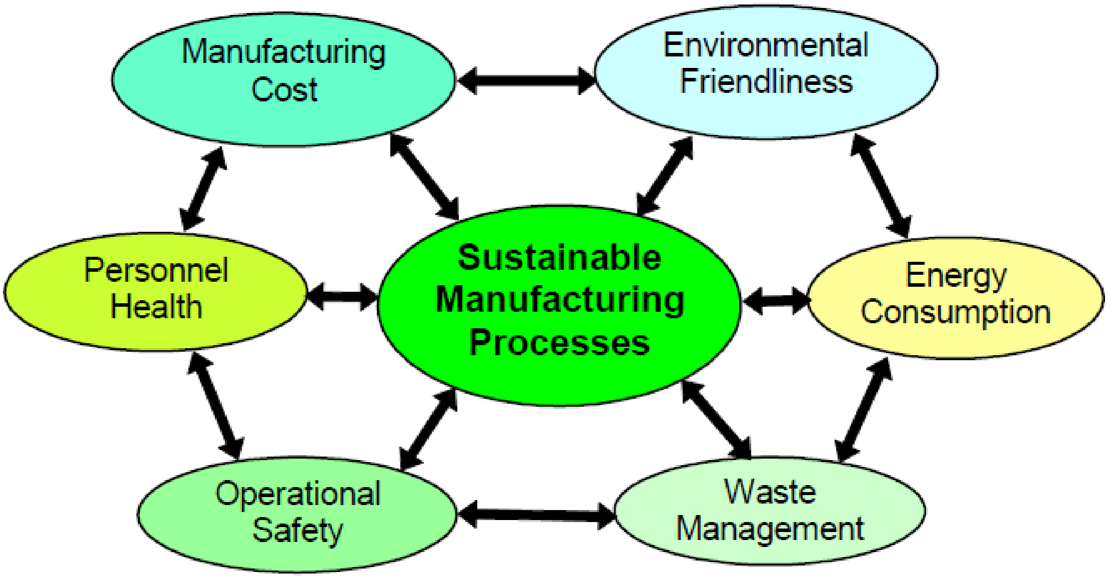


Figure 3. Major topics related to sustainable manufacturing processes (Jawahir et al., 2013).

The research has been developed focusing in these three topics, which have been detailed in some case studies, as summarized in **Figure 4**, in order to design a sustainable ISF process. More in detail, the ISF process, in the next chapters, will be compared with the traditional and well known deep drawing process (Petek et al., 2007; Ingarao et al., 2011c), as well as will be deeply investigated from a sustainability point of view. The life cycle assessment methodology will be followed, thus the ISF process will be divided in phases and materials, lubricant and energy consumption will be determined, as well as CO_2 emissions.

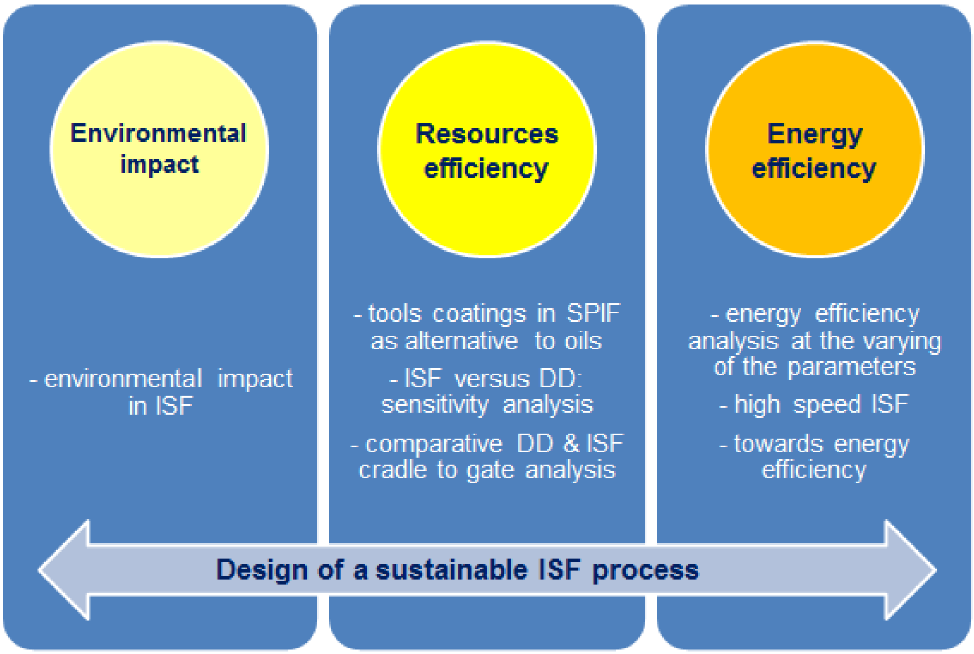


Figure 4. ISF process: sustainable design.

A research is available in literature that calculates the theoretical energy necessary for deforming and this energy is correlated to greenhouse gas emissions, using the specific local power grid. This procedure, whose name is Carbon Emission Signature method, connects directly the electrical energy to the carbon emissions and it can be applied both to machining and manufacturing processes (Jeswiet and Kara, 2008; Nava et al., 2010). Of all the sustainability factors taken into account (see **Figure 4**), in this research energy represents the most important one. Firstly, the theoretical energy consumption will be taken into consideration by comparing the ISF technology with the more conventional Deep Drawing one. The result is that ISF process is the worst one, as far as the energy consumption is concerned, whereas is the best one relatively to material wasting . Subsequently, after dealing with theoretical energy consumption, the real energy consumption for ISF is determined executing some experimental tests at the laboratory of mechanical, energy and management engineering department. This investigation will determine either the influence of various process parameters or the inefficiencies which have to be eliminated in order to make the process more competitive. As for the energy aspect, the duration of the process is very important: the issue of process slowness will be overcome by proposing an innovative process, such as the high speed incremental forming. This technique reduces drastically the process duration, without compromising the surface quality and thus industries will finally take into account the ISF process as new innovative and profitable technique (Ambrogio et al., 2013). Always in energy field, the comparison between different ways of heating the sheets in order to hot form different lightweight materials, in particular Titanium alloys, will be done in order to establish the best one, that means that one less energy consuming. The three methods compared will be: laser assisted heating, electrical heating and thermo-mechanical heating. Dealing with lubrication problem, an alternative way to reduce the use of lubricant is proposed, based on the application of coatings. In the study, an appropriate tool coating (AlSiTiN) will be proposed, which consents to completely avoid the lubricant use. In brief, the goal of the present PhD thesis has been to investigate incremental sheet metal forming processes from a new perspective, that one of sustainability, and thus some ideas will be proposed in order to make the processes more sustainable and profitable for industries.

Chapter 1

THE SUSTAINABILITY CONCEPT

1.1 History in brief

The first discussion on sustainability started in 1972 in Stockholm. At the Stockholm Conference representatives from 113 countries were present. This was the first United Nations conference on the environment. It was, also, a first relevant international gathering answering to the question: what kind of human actions can be prepared in connection with the environment, in order to reduce human impact on the environment? How can the environment be defended and improved? Since the most important problems affecting the environment are global, this goal requires action at an international level and consequently it solicits an extensive cooperation with all countries (Eoearth, 2013). This Conference is better known as "the 1972 United Nation Conference on the Human Environment". It has symbolized the beginning of the public awareness of global environmental problems. The greatest achievement of this Conference was the creation of the United Nations Environment Program, whose mission was "to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and people to improve their quality of life without compromising that of future generations" (Eoearth, 2013). In order to pursue the Conference mission, a set of recommendations is defined:

- promoting international cooperation in facing environmental issues;
- continuously monitoring the degree of the global environment;
- pushing for environmental awareness in all society, all governments and in the private sector as well;
- developing local programs for achieving sustainability;

- supporting authorities to develop international environmental laws (Eoearth, 2013).

Later, in 1980, the International Union for the Conservation of Nature was founded. It is an international organization whose vision is “a just world that values and conserves nature”. The mission of the International Union for the Conservation of Nature is to influence, to encourage and to assist societies throughout the world to conserve nature and to ensure that any use of natural resources is equitable and ecologically sustainable” (Iucn, 2013). The International Union for the Conservation of Nature programme for 2013-2016 is shown in **Figure 1.1**.

Figure 1.1. The International Union for the Conservation of Nature programme for 2013-2016 (Iucn, 2013).

This programme has three main areas:

1. Valuing and conserving nature, that enhances International Union for the Conservation of Nature’s heartland work on biodiversity conservation.
2. Effective and equitable governance of Nature’s use, that consolidates International Union for the Conservation of Nature’s work on people–nature relations, rights and responsibilities.
3. Deploying nature-based solutions to global challenges in climate, food and development that expands International Union for the Conservation of Nature’s work on nature‘s contribution to tackling problems of sustainable development,

particularly in climate change, food security and social and economic development (Iucn, 2013).

“Sustainability” means different things to different people and there is no universally acceptable definition for this term, but the most commonly known definition comes from the 1987 United Nations Brundtland Commission, who coined the term “sustainable development” and attributed to it the following definition: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations World Commission on Environment and Development, 1987)”. “Our Common Future” is the report realized by the Brundtland Commission already in 1987. About energy sources problems, it is explicitly affirmed that “any new era of economic growth must therefore be less energy intensive than in the past. Energy efficiency policies must be the cutting edge of national energy strategies for sustainable development, and there is much scope for improvement in this direction. Modern appliances can be redesigned to deliver the same amounts of energy-services with only two-thirds or even one-half of the primary energy inputs needed to run traditional equipment”. That affirmation poses the question about what in terms of energy has been done in the recent 26 years. To sustain the human progress it is imperative a safe, environmentally sound and economically viable energy pathway. As affirmed in the Report “the sustainable development involves more than growth. It requires a change in the content of growth, to make it less material and energy intensive and more equitable in its impact. These changes are required in all countries as part of a package of measures to maintain the stock of ecological capital, to improve the distribution of income, and to reduce the degree of vulnerability to economic crises (United Nations World Commission on Environment and Development, 1987)”. “The Earth's natural resource base must be conserved and enhanced. Major changes in policies will be needed to cope with the industrial world's current high levels of consumption, the increases in consumption needed to meet minimum standards in developing countries, and expected population growth (United Nations World Commission on Environment and Development, 1987).” Each year the number of human beings increases, but the amount of natural resources by which to sustain this population, to improve the quality of human lives and to eliminate mass poverty, remains finite. On the other hand, expanding knowledge increases the productivity of resources (United Nations World Commission on Environment and Development, 1987).

1.2 Different approaches to sustainability

As already stated, the term “sustainability” means different things to different people. Also in literature, a lot of different meanings have been attributed to the word “sustainability” and several approaches can be adopted to deal with sustainability problems. Some of the most commonly known sustainability terms are: environmental sustainability, economic sustainability and societal sustainability. Some possible approaches are sketched in **Figure 1.2** and summarized in the following list:

- Energy. It means to pay a great attention to energy consumption, especially that energy originated from fossil fuel consumption.
- Efficient use of resources, such as energy, water, materials. Since resources must be utilized in order to produce, they should be used in the most efficient way.

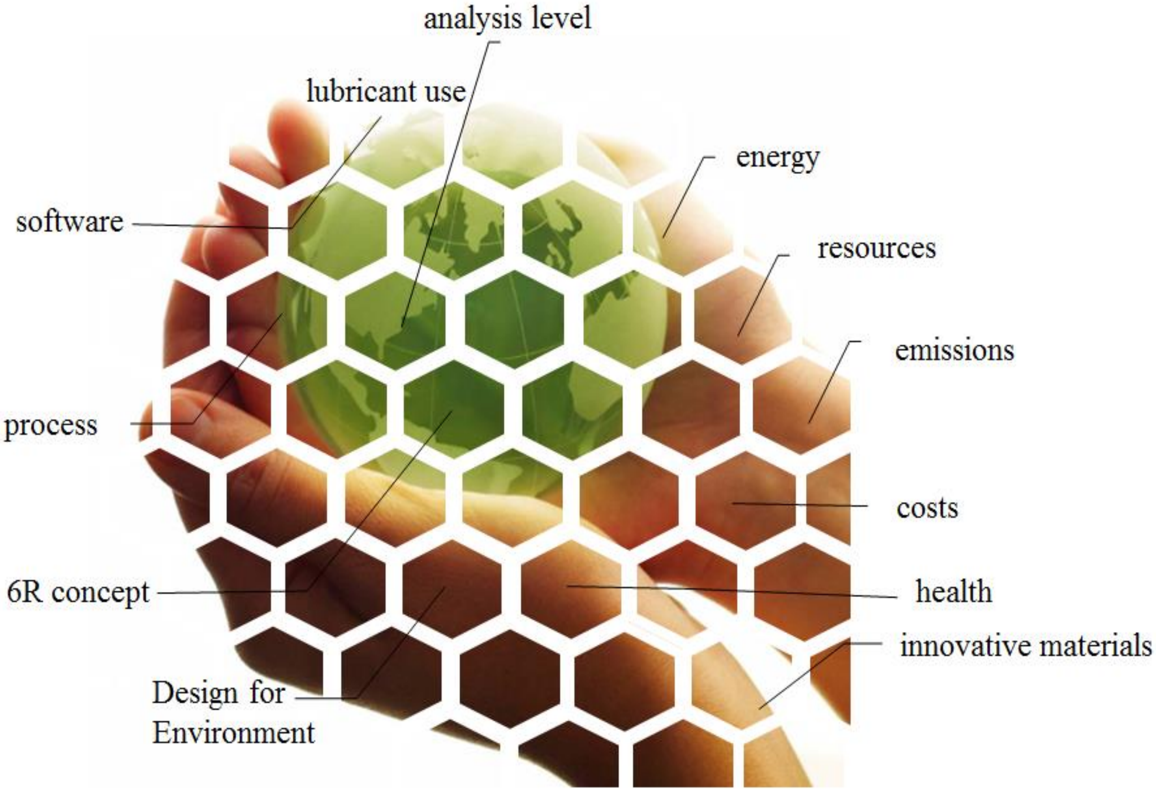


Figure 1.2. Sketch of sustainability concept complexity and multi-approaches.

- Environmental impact, either in terms of air emissions, or water emissions or solid waste.

- Costs: it is quite a common point of view that making sustainable choices in industrial context imply a great waste of money.
- People health, but also animals, plants and generally Earth health.
- Innovative materials use. An urgent request from the Earth imposes to researchers of all over the world to find out new material more environmental friendly than the previous ones.
- Design for Environment which includes procedures and guidelines to design products with the aim to minimize their environmental burden over their entire life cycle.
- 6R concept (Recover, Reuse, Recycle, Redesign, Reduce, Remanufacture) which represents the evolution of the 3R concept, and both the procedures are summarized in **Figure 1.3**. In particular, the possibility of recycling an old product or appliance is very important since that recyclability prevents from producing waste and consents a new life for the product itself. The "Design for Recycling" consists of procedures and guidelines to design products that are suitable for recycling.

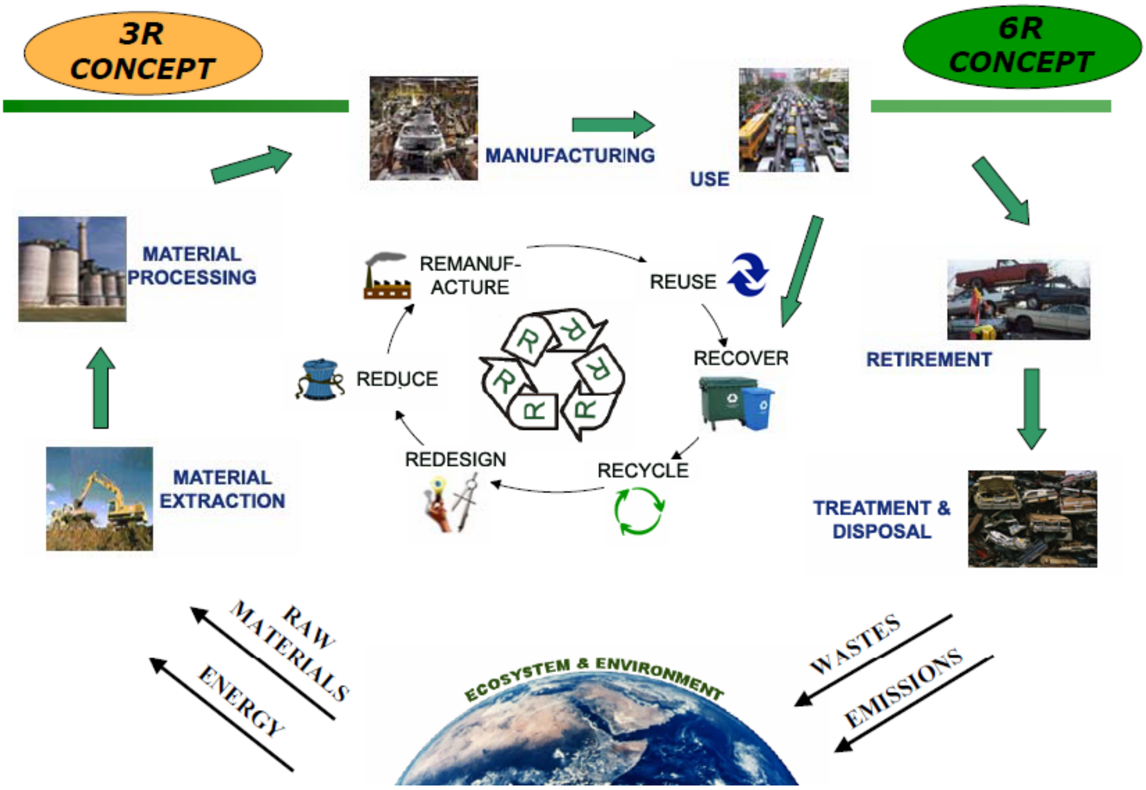


Figure 1.3. Sustainable manufacturing: evolution form 3R into 6R concept (Jayal et al., 2010).

- Finding out different processes, more environmental friendly than the actual ones.
- Software. In order to help industries to reach sustainability there are available some software for life-cycle assessment.
- Lubricants use. Oils and emulsions are still largely used in industrial fields, even if they are responsible of the environmental burden and of damaging population health. Thus, the industry attention is focused on reduction and, if possible, on complete suppression of the lubricant use.
- Analysis level: in-depth level or “scratch” level. It is fundamental to decide from what point of view to analyze a certain process or product. A choice could be to do a detailed analysis that scrutinizes every aspect of the process, or about all stages (from cradle to grave). A different choice could be to do a briefer painting, that is an essential examination of the process (Ashby, 2009).

1.2.1 Life cycle assessment methodologies

Due to the growing interest of academia and industries towards sustainability, the International Standards Organization (ISO) undertook a global standardization process for Life Cycle Assessment (ISO, 2006a). Life Cycle Assessment (LCA) documents all kind of resources consumed and the emissions excreted during each phase of life for a certain product. On the basis of the system boundaries, the LCA can be either “from cradle to grave” (that means it starts from raw material extraction, passes through the material processing, the manufacturing phase, the distribution, the use, the maintenance, eventually the repair phase and finally ends with the disposal or recycling) or “cradle to gate” (from raw material extraction to any intermediate life cycle phase) or “gate to gate” (ISO, 2006a). LCA gives a sort of biography, documenting in detail where the materials have been, what they have done, and what are the consequences for their surroundings. From 1997 on, a set of standards for conducting a LCA was thus issued by the International Standards Organization: ISO 14040 and its subsections 14041, 14042, and 14043. These prescribe procedures for “defining goal and scope of the assessment, compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.” According to the ISO standards, the study must examine energy and material flows in raw material acquisition, processing and manufacture, distribution and storage (transport, refrigeration, and so forth), use, maintenance and repair, recycling, and waste management.

A sketch of the material life cycle is shown in **Figure 1.4**.

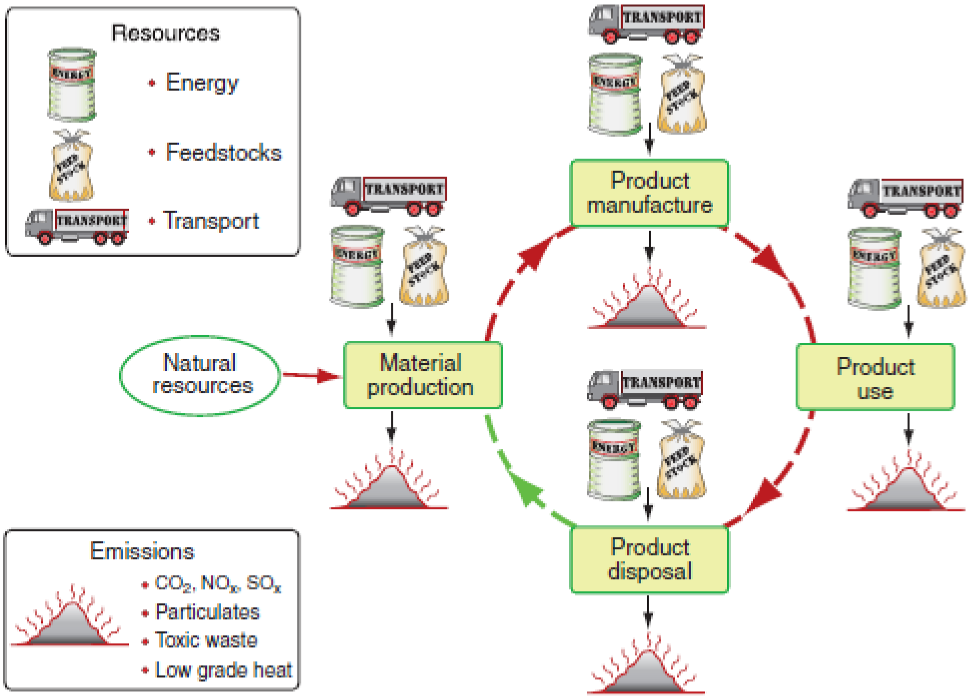


Figure 1.4. The material life cycle (Ashby, 2009).

In this scheme, minerals and natural resources, in general, are obtained and processed to produce a raw material; this material is manufactured into a product that is used, and at the end of its life, it is discarded, recycled, or, less commonly, refurbished and reused. Energy and materials are consumed in each phase, generating waste heat and solid, liquid and gaseous emissions.

LCA methodologies together with Design for Environment are hugely used by industries and investigated by research teams (Hauschild et al., 2005). The LCA framework can be summarized as shown in **Figure 1.5**. The main steps are:

- Goal and scope definition: the LCA objective is clearly defined as well as the functional unit, the technological and temporal scope of the product or process, and the boundaries of the product system. The assessment parameters are also defined in this phase.
- Inventory analysis: in this phase input and output data flows are collected, according to the already defined functional unit.

- Impact Assessment: in this phase, the potential impact is calculated category by category, starting from the data collected in the previous step.
- Impact Interpretation: this phase comes after Life Cycle Inventory and Life Cycle Impact Assessment, and results necessary to compare products and processes to each other or to a specific target.

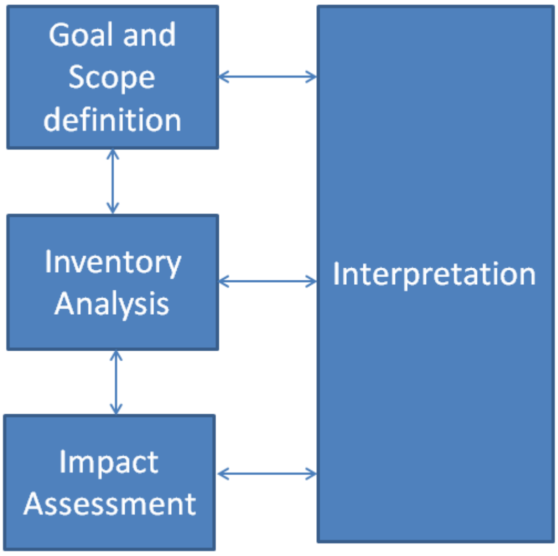


Figure 1.5. LCA framework for the ISO 14000 standards.

In literature there are many LCA methodologies, such as CML 1996, CML 2001, EDIP 1997, Impact 2002, TRACI, Eco-Indicator 95 and Eco-Indicator 99 (Jolliet et al., 2003).

1.2.2 Software

Nowadays, industries of any sectors are trying to make their products or services greener, to compare different products between them as regards to their environmental impact, to make people aware, through advertisement, of the efforts done in terms of green choices. To help industries to reach their goals, LCA methods are always more frequently used. Some tools that do LCA are available and some of them are software. The most important and used software are listed in **Table 1.1**. Some software, the most complex ones, follow the ISO 14040 prescriptions, but some do not. Some software are thought for educational purposes. Some of these are intended to specific sectors (building materials rather than vehicle design, or paper making).

Table 1.1. The most important LCA software (Ashby, 2009).

Tool name	**Brief description**	**Provider: web site**
Gabi	This is a complete and sophisticated tool, that respects European legislation. It allows to optimize the processes and to analyze costs, as well as environmental, technical and social aspects.	PE International: http://www.gabi-software.com
SimaPro (2008)	This tool follows the ISO 14040 series recommendations. An educational version is available. This software monitors the environmental performance of both products and services.	Pré Consultants: www.pre.nl
CES Eco (2009)	This tool is widely used for teaching engineering students about materials and processes selection and use.	Granta Design, Cambridge UK: www.grantadesign.com
GREET (2007)	GREET stands for Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. It is a free spreadsheet that runs in Microsoft Excel. There is an available version for vehicle-cycle analysis. The model allows to calculate the emissions of CO_2 equivalent, some pollutants and the power consumption.	US Department of Tansportation: www.transportation.anl.gov
MIPS (2008)	MIPS means Material Input per Service Unit. Actually MIPS is an elementary measure to estimate the environmental impacts. This software takes in consideration the entire life cycle (from cradle to grave) of a product, a process or a service.	Wuppertal Institute: www.wupperinst.org
KCL-ECO 3.0	It is an LCA tool designed expressly for the paper-making industry.	KCL Finland: www.kcl.fi
Eiolca (2008)	Eio-lca stands for Economic input/output LCA. This tool does not allow to make LCA assessment of products. It calculates emissions starting from input/output data for the sectors of the North American Industry Classification Scheme.	Carnegie Mellon Green Design Institute, USA: www.eiolca.net
Aggregain (2008)	It is a free analysis tool that runs in Microsoft Excel. Its scope is to encourage recycled materials use for the construction industries.	WRAP: www.aggregain.org.uk
TEAM (2008)	It has a large database and allows to model systems associated with products and processes. It follows the ISO 14040 series of standards.	PriceWaterhouseCooper: www.ecobalance.com
MEEUP method (2005)	MEEUP stands for Dutch Methodology for Ecodesign of Energy-Using Products. It is a tool that follows the ISO 14040 series of guidelines. It analyses the products that use energy.	VHK, Delft, Netherlands: www.pre.nl/EUP/
Boustead Model 5 (2007)	This software allows to make life-cycle inventory calculations, broadly following the ISO 14040 series recommendations.	Boustead Consultants: www.boustead-consultaing.co.uk

Some software are free, some need the constant presence of a consultant because of their complexity. Some software do the entire life-cycle analysis, but some are limited to only some stages (Ashby, 2009).

1.2.3 Lubricant use and potential alternatives

Since it is generally agreed that emulsions and oils are detrimental for environment and population, all the scientific world thinks that manufacturing processes have to be re-designed either with the aim of reducing, eliminating and/or recycling wastes, or with the aim of abolishing, where it is possible, chemical and physical substances which represent a concrete danger for human health and environment. Already in 2005, Gantar et al. (2005) suggested that, reducing the environmental impact in Incremental Sheet Forming processes, two aspects must be considered: the first one is the efficiency in material use, whereas the second one is lubrication and the consequent cleaning. In this second case, it is important to highlight that environmental impact caused by the cleaning process, in terms of energetic consumption and auxiliary materials use, is much higher than the one due to lubricant use. Following this intuition, other researchers are verifying the workability of sheets in “dry” conditions or are utilizing lubricants made by nature, that means eco-benign oils, as potential alternative to the oils traditionally used to obtain lubrication. In literature, plant seed oil, animal fat and used cooking oil are diffusely investigated in order to find out if they can be used as substitutes for mineral oil (Hermann et al., 2007). The oils of plant seeds, for example, thanks to their technological performances, can be valuable substitutes of mineral oils. The continuous research of more effective and competitive solutions, determines the application of sustainability principles not only to large scale production, but also to those innovative process categories like ISF (Ambrogio et al., 2004), that will be described later. In literature, lubricants function in ISF processes, has not yet defined and also the concrete and adequate possibility of reducing their quantity. Hereinafter, a case study (see section 3.5) contemplates the possibility of avoiding lubricants use, either totally or partially, through tools coatings.

1.3 Sustainable manufacturing

The most widely accepted general definition of sustainable development is provided by the United Nations’ Brundtland Commission: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations World Commission on Environment and Development, 1987)”. However, the practical implementation of each sustainability improvement has to be suitable to the specific case. More precisely, in order to make manufacturing more sustainable, it is necessary to consider all the issues at each level: product, process, and system (Jayal et al., 2010). In fact, sustainable manufacturing deals with three integral elements (products, processes and systems) and to achieve sustainable production, each of these three integral elements is expected to demonstrate (Jawahir et al., 2013):

"(a) reduced negative environmental impact
(b) offer improved energy and resource efficiency
(c) generate minimum quantity of wastes
(d) provide operational safety
(e) offer improved personal health
while maintaining and/or improving the product and process quality" (Jawahir et al., 2013).

There are many definitions for sustainable manufacturing, but in almost all such definitions the connectivity among the above integral elements is not clear. A more complete definition is the following one: "sustainable manufacturing offers a new way of producing functionally superior products using sustainable technologies and manufacturing methods through the coordination of capabilities across the supply chain" (Jawahir et al., 2013). If there is an integrated sustainable manufacturing, sustainable value creation for all stakeholders must be enabled. This entails following a co-creative model by taking account of the dependencies between the producer, the consumer and the wider social and natural environment (Ueda et al., 2009).

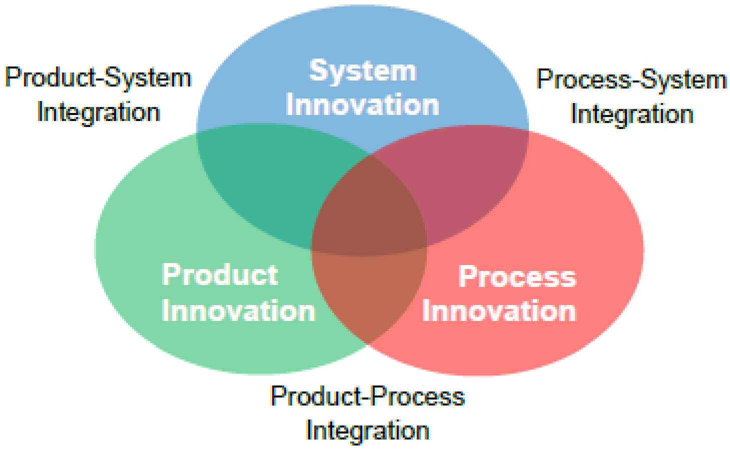


Figure 1.6. Innovation in sustainable manufacturing at integrated product, process and system level.

A lot of studies have shown that sustainability is a driver to have innovation. To enable the innovation in sustainable manufacturing, innovation must be accepted either at the product level or at the process level or at the system level, and all the levels must have close interactions, as shown in **Figure 1.6**.

As the product level is concerned, it is important to move beyond the traditional 3R concept (Reduce, Reuse and Recycle) to the more recent 6R concept (Reduce, Reuse, Recover, Redesign, Remanufacture, Recycle). In this way, starting from an openloop, single life-cycle paradigm, the arriving is a theoretically closed-loop, multiple life-cycle paradigm (Joshi et al., 2006). As the process level is concerned, the urgency is planning for reducing energy and resource consumptions, occupational hazards, wastes (especially the toxic ones), and for improving product life (Jawahir and Dillon, 2007).

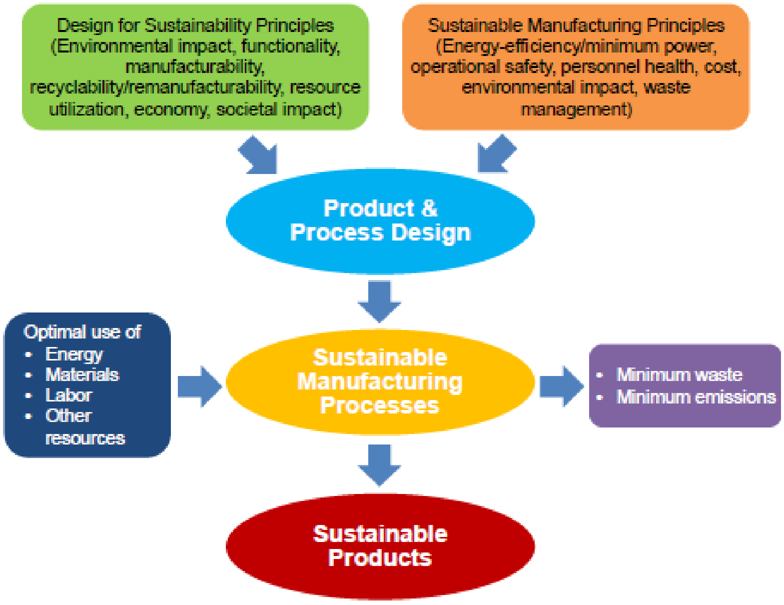


Figure 1.7. A methodology for producing sustainable products from sustainable processes (Jawahir et al., 2013; Badurdeen et al., 2009).

At the system level, all aspects related to the entire supply chain, and all the major life-cycle stages (such as pre-manufacturing, manufacturing, use and post-use) must be taken into account (Badurdeen et al., 2010). Recently, it can be observed that if sustainable products are developed from sustainable processes, the environmental, economic and societal values of product manufacture have been doubled. **Figure 1.7** shows a scheme of the different activities involved in order to produce sustainable products from sustainable processes (Jawahir et al., 2013).

A work published in the Harvard Business Review presents a five-stage approach with the innovation opportunities discussed at each stage (Jawahir et al., 2013; Nidumolu et al. 2009):

- Stage 1: viewing compliance as an opportunity;
- Stage 2: making value chains sustainable;
- Stage 3: designing sustainable products and services;
- Stage 4: developing new business models;
- Stage 5: creating next practice platforms.

A more recent MIT study (Kiron et al., 2013) shows that many companies generated profits from sustainability. With this purpose, they suggest five practices:

1. need to change the business model;
2. leading from the top to integrate the effects;
3. measuring and tracking sustainability goals and performance;
4. understanding the customer expectations for sustainability in terms of value and cost;
5. collaborating with individuals, customers, businesses and groups (Jawahir et al., 2013).

It is well known that manufacturing processes are responsible for a valuable part of the environmental impact of the products. However, manufacturing processes have not been well documented in term of their environmental impact. One first attempt to address these shortcomings is represented by the CO2PE!–initiative (Cooperative Effort on Process Emissions in Manufacturing). The principal objective is collecting and documenting accurate Life Cycle Inventory data for a big number of available and emerging manufacturing processes and providing guidelines to improve these. Moreover, the partners of CO2PE!-initiative are many research institutes and industries from all over the world, which are sharing their expertise and facilities (Duflou et al., 2011b). The methodology is summarized in **Figure 1.8**. The data collection must be based on industrial measurements and consists in four different steps: 1) a time study, made in order to identify the different modes/phases of a process; 2) a power study and consequently a 3) consumables study and 4) an emission study were done for each mode of the process (Duflou et al., 2011a).

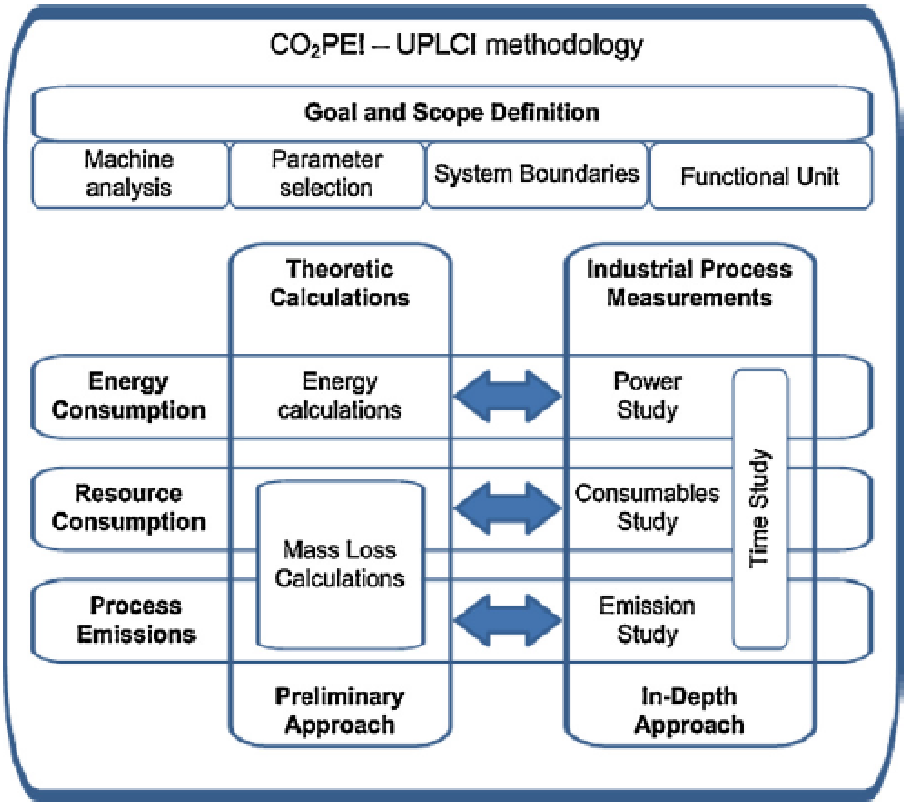


Figure 1.8. CO2PE! – Unit process Life Cycle Inventory methodology (Duflou et al., 2011b).

Implementing this methodology, some manufacturing case studies, conducted at the Katholieke Universiteit Leuven, were performed (Duflou et al., 2011b). A case study was performed on a CO_2-laser cutting machine tool: different production modes were identified (respectively cutting, table changing and idle machine time) and the average energy, the resource and emission flows during 1 hour of laser cutting activity were reported (Goedkoop et al., 1998). Analyzing these data, since energy consumption impacts for 68% on total impact, the possibility of reducing energy consumption was analyzed and an alternative laser machine was proposed, allowing a reduction of 20% of the total impact. A different case study was performed on a selective laser melting machine tool (Duflou et al., 2010). The identified production modes were start-up mode, melting, sweeping, product removing and cleaning. The energy, resource and emission flows for a production time of 4 hours was determined and impact reduction opportunities have been found in various aspects (Duflou et al., 2011b). An additional case study was performed on air bending process. After having identified three different production modes, the power profile of an air bending operation on four different machine tools was represented, and only from energy consumption point of view, a reduction up to 60% in consumed energy can be obtained based on machine tool characteristics (Duflou et al., 2011a).

In the next chapters, a first attempt is done in order to have some more information about the Incremental Sheet Forming process from a sustainable point of view and some case studies have been detailed highlighting three aspects: the environmental impact, the material and the energy efficiency.

Chapter 2

INCREMENTAL SHEET FORMING TECHNOLOGY

2.1 Incremental Sheet Forming technology: what is it?

Modern enterprises strategy is based on three fundamental topics: costs reduction, product quality, time to market shortening. Moreover, market requirements impose manufacturing industries attention to flexibility, and small batches production is one of its aspect. Traditional metal forming and metal stamping processes are oriented to large-scale production, satisfying in this manner the request of costs control (because the high costs are distributed over a very large number of parts), but they do not guarantee flexibility and they are not suitable for small batches production.

As better answer to the market needs, literature recommends an innovative technology: Incremental Sheet Forming. It was patented in 1967 (Leszak, 1967), well before its actual implementation and was originally referred as Incremental Dieless Forming. Instead of incremental sheet forming (Kim and Park, 2003), two different names are currently in use for this process, such as sheet incremental forming, or kinematical incremental sheet forming (Jadhav, 2004). Jeswiet et al. (2005) put forward the following name and definition: "Asymmetric Incremental Sheet Forming (AISF) is a process which:

1. is a sheet metal forming process,
2. has a solid, small-sized forming tool,
3. does not have large, dedicated dies,
4. has a forming tool which is in continuous contact with sheet metal,
5. has a tool that moves under control, in three dimensional space,
6. can produce asymmetric sheet metal shapes."

The first experimental studies on the process were carried out in the first years of nineties. This technique offers more flexibility and efficiency, since it does not require neither expensive equipment nor set-up operations, that are highly time consuming. One of the most promising forming philosophy consists of applying a simple hemispherical punch, which moves along a fixed trajectory, in order to impress a local deformation on a blank to obtain at the end the desired profile. This process is able to produce complex sheet components by Computer Numerical Control movement of a simple tool starting from very simplified dies: thanks to this process the use of dedicated tools is eliminated (Ambrogio et al., 2011). In the last twenty years, several efforts have been spent in order to improve the process suitability from an industrial point of view.

2.2 Incremental sheet forming processes: a state of the art

It is worth to mention that although the first idea of this process was described and patented by Leszak in 1967 at that period the CNC controllers were not available, so the industries and the researcher focused their attention on ISF is from the 1990s.
ISF presents the typologies summarized in the following.

2.2.1 Single point incremental forming (SPIF)

The characteristic feature of SPIF is that a part is shaped by the action of a CNC controlled forming tool that has a single-point contact with the sheet metal. The blank is clamped in a blank holder that remains at a constant height (see **Figure 2.1**). This process variant is truly dieless if no support tool is used. In most cases, however, a dedicated rig or backplate is used to create a defined transition between the flange and the actual part. Both variations of the SPIF process are displayed in **Figure 2.1**.

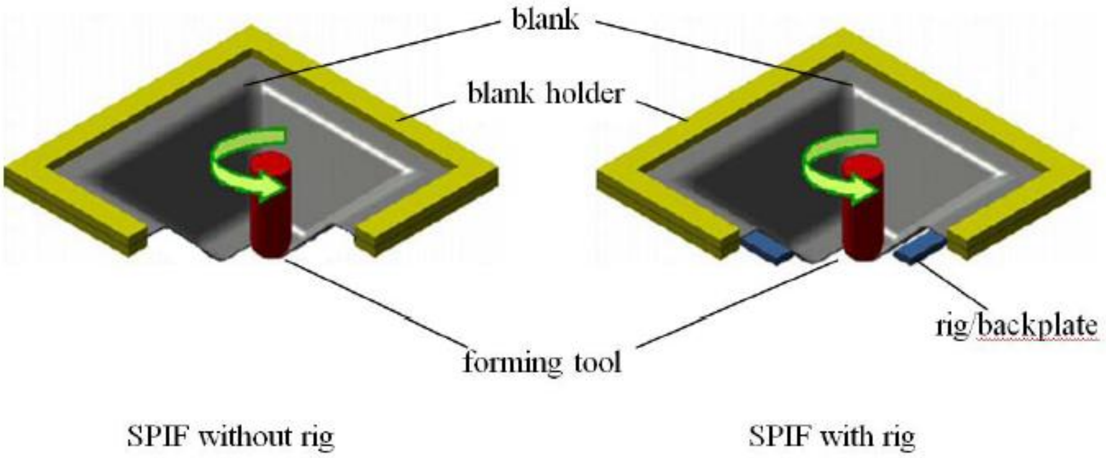


Figure 2.1. Scheme for single point incremental sheet forming process without rig, on the left, and with rig, on the right (Bambach et al., 2003).

It is worth mentioning that there is no single-point contact when a backplate is used. Nevertheless, the acronym SPIF is well-established. In the following chapters, the SPIF has been the process under investigation, and it will be referred to generally as ISF.

2.2.2 Two point incremental forming (TPIF)

TPIF was introduced by Matsubara (1994) to meet the need for quick, inexpensive production of low volume asymmetric sheet metal parts. With the TPIF process, the metal blank moves vertically on bearings which move on blank holder posts, along the z-axis, as the forming tool pushes into the sheet metal. This process has two points where the sheet metal is pressed, simultaneously, hence it is called Two Point Incremental Forming (TPIF) in order to differentiate it from Single Point Incremental Forming (SPIF), which has just one point at which force is applied. The point, where plastic deformation occurs, is directly under the forming tool. When it is used in a CNC mill, it is mounted in the spindle. The forming tool pushes down on the sheet metal, causing plastic deformation at a point, during its trajectory, which is the outline of the shape being manufactured. In TPIF, one tool presses into the sheet and the other acts as a partial die. Because of the partial die, TPIF is not truly dieless, although it is often called that. The TPIF apparatus, shown in **Figure 2.2**, consists of an apparatus, which clamps the sheet metal (blankholder), and allows for downward movement with the tool-path increments in the z-axis direction

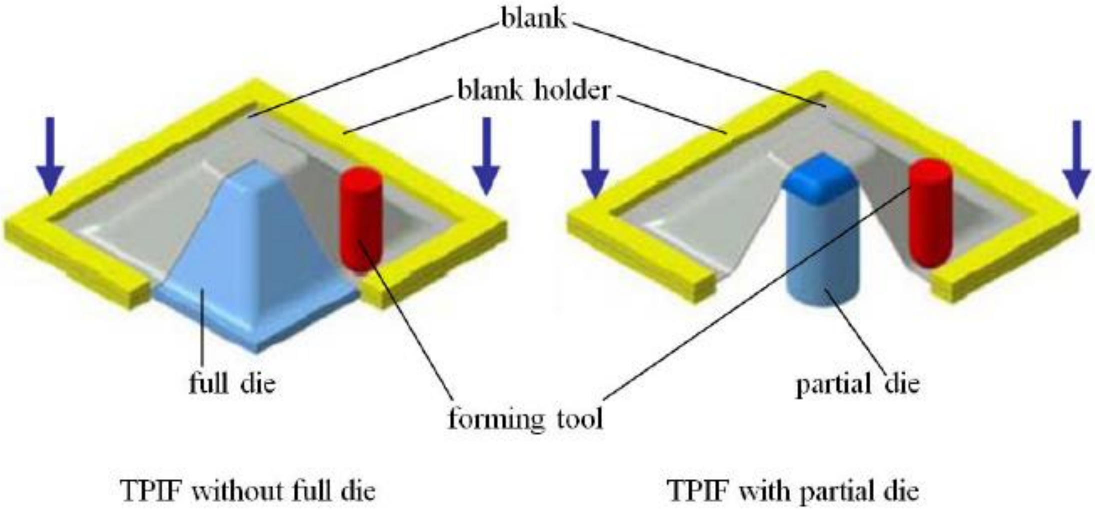


Figure 2.2. Two point incremental sheet forming TPIF without full die (on the left) and with partial die (on the right).

The centre of the blank is supported with a stationary post (a partial die) and a clamped perimeter (blankholder) that moves down as deformation of the sheet progresses. To prevent twisting of the shape about the partial die there is a support plate under the blank.

2.2.3 Kinematic incremental sheet forming (KISF)

In this new development two forming tools are used (one on either side of the blank), which are actuated simultaneously. It is illustrated in **Figure 2.3**. This process variant is a truly dieless sheet metal forming process. It offers additional flexibility over the SPIF process. Currently, the biggest challenge in the development of KISF seems to be the definition and synchronization of the tool paths of the master and slave tool.

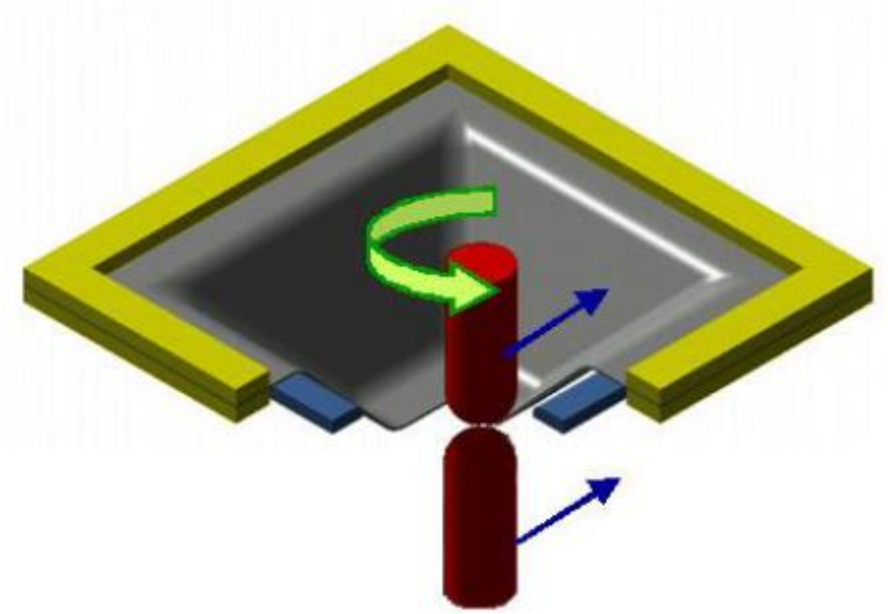


Figure 2.3. Kinematic incremental sheet forming KISF.

2.2.4 ISF in the present research

In the actual PhD research activity this process and, in particular, the simplest configuration, i.e. the well-known Single Point Incremental Forming, from now on indicated generally as ISF, has been considered in order to derive sustainability considerations. This configuration strongly emphasizes Schmoekel’s vision (Schmoekel, 1992), since the process equipment is limited to the minimum: a simple frame, able to clamp the steel plate, and a hemispherical punch, which follows a fixed trajectory (see

Figure 2.1). The basic apparatus for SPIF process is shown in **Figure 2.4:** a single forming tool is acting on a sheet clamped under a frame, that is stationary.

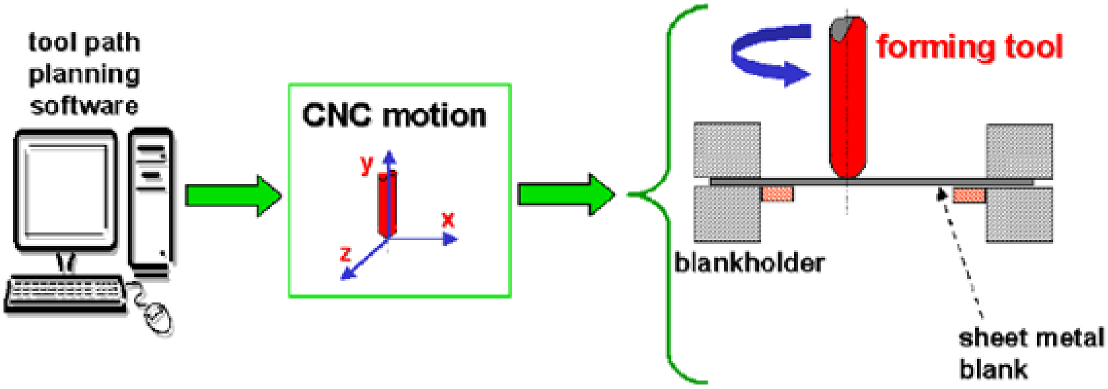


Figure 2.4. Basic apparatus for SPIF process.

Actually, this process is not widely used in manufacturing production, being not really attractive from the industrial point of view because of its high time consuming. Up to now, few applications exist related to the field of rapid manufacturing of single parts. Nevertheless, the advantages that SPIF presents are undeniable and they can be summarized as follows:

- it does not require neither positive nor negative dies;
- it guarantees a high degree of flexibility, so possible changes in part design sizes are easily and quickly arranged;
- the incremental nature of the process contributes to increase formability;
- it requires, in the simplest way, a conventional CNC milling machine;

The simplest typology of Incremental Forming has been utilized at the University of Calabria, and it is characterized by four basic elements (**Figure 2.2**):

- a sheet metal blank;
- a blankholder;
- a single point forming tool;
- CNC motion.

The equipment necessary to incrementally form sheet metal includes a forming solid tool, a machinery that moves it in a controlled manner and rigid blankholders to clamp the sheet. In general, a wide variety of tools can be used, but usually solid hemispherical head is employed, because this shape assures a continuous contact between the sheet and the punch. Generally, the ball-head tools are made of steel; nevertheless, in order to reduce friction and to increase lifetime, the punch can be coated with or even be made out of cemented carbide (also referred to as Tungsten carbide - WC).

In addition, lubrication is useful to reduce the wear. All CNC-controlled three-axis machines are suitable to perform the SPIF, but they are not the only ones. All the types of machines available to do incremental forming are: CNC milling machines, purpose built machines, robots, Stewart platforms and Hexapods.

2.3 Limits of ISF

Furthermore, in the last few years another trend is clearly discernible in the metal forming industries, namely the development of flexible forming processes, well suitable for small scale or niche productions (Jeswiet et al., 2005). One of the most recent and interesting processes is Incremental Forming, which has shown, among the other advantages, the enhancement of material formability due to the peculiar process mechanics (Filice et al., 2002). Several incremental forming applications have been proposed in technical literature, mainly on steels and Aluminium alloys. In literature, there are also some results of a wide study focused on the application of incremental forming to Magnesium alloys (Ambrogio et al., 2007). The main objective of the research was the analysis of process suitability, through the evaluation of material formability and the assessment of the role of the most important process parameters.

In spite of many advantages, the ISPF process presents several disadvantages. Moreover, as detailed in Bambach (2008), for a wider industrial use of ISF it is mandatory to find solutions to the main limitations of the process, which are: (i) the long process time, (ii) the sheet thinning, (iii) the limited geometrical accuracy and (iv) the lack of dedicated process planning and modelling tools (Jadhav, 2003). Each of the process limits will be analysed separately.

2.3.1 Sheet thinning

Thinning in ISF depends on the wall angle α according to the so-called sine law (Kitazawa and Nakajima, 1999). For parts with wall angles greater than 60-70 degrees, multistage forming strategies have to be used to avoid excessive thinning. In multistage forming, a pre-form, several intermediate shapes and the final part geometry are formed by AISF. As reported by Hirt et al. (2005), a process time of approximately 7 hours is required to produce a square box of 200 x 200 x 60 mm^3 in 15 forming stages. The intermediate stages had to be found by trial and error. As a consequence, this approach cannot be easily transferred to more complex parts. An improved forming strategy detailed in (Hirt et al., 2005) generates a pre-form by stretching the sheet metal roughly over the male die using AISF with a large step-down. A stiffening brace was manufactured using this strategy (Hirt et al., 2005), but pre-stretching by AISF leads to large forming forces and increases the likelihood of wrinkling, which makes it hard to transfer this approach to other part geometries.

2.3.2 Geometric accuracy

Recently, Micari et al. (2007) have studied the feasibility of some forming strategies that aim at improving the accuracy of parts formed by AISF, identifying tool path overbending as a promising approach to improve the accuracy of a part. In contrast, the work detailed by Hirt et al. (2004) shows that overbending induces waves on the formed part, and that a part manufactured by AISF will contain considerable residual stresses as a consequence of the cyclic loading and unloading during forming.

2.3.3 Forming time

AISF is an incremental forming process. The time to manufacture a part is determined by the length of the tool path and the average travelling speed of the forming tool. Bambach (2008) shows that the process time required to manufacture a conical frustum of height h, bottom radius r=h and top radius 2r scales quadratically with h. Assuming an average speed of 500 mm/s and a step-down of 0.2 mm for the tool path, the forming time is already greater than one day for a conical frustum of 1 m height.

2.4 ISF and the new materials

According to the new keywords which are influencing the approach to the industrial problems in the last years, energy saving is probably one of the most relevant since it is clear that the energetic resources are limited and, in the next time, they will constitute a strategic problem all over the world. The Green House effect and the Kyoto protocol pushed the researchers all over the world to study the production taking into account the environmental impact. Thus, the farms and the research focalized their attention on new process solutions and on new materials. Industry is changing its strategies and the use of the lightweight materials become a key-factor for instance when mobile structures are designed, such as automobiles.

It is quite obvious that the development of new materials characterized by a favorable strength versus mass ratio surely represents a strategic issue: such materials would permit to manufacture lightweight vehicles, allowing lower CO2 emissions. New materials, in turn, introduce some criticisms, mainly related to the higher costs and sometimes to the lower workability (Neugebauer et al., 2006). Considering the new materials in the last decade, it is clearly discernible a wide trend focused on the light alloys characterized by an high ratio strength versus density. In fact in term of pollution reduction, a suitable way to obtain that is surely the weight reduction politics. Moreover, from a manufacturing point of view, the light alloys introduced some new criticism due to the lack of knowledge in particular in the sheet metal forming processes. In fact, it is usual to produce some components in light alloy by casting or forging processes, but in the sheet metal domain the not fully understood material behavior is the main drawbacks which border a wide and easy industrial application. In detail, the light alloys, due to their microstructure, show poor attitude to be deformed at room temperature but this aspect is improved increasing the process temperature. Moreover, up to now, due to the not fully understood process mechanic the incremental forming process shows some relevant drawbacks with a strong impact on the industrial applicability.

In this thesis, with the aim to fill a part of the aforementioned lacks of knowledge, the manufacturing of new materials is investigated by studying the application of light alloys (especially Aluminium alloys and also titanium alloys) in a traditional deep drawing process. Among new materials, Magnesium alloys show interesting features, since their cost is not prohibitive and there is already some technical knowledge available on their workability which permits feasible applications. In fact, some components in automotive and transportation industry are already produced in Magnesium alloys.

More in detail, Magnesium alloys require a forming temperature higher than room temperature and it is usually worked in warm conditions, namely at a temperature ranging between 200°C and 300°C (Iwanaga et al., 2004; Zhang et al., 2006). These temperatures, in fact, permit to activate new sliding planes and dramatically increase material formability.

Titanium alloys are substituting Aluminium for manufacturing an increasing number of mechanical components due to a higher strength versus mass ratio. A systematic study on the manufacturing of aircraft parts by using hot forming process is presented by Ambrogio et al. (2010). The development of lighter transportation vehicles has been one of the proposed solution; thus, new cars, trains and aircrafts have been designed using new classes of materials, both composite and metallic. The latter are the so called lightweight alloys that allow a strong mass reduction guaranteeing, at the same time, improved safety conditions for carrying load air-structures. Among those materials, titanium can surely take a leadership due to its excellent mechanical characteristics even if some processing problems are not yet solved.

Titanium alloys, in fact, show a very low cold workability; for instance, sheet forming presents significant difficulties due to the low Young's modulus, compared to steel, and high yield stress, which are responsible of a relevant springback that can strongly affect the final part accuracy. For this reason, titanium alloys are mainly processed at high temperature. However, their hot workability may be limited by the generation of various internal defects (such as cavities and shear bands) that can produce gross failures (Semiatin et al., 1998). The stamping formability of titanium alloys was deeply investigated by Chen and Chiu (2005), in order to generally improve the quality and the productivity of manufactures optimizing the process variables and the die design.

2.5 The market for incremental sheet forming processes

Due to its intrinsic characteristics, the ISF process cannot replace the conventional processes, like deep drawing, for mass production. The ISF process can be applied in the small batch production. For sake of clarity, a short overview onto the actual market and on its perspectives and trends is reported. The small batch production market is a part of the traditional market involving the niche production, but also in the traditional applications like automotive industries a deeper analysis can show more potential application field for ISF process. In fact, considering the automotive field, the prototyping or the production of highly customized car, like ambulance, limousine, funerary vehicle or more the restoration of veteran or vintage car can be considered as a niche production.

The car industry in Germany employed approximately 766000 people in 2005, representing 13.2% of the total industrial workforce. Since 2003, one third of the total R&D investments in Germany has stemmed from the German automobile industry. This makes the car industry a key player in the economy. With stalling global production and sales figures, it is forecast that the trend towards batch size reduction will continue, especially in the premium car segment, which is stated to be of great importance to German car manufacturers. This example of the German car industry blends well into a general trend towards individualized production in high-wage countries. Besides producing individualized products from scratch, ISF offers a way to customize mass products, e.g. to produce cars with an individual design based on series cars.

2.5.1 New market perspectives

ISF offers a number of favorable features that might open new markets. One salient feature is that complicated, almost arbitrarily shaped free-form surfaces can be manufactured. This includes parts that cannot be manufactured by deep-drawing. Thus, ISF enables potential applications in architecture and design, domestic appliances, etc.. The Italian company MONTES was reported to manufacture up to 20 pieces of design furniture per month by ISF. An advantage of ISF over deep-drawing is that forming forces do not increase when the size of the part increases since the plastic deformation is induced locally. This might open the possibility to use ISF for very large sheet metal parts, e.g. in the aerospace industry or in civil engineering/architecture. Other potential applications are the replacement of rapid prototyping parts that are currently made of non-metallic materials, the rapid manufacturing of dies (e.g. for injection-moulding, the production of composite materials, etc.).

Moreover, there are some industrial field, like aerospace industries, in which the market is traditionally determined by large parts in relatively small batch size.

Despite almost 20 years of development and research on incremental forming processes, the limits are not overcome and moreover the not fully understood process mechanic border their industrial applications although the noticeable advantages recognizable from a literature review.

On the other hand, new materials showing a high formability introduce, in turn, some criticisms, mainly related to the higher costs and sometimes to the lower workability. In fact, the light alloys can show interesting features since the cost is not prohibitive and there is already some technical knowledge available on their workability which permits feasible applications.

The new technique known as high speed ISF consents to produce a component, maintaining the same quality level, but reducing the forming time, thus allowing a reduction of the total energy consumed, as better explained further. This new technology can allow a wider diffusion of ISF technology within manufacturing industries.

Finally new processes have been introduced namely Warm Incremental Forming and Hybrid Incremental Forming in order to extend the formability or, in the case of Hybrid Incremental Forming, to overcome some process limitations such as process time, geometrical accuracy and part feasibility.

2.6 Measurement equipment

Measurement systems for the analysis of force, strain, geometry accuracy were used during the experimental tests reported in this thesis. In this paragraph an overview of the used systems is reported.

2.6.1 Force measurements

The force measurement can give important information concerning the force requirements for a given manufacturing process. In particular, these information can be used to avoid machine overload and to build suitable process models. Moreover another important application of force measurement can be the FE model validation.

Concerning the deep-drawing experiments, the force measurement system is well assessed and normally consist in a load cell placed in the mechanical, hydraulic or pneumatic press. Regarding the ISF process, some different approaches to measure the process load are recognizable in literature.

State of the art in force measurement in ISF

Different approaches were proposed in literature for on-line measurement off process loads, the main difference between these system is due to the sensor positioning. In fact, Jeswiet et al. (2005) proposed a system based on a Weathstone bridge of strain gauges mounted on the tool, Bambach (2008) used a piezoelectric sensor mounted on the tools; while Filice et al. (2006) and Ambrogio et al. (2006) used a piezoelectric sensor mounted below the clamping frame. Moreover to remark the importance of force measurements it is worth to say that an approach of failure prevision, based on force trend control has been proposed by Ambrogio et al. (2006).

The used equipment

In this work the load measurement has been carried out following the method proposed by Filice et al. (2006). In particular, the latter has been implemented on a CNC milling machine mounting the piezoelectric system on the machine frame. The system is reported in **Figure 2.3** and **Figure 2.4**.

Figure 2.3. The ISF equipment for forces measurements on CNC machine.

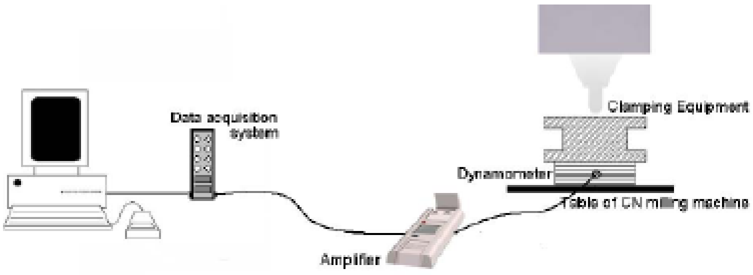


Figure 2.4. The utilized data acquisition system on the CNC machine.

The vertical force exchanged between the punch and the sheet, F_Z, was measured all over the process and any twisting effect was neutralised by the high global stiffness of the equipment. Of course, taking into account the current inclination of the lateral surface of the formed part, both the normal (F_N) and the tangential force (F_T) may be easily calculated. In fact: $F_N = F_Z \cos \alpha$ and $F_T = F_Z \sin \alpha$.

Moreover it is worth to mention that for the experiments carried out with the MAZAK CNC machine, the load measurement has been done also with the MAZAK load control. This control allows the user to avoid the machine overload but can be used to read the process forces.

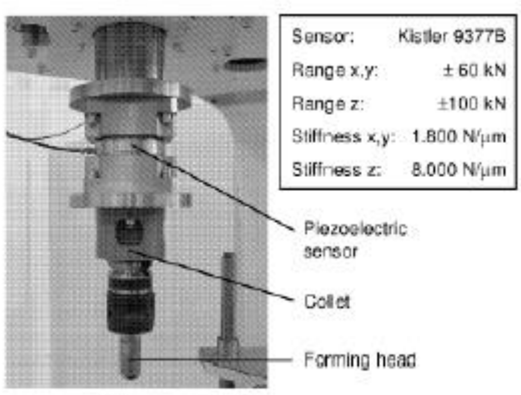


Figure 2.5. Set-up for on line force measurements.

The process loads can be measured mounting a piezoelectric sensor on the punch as showed in **Figure 2.5**. In particular, force measurements can be realised by mounting a piezoelectric sensor between the sleeve and the collet of the forming head (**Figure 2.5**). The sensor records the three force components that the tool experiences during forming.

2.6.2 Strain measurements

The strain analysis can be executed in two different way: on-line and off-line. The more diffused are surely the off-line strain measurement because of the simplicity and economical motivation. The concept of off-line strain measurement consists of a comparison between a segment on the part measured before and after the deformation. This measurement can be executed by printing a grid circle on the part surface and measuring with an optical device the final dimension of the circles.

In the experiments carried out at the Mechanical Department of University of Calabria the aforementioned methods have been used.

2.6.3 Thinning measurements

The thinning measurements were carried out by traditional contact methods or optical device as Leica stereo zoom or more with ATOS system. The latter system is discussed in the next paragraphs.

2.6.4 Accuracy measurements

Laser scanner measurements system

Speaking of geometrical accuracy, the whole field of discrepancies was rebuilt utilizing a proper contactless reverse engineering technique. In particular, a Minolta Vivid 300 laser scanning systems has been used. This system (Varady et al., 1997) is able to rebuild the product geometry by laser triangulation principle (see **Figure 2.7**). This technique is based on a laser source which irradiates a body by a reflected beam. The diffused light is then revealed by a CCD sensor, placed at a known distance from the laser source. Subsequently, starting from the obtained CCD image, the spatial coordinates of some surface points may be calculated.

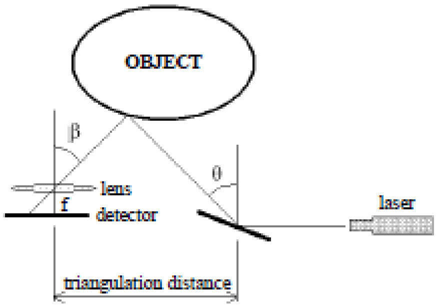


Figure 2.7. The laser triangulation principle.

The utilized set-up consists of the described scanning system and a rotating support on which the deformed workpiece can be univocally placed. In this way any problem due to the repositioning of the sample is avoided (**Figure 2.8**).

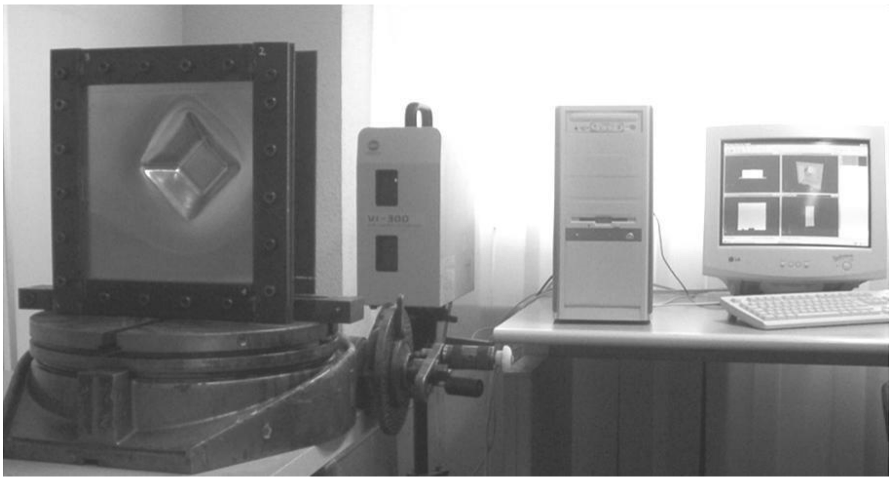


Figure 2.8. The laser based scanning system set-up.

Chapter 3

SUSTAINABILITY APPLIED TO THE INCREMENTAL SHEET FORMING PROCESSES

3.1 The indicators of a sustainable process

The sustainable manufacturing deals with three elements which are integrated: system, process, product (Jawahir et al., 2013). As already stated in chapter 1, to realize a sustainable production, the product, the process and the system must demonstrate to be environmental friendly and that means to produce a reduced environmental impact, to use

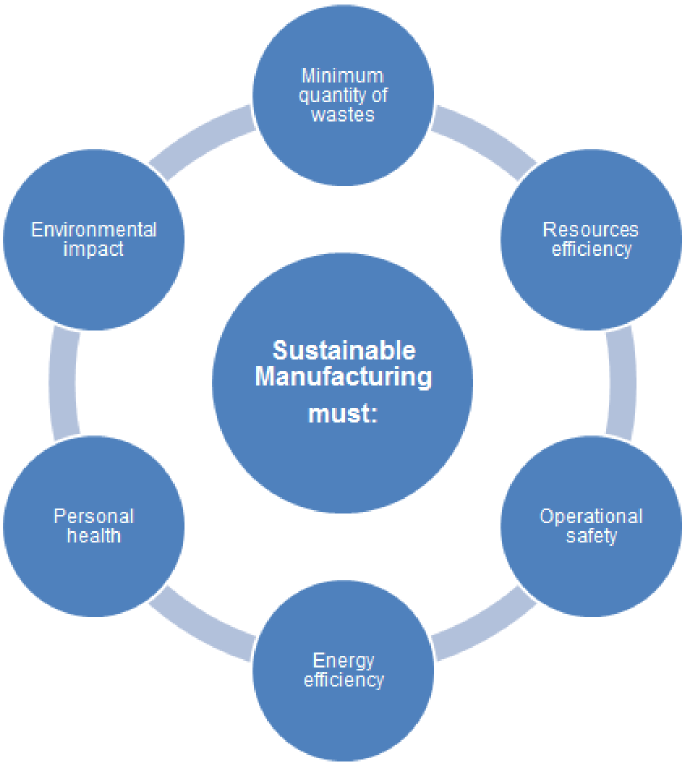


Figure 3.1. The six major key-points to define a sustainable manufacturing (adapted from Jawahir et al., 2013).

energy and materials in an efficient way, to provide operational safety and personal health, as shown in **Figure 3.1**. During this PhD course, some key-points have been considered as crucial: environmental impact, materials efficiency and energy efficiency. The first issue is to establish how the environmental impact can be defined and that is the aim of the first case study. Then, since an important topic is the material efficiency, this topic will be a matter of the following sections and case studies.

3.2 Case study 1: determination of environmental impact in incremental sheet forming

As previously stated, in the PhD research activity, the ISF has been considered in order to do sustainability considerations. In particular, a first line of research investigated during these years concerns some of the most significant aspects of environmental impact of the ISF process. Gutowski (2004) affirmed that many of the environmental problems coming from manufacturing industries are related to both energy aspect and materials usage.

Table 3.1. Manufacturing processes and the relative environmental burden (Gutowski, 2004).

Environmental Concerns	Linkage to Manufacturing Processes
1. Global climate change	Greenhouse gases emissions coming from direct and indirect energy use, landfill gases, etc..
2. Human organism damage	Emissions of toxins, carcinogens, etc., including use of heavy metals, acids, solvents, coal burning.
3. Water availability and quality	Water usage and discharges, e.g. cooling and cleaning use.
4. Depletion of fossil fuel resources	Electricity and direct fossil fuel usage, e.g. power and heating requirements.
5. Loss of biodiversity	Land use, water usage, acid deposition, thermal pollution.
6. Stratospheric ozone depletion	Emissions of chlorofluorocarbons, hydrochlorofluorocarbons, nitrous oxides, e.g. for cooling requirements, refrigerants, cleaning methods, use of fluorine compounds.
7. Land use patterns	Land appropriated for mining, growing of biomaterials, manufacturing, waste disposal.
8. Depletion of non-fossil fuel resources	Material usage and waste.
9. Acid deposition	Sulfur and NO_X emissions from smelting and fossil fuels, acid leaching and cleaning.

More specifically, Gutowski (2004) identified environmental concerns and their connections with manufacturing processes, as shown in **Table 3.1**.

3.2.1 The ISF process after being functionally decomposed

As first application of sustainability in a ISF process, the functional decomposition of the ISF in phases has been proposed. Moreover, for each step, lubricant, energy and material input and output are analyzed and quantified. The basic apparatus for ISF, as better explained in the previous chapter, is characterized by the following elements: a sheet metal, a blankholder, a forming tool, and a CNC motion. In this study, a common milling machine is considered, that is suitable to perform the ISF process, as clearly assessed in literature (Jeswiet et al., 2005). As desired output (**Figure 3.2**), a frustum of pyramid is fixed as specimen profile. Dimensions of the truncated pyramid are the following ones: it has a side of 100 mm, a slope wall angle of 55° and a final depth of 50 mm. The worked material is in an Aluminium alloy: AA 6082-T6, 1 mm thick. In ISF, the initial blank shape must be larger than the largest spire in order to assure a proper fastening under the blank holder. Conventionally, it is frequent to consider a frame dimension equal to 10 mm all along the sheet outline.

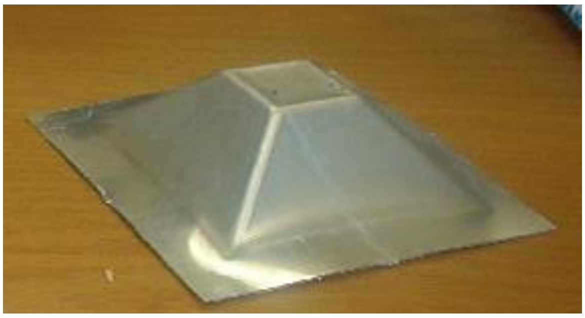


Figure 3.2. Desired output: frustum of pyramid.

According to the simplest configuration, one manufacturing step without polishing or piercing is considered. In **Figure 3.3** a functional decomposition of the process is shown: the ISF has been divided into two steps, and the inputs and outputs relative to environmental aspects are briefly represented.

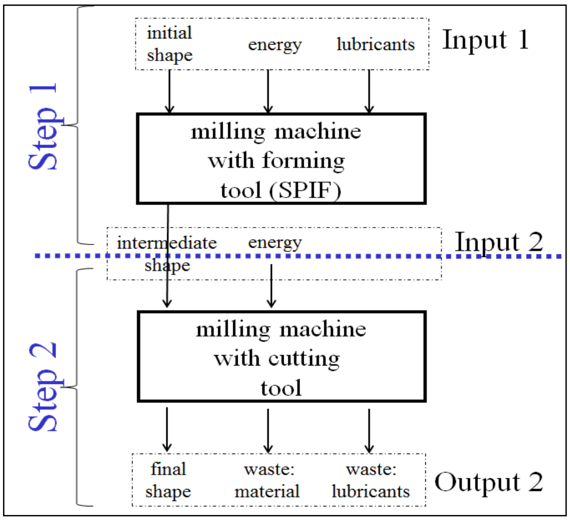


Figure 3.3. ISF process divided into phases.

The phases mentioned in **Figure 3.3** can be better explained and detailed. Step 1 specific actions within the ISF process are: a) clamping; b) lubricants; c) manufacturing. Step 2 specific actions are the following ones: d) punch removal and preparing equipment for cutting; e) cutting; f) cleaning (lubricants).

In order to quantify the energy input for Step 1, the energy required by the incremental forming process can be evaluated as:

$$E_{INPUT,1} = \int F_x \cdot dx + \int F_Y \cdot dy + \int F_Z \cdot dz \tag{1}$$

where the three components of the contact force can be measured through an experimental procedure described in the literature (Ingarao et al., 2011a). The forces values were determined by a dynamometer, whose precision is ± 2%. Each test configuration was repeated three times, in order to validate the procedure generalization. The forces trend in all three tests executed was very similar, maintaining the same conditions. The energy was so calculated considering the area with respect of the average force distribution.

An energy consumption of 2682 J is estimated for the same ISF process analysed in this study.

The energy required by the cutting process (Step 2 in **Figure 3.3**), by which the area used for clamping the initial shape is removed, can be quantified by assuming a constant cutting force, given by:

$$F_Z = \tau_{US} \cdot p \cdot t = 0{,}577 \cdot \sigma_{US} \cdot p \cdot t \tag{2}$$

where σ_{US} and τ_{US} are the ultimate tensile and shear stress of the material respectively, p is the perimeter and t the thickness of the initial shape. Assuming a negligible error for determining p and t, and using a value of $\sigma_r = 290\ MPa$ for AA 6082-T6, a constant cutting force of 66932 kN is calculated, which requires an energy input of 67 J, as reported in **Table 3.2**.

Table 3.2. Input 1.

Step 1- Input 1	Quantity per piece
Case (a): Blasocut 2000 Universal	0.533 ml
Case (b): Castor oil	5 ml
Initial shape area	24400 mm^2
Energy	$E_{INPUT,1}$=2682 J

Table 3.3. Input 2.

Step 1- Input 1	Quantity per piece
Case (a): Blasocut 2000 Universal	0.134 ml
Case (b): Blasocut 2000 Universal	0.134 ml
Case (b): Castor oil	-
Energy	$E_{INPUT,2}$=67 J

The second aspect of ecological impact of the ISF is related to waste materials. For this case study the clamping area, which is cut off in the second phase of the process, is about 30% of the initial area. Waste materials are an ecological cost that cannot be avoided in ISF, since it is not possible to incrementally manufacture a blank without a proper clamping area. The ecological impact of waste materials, however, can be limited if materials with high recycling efficiency, as in this case, are used: for Aluminium and its alloys a 100% recyclability is estimated.

Generally, during the first step of the process, lubrication, that is absolutely indispensable, can be obtained by using liquid oils/emulsions or the same mineral oil-based coolant employed by the milling machine for refrigerating purposes. Both the alternatives are taken into account.

Lubrication: first case (a)

To properly work, the milling machine needs a mineral oil-based coolant. This coolant, at the end of several manufacturing and cutting cycles, can be collected in convenient cans and sent to treatment plants, as explained farther. As mineral oil-based coolant, Blasocut 2000 Universal, that presents a mass density of about 0,96 g/cm^3, has been chosen. The following considerations can be done to quantify the amount of lubricant required to process one piece. Typically, a milling machine is fulfilled with 20 litres of a mixture of water and Blasocut 2000 Universal, with a volume composition in water of 90%, each 3 months. Supposing that the milling machine works all the year on one work shift, the amount of Blasocut 2000 Universal per piece is equal to 0.667 ml. In terms of time, step 1 covers 80% of the full process timeline and a constant coolant flow rate is expected, so this quantity can be split into 0.533 ml and 0.134 ml for Step 1 and Step 2 respectively.

Lubrication: second case (b)

In this case, during Step 1 the lubrication is obtained by using liquid oils/emulsions. At the end of the manufacturing process, the oil or emulsion is taken away with paper napkin and it is difficult to reclaim the used lubricants. At the end of the process, the waste of lubricant for this case (b) will be the same quantity as in input. As lubricant, Castor oil has been chosen, with a mass density of about 0.96 g/cm^3. The quantity of Castor oil adequate to assure a proper lubrication during Step 1 of the forming process is about 5 ml per piece. In case (b), in addition to Castor oil, which is used during Step 1, Blasocut 2000 Universal, strictly limited at the Step 2, is also employed. In fact, as for case (a), the full process timeline can be split into 80% for Step 1 and 20% for Step 2. For case (b), considering the same conditions described above, there is no reason to suppose a different coolant quantity for the cutting phase, which will be 0.134 ml. In case (b), the milling machine used for ISF processes, will be fulfilled with 20 litres of a mixture of water and Blasocut 2000 Universal, with a volume composition in water of 90%, each 12 months instead of 3 months (case (a)).

The lubricant input for the two phases are summarized in **Table 3.2** and **Table 3.3**. In **Table 3.4** the output of the process in terms of waste lubricants and material is summarized.

Table 3.4. Output 2.

Step 2 - Output 2	Quantity per piece
Waste lubricants (Castor Oil)	case (a) → 0 ml case (b) → 5 ml
Waste mineral oil-based coolant (Blasocut 2000 Universal)	case (a) → 0.667 ml case (b) → 0.134 ml
Waste material	4400 mm^2

Based on the functional decomposition and input/output analysis illustrated above, CO_2 emissions due to the use of lubricants and electric energy have been quantified.

3.2.2 Emission of CO_2

It is well known that fossil fuels, such as coal, petroleum and natural gas, represent the most common primary source of energy, even if they are non-renewable resources. Energy production is obtained in thermal power stations by means of a combustion process, during which carbon dioxide (CO_2) is released as a consequence the high percentage of carbon in the fuel. CO_2 is one of the primary greenhouse gases (GHG), as better clarified below.

The most common greenhouse gases

The most common GHG are listed in **Figure 3.4**: as shown, they can derive from both natural and industrial processes. The atmospheric concentration of both the natural and man-made GHGs have been rising over the last two centuries due in large part to the industrial revolution (Spahni et al., 2005).

One-Hundred-Year Global Warming Potential. The Global Warming Potential (GWP) of a GHG is defined as the ratio of the time-integrated irradiative effect from the instantaneous release of 1 Kilogram of a substance relative to the instantaneous release of 1 kilogram of a reference gas (IPCC, 2001). The integration time horizon is usually one hundred years; the reference gas is CO_2.

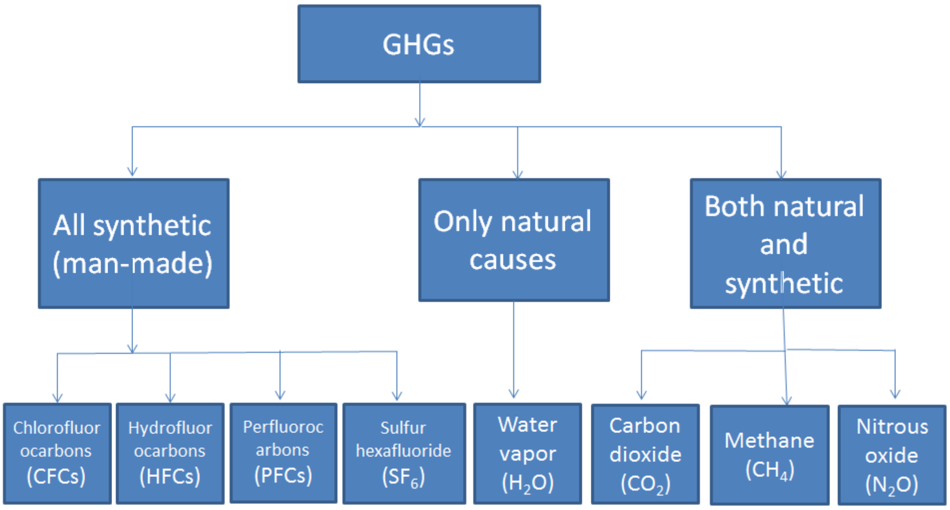


Figure 3.4. Major greenhouse gases (Sondergard, 2009).

Various gases in the atmosphere can have direct and indirect consequences on the greenhouse effect.

- Direct effect. If the gas is a GHG, then it will have a direct effect by directly absorbing infrared radiation, and this effect will be proportional to the atmospheric lifetime of each GHG (for instance SF_6 lifetime is about 3200 years, whereas methane lifetime is between 10 and 12 years, as shown in **Table 3.5**).
- Indirect effect. There are some gases that can chemically react with other gases: for instance, methane is quite instable and produces into the atmosphere some water vapour, whereas CO_2 is much more stable.

Table 3.5. The 100-years GWP for various gases (IPCC 2001 third Assessment Report; IPCC 2007 Fourth Assessment Report; Sondergard, 2009).

	Chemical Name	GWP Note that these GWP data have an uncertainty of about ±35%	Atmospheric Lifetime [years]	Current Level [ppm means "part per million"; ppt means "part per trillion"]	Pre-industrial level
CO_2	Carbon Dioxide	1	50-200	380 ppm	280 ppm
CH_4	Methane	23	10-12	1.77 ppm	0.72 ppm
N_2O	Nitrous Oxide	296	114	0.32 ppm	0.27 ppm
SF_6	Sulfur Hexafluoride	23900	3200	5.4 ppt	0.0 ppt
CF_4	Carbon Tetrafuoride	6500	>50000	80 ppt	40 ppt

First fraction of CO_2 emitted, due to energy consumption

In **Table 3.6** the amount of CO_2 released for each GJ of energy produced by the most common fossil-fuel combustion reactions is shown. As reminded in chapter 1 there are also renewable resources, which produce clean energy, i.e. without generating CO_2 emissions.

Table 3.6. CO_2 released during different combustion reactions (Jeswiet and Kara, 2008).

Combustion reaction		**CO_2 emissions [Kg] per GJ of energy produced**
Coal	$C+O_2 \rightarrow CO_2$	112
Heavy oil	$C_{20}H_{42}+30O_2 \rightarrow 20CO_2+21H_2O$	66
Biomass	$CH_2O+O_2 \rightarrow CO_2+H_2O$	100
CH_4	$CH_4+ 2O_2 \rightarrow CO_2+2H_2O$	49

If only clean energy is used during an industrial process, no CO_2 emissions are chargeable to the process itself.

Table 3.7. Electrical power grid for Italy in 2009 (Terna, 2010).

Energy resources	Coal	Natural gas	Petroleum and petroleum by-product	Other	Renewable	Balance from foreign countries
[%]	11.9	44.2	4.8	4.8	20.8	13.5

In this research, an energy analysis method, studied and proposed by Jeswiet and Kara (2008), has been used to connect the energy required by the ISF process directly to the carbon dioxide emissions. Since the environmental impact, in terms of CO_2 released, does not depend only on the total energy consumed during the process, but also on the method used to generate such energy, the distribution of the different electric sources in a certain country at a fixed time must be considered in order to do a correct analysis. The electrical power grid for Italy at the end of 2009, shown in **Table 3.7**, is taken into account to evaluate the ecological impact of the ISF process in that country. For a given electrical power grid, the amount of CO_2 emitted per GJ of energy produced, which is known as Carbon Emission Signature (CES) index, can be quantified by taking into account the fractions of non-renewable energy resources. If only coal, petroleum and natural gas are considered, based on the CO_2 emission data listed in **Table 3.6**, the CES^{TM} index can be calculated as:

$$CES = \frac{1}{\eta}\left(112 \cdot \kappa_C + 49 \cdot \kappa_{NG} + 66 \cdot \kappa_P\right) \tag{3}$$

where η is an efficiency factor that takes into account energy dissipations occurring during production, transportation and storage. A value of $\eta = 1/3$ is considered, as suggested by Jeswiet and Kara (2008). In (3), κ_C, κ_{NG} and κ_P are, respectively, the coal, natural gas and petroleum fractions for the grid under study. By using the data listed in **Table 3.7** and ignoring the energy fraction coming from foreign countries (that is mainly coming from nuclear energy), the CES^{TM} index for Italy is calculated and shown in **Table 3.8**.

Table 3.8. CES^{TM} for different European countries. [Germany, France and UK data source: International Energy Agency – 2006. Italy data source: Terna – 2009 (www.terna.it)].

Country	CES [gCO_2/J]	Coal (%)	Natural Gas (%)	Petroleum (%)
France	0.023	4.62	3.67	1.25
Germany	0.182	48.03	12.09	1.52
UK	0.185	38.52	35.83	1.27
Italy	0.114	11.9	44.2	4.8

Looking at data in **Table 3.8**, the CES^{TM} index of France appears to be the lowest, since this country makes extensive use of nuclear source (about 79%). On the contrary, Germany and UK are particularly penalised by the large consumption of coal. The Italian situation is intermediate between the others and characterized by a large use of natural gas. Starting from the CES^{TM} value, the amount of GHG emitted, as a consequence of energy consumption, during a manufacturing process, can be calculated as:

$$GHG_{emitted} = Energy\_Consumed \cdot CES^{TM} \qquad (4)$$

By combining the energy input data shown in **Table 3.2** and **Table 3.3** with the Italian CES^{TM} index, the amount of CO_2 emissions per produced piece is calculated and shown in **Table 3.9** for each phase of the ISF process.

Table 3.9. CO_2 emissions for the ISF process, due to the consumed energy.

Process	Energy [J]	CO_2 emitted [g]
Step 1	2682	305.7
Step 2	67	7.6
Total	2749	313.3

Second fraction of CO_2 emitted, due to lubricant use

In manufacturing processes a full use of lubricants is made, even if they are harmful to the health of workers and environmentally disadvantageous. The environmental impact of lubricants has been calculated according to two different methods: the first approach considers the whole life cycle of oils, whereas the second one is related to oil end-of-life.

Method number 1: following a life cycle perspective

To reduce friction and, hence, wear in the contact area during incremental sheet forming processes, it is necessary to supply lubrication. As already stated in chapter 1, Hermann et al. (2007) revealed that potential alternatives to oils are the eco-benign lubricants, which are based on vegetable or animal fat oil esters. Thanks to their technological peculiarities, the eco-benign lubricants can be considered as suitable substitutes for traditional oils. Furthermore, the CO_2 emitted during the entire life cycle of a specific eco-benign lubricant, are significantly lower than the ones coming from mineral oils life cycle. Following Nava et al. (2010), CO_2 emissions, due to the use of lubricants during a specific process, can be calculated multiplying the amount of lubricant used by the CO_2 emitted per unit mass of the lubricant itself. CO_2 emissions, calculated with a life cycle perspective for the most commonly used lubricants, are listed in **Table 3.10**.

Table 3.10. Life cycle CO_2 emissions per unit mass of different lubricants (Dettmer, 2006).

Lubricant	Mineral oil (Castor)	Used cooking oil	Animal fat ester	Palm oil ester	Rapeseed oil ester
gCO_2/g lubricants	3.08	0.59	1.11	1.46	3.04

The life cycle method has been applied to calculate the CO_2 emissions due to the use of Castor oil in Step 1 – case (b) of the ISF process. The amount of Castor oil that ensures a proper lubrication during the forming process is about 5 ml per piece, while the cutting phase does not require it, as summarized in **Table 3.2** and **Table 3.3**. As previously stated, a mass density of 0.960 g/ml is supposed for the oil, the CO_2 emissions per piece, due to the use of Castor oil during the whole process, are:

$$GHG_{Castor\_oil} = 5\ ml \cdot 0{,}96\ g/ml \cdot 3{,}08\ gCO_2/g \cong 14{,}78\ gCO_2 \tag{5}$$

About Blasocut 2000 Universal, since no data are available in literature that allow to analyse the environmental impact of this coolant from its production to its end-of-life, the CO_2 emissions due to the use of this coolant cannot be calculated with the life cycle method. In this case the waste lubricant is collected and sent, at the end of the manufacturing process, to treatment plants; thus, a different method, based on an end-of-life perspective, has been used to quantify its ecological impact, as it illustrated farther.

Method number 2: following an end-of-life perspective

Coou (2010) is an independent Italian Environmental Consortium, established by law with the aim of implementing the European Economic Community directive 75/439 on “dangerous wastes”. Coou has operated since its establishment on waste oil management, by ensuring either the collection or the recycling of used oils. In the consortium system, a lot of different subjects are involved: oil holders, collectors and treatment plants.

The treatment plants are:

1. refineries, where the used oils are re-refined in order to obtain regenerated base oils. This destination has top priority because it allows the full recovery of used oils;
2. combustion plants, where the oils are burned as fuel;
3. incinerators, where the used oils (considered unrecoverable because of a high level of contamination) are thermally destroyed.

According to Coou data and to the relative 2009 sustainability report (Coou, 2010), about 200000 tons of used oils were collected and sent to the most convenient destinations, whose distribution is: 85% for used oils sent to refineries for regeneration, 14.1% for combustion, finally 0.1% for thermo-destruction. In the same report, the impact of used oils on the environment (environmental performance) during the collection and the treatment phases is analysed by taking into account several indicators.

The collection phase network is organized on two levels: companies that collect from holders (primary collection) and the Coou that collects from collectors to consortium deposits (secondary collection).

In the storage and re-refining phases, the main environmental aspects are energy and water consumption, waste production, water and air pollutant emissions.

Table 3.11. Environmental impact of waste oils in the primary and secondary collection phases.

	Primary collection		Secondary collection	
CO_2	27	Kg/ton oil	11.8	Kg/ton oil
Hydrocarbon	34.7	g/ton oil	8.4	g/ton oil
NO_X	205.2	g/ton oil	61.4	g/ton oil
Dusts	5.7	g/ton oil	1.1	g/ton oil
CO	159.9	g/ton oil	28.5	g/ton oil

Table 3.12. Environmental impact of waste oils in the storage and re-refining phases.

Emissions into the atmosphere		
CO_2	362	Kg/ton oil
SO_2	0.7	Kg/ton oil
NO_X	0.4	Kg/ton oil
PST	0.02	Kg/ton oil
CO	0.01	Kg/ton oil

Table 3.11 provides basic information to calculate the environmental impact of waste oils in the collection phase, while the environmental indicators related to the storage and re-refining phase are reported in **Table 3.12**, where data related to water pollution, waste production and natural resources consumption have been deliberately omitted. If used oils are treated in combustion plants, the main environmental aspect is air pollution. By using the performance indicators in **Table 3.11** and **Table 3.12,** and limiting the analysis to the re-refined used oils (86% of the total), the environmental impact of waste oils in terms of CO_2 emissions can be quantified as:

$$CO_2 = CO_2{}^{\substack{Primary\\Collection}} + CO_2{}^{\substack{Secondary\\Collection}} + CO_2{}^{\substack{Storage\ \&\\Re-refining}} \cong 0{,}40\ gCO_2 / g\ lubricant \tag{6}$$

The significant differences between this value and those shown in **Table 3.10** can be easily explained reminding that Hermann et al. (2007) calculated the value of CO_2 with a logic of life cycle analysis, whereas, in this case, Coou data refer to end-of-life CO_2 emissions only. On the basis of the output analysis summarized in **Table 3.4**, assuming the same mass density of the Castor oil, the CO_2 emissions per piece due to the Blasocut 2000 Universal can be calculated as:

$$GHG_{Blasocut}^{Case\ a} = 0{,}64\ g \cdot 0{,}4008\ gCO_2 / g \cong 0{,}25\ gCO_2 \tag{7}$$

$$GHG_{Blasocut}^{Case\ b} = 0{,}128\ g \cdot 0{,}4008\ gCO_2 / g \cong 0{,}05\ gCO_2 \tag{8}$$

Looking at gCO_2 calculated in (7) and (8) comparing case (a) and case (b), the Blasocut quantity that is necessary to process one piece is much higher in the case (a) (five times more), and it appears to indicate the case (b) as the best one from an environmental point of view. However, in case (b), there are two kinds of lubrication system (Castor Oil for

Step 1 and Blasocut for Step 2), and the quantity of mineral oil necessary for manufacturing one piece is about 5 ml (**Table 3.4**) and the CO_2 emissions per piece, due to the use of Castor oil during the whole process, are about 14.78 gCO_2, as shown in (5). Therefore, considering only the CO_2 emissions per piece, the best choice is case (a). Furthermore, it is worth pointing out that a disadvantage of the case (b) is that the oil is taken away with paper napkin and it is not possible to reclaim it, whereas an advantage of the case (a) is that the coolant is entirely recycled.

3.3 Case study 2: ISF versus deep drawing and related sensitivity analysis

The first research activity, aimed at obtaining a judgment about the sustainability of ISF, opened the second research line based on the comparison between the ISF and the traditional stamping process. In particular, a sensitivity analysis is here presented in order to compare, from a sustainability point of view, a classical stamping process with an incremental forming one. The worked material, in both cases, have been Aluminium alloys. Different process parameters and different materials are considered and 5 tests for each parameters setting were done, in order to evaluate the influence of such parameters on process energy and material wasting.

3.3.1 ISF and stamping processes modeling

An ISF operation and a classical stamping one are analyzed from two points of view: material use and quantification of energy required to develop the operation. In particular, the analysis of the ISF operation was carried out on the basis of experimental data obtained in the laboratory of the University of Calabria. The stamping operation was numerically investigated by using an explicit formulation. Speaking of ISF technologies in comparison to conventional stamping operations, a first thing to stress is that ISF technologies entail higher strains level (Jeswiet et al., 2005), and that there are many peculiar aspects to be considered which depend on the particular considered processes (tooling systems, operative parameters, GHG emissions, number of forming steps required in a manufacturing cycle, lubricating conditions, temperature effects) and all of them should be properly compared for a wide and comprehensive analysis (Ingarao et al., 2011b). Regarding the objective of quantifying the process from a sustainability point of view, for a given shape to be obtained, a general model is not applicable, since the differences in the processes which could be utilized are so huge to obstacle a unique quantification method. Moreover, the above mentioned issues are influencing each other, therefore only an ”integrated” vision is necessary and is able to take into account all of them. Nevertheless, in literature there is a lack of quantitative models able to consider all the issues in forming process sustainability evaluation. In this case study, the focus is: what is the contribution of forming process design to the reduction of process energy consumption and material wasting? It is well known that, given the same component, the loads required for an ISF operation are lower than those ones deriving from a stamping operation, but in the first case much higher cycle time is necessary. Thus, it is obvious to ask if the total required energy is lower with ISF or DD. In the matter of material used, ISF requires lower material quantities (the shapes are indeed obtained exclusively by stretching mechanics). In order to develop also a sort of sensitivity analysis, in the next sections, different conditions are investigated, such as two different materials and also two different geometries for the final components.

3.3.2 ISF: experimental setup and energy calculation

To establish how the part shape influences the process energy, two different components shapes have been investigated, i.e. a truncated pyramid and a truncated cone. The two Aluminium alloys analyzed have been AA-1050 and AA-5754, which present different mechanical properties (Davis, 1998): more in detail, the former alloy presents higher ductility, lower yield and ultimate stress compared to the latter one.

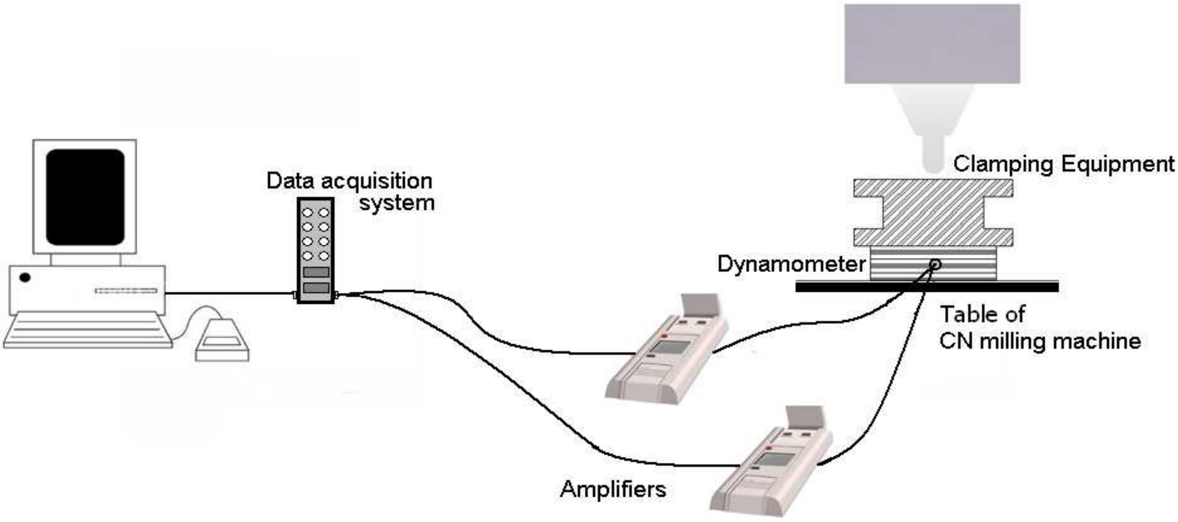


Figure 3.5. Equipment devises scheme for the force acquisition during the ISF process.

The experimental campaign for ISF operations, which consisted in 5 tests for each parameters setting, was carried out through an equipment, that is sketched in **Figure 3.5**, consisting of a 4-axis CNC vertical machine center, equipped with a dynamometer, linked to a data acquisition system, able to measure the force components.

The sheet thickness has been 1 mm. The experimental plan, including the geometrical details of the shapes, is reported in **Table 3.13**.

Table 3.13. Tests carried out during the experimental campaign.

Test	Shape	Material	Dimension (mm)	Height (mm)	Angle (°)
A	Truncated Cone	AA-1050	ϕ_{max}=120	40	45°
B	Truncated Cone	AA-5754	ϕ_{max}=120	40	45°
C	Truncated Pyramid	AA-1050	L_{max}=120	40	45°
D	Truncated Pyramid	AA-5754	L_{max}=120	40	45°

As far as the experimental measurements are concerned, two force components were acquired: Fx, a component along the forming plane and Fz, the component perpendicular to the forming plane (**Figure 3.6**).

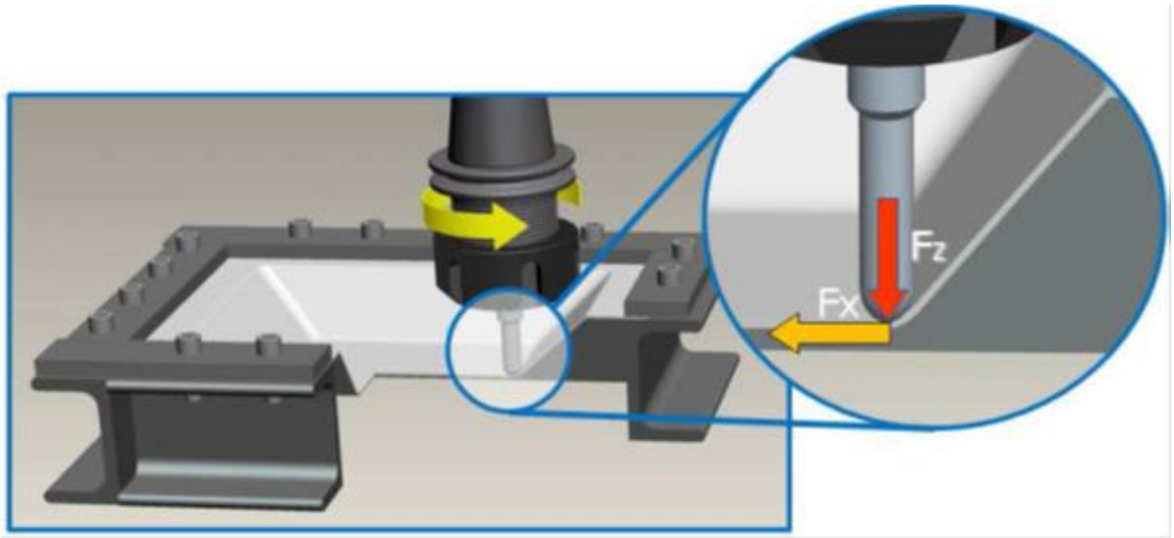


Figure 3.6. Acquired force components sketch.

The remaining third force component (Fy) can be directly derived by the Fx, due to the symmetric shape. During the whole experimental campaign, the other process parameters kept constant have been the following ones:

Table 3.14. The list of parameters kept constant.

Tool diameter	15 mm
Tool depth steps	1 mm
Tool feed	2000 mm/min
Tool speed	200 revolutions per minute
Lubricant	emulsion of mineral oil

The forces trend, experimentally measured, is displayed in **Figure 3.7** and **Figure 3.8**, where it is evident that, after a transitory stage (Filice et al., 2006; Duflou et al., 2007a), the force reaches a steady state (this happens because for both the investigated materials, the wall inclination angle equal to 45° is sufficiently far from the critical value (Fratini et al., 2004). For all 5 tests executed for each parameters setting, the forces trend was almost the same, being the dynamometer accuracy of about the 2%; for this reason it was calculated the average distribution and, as a consequence, the energy value was derived from the area below the average curve.

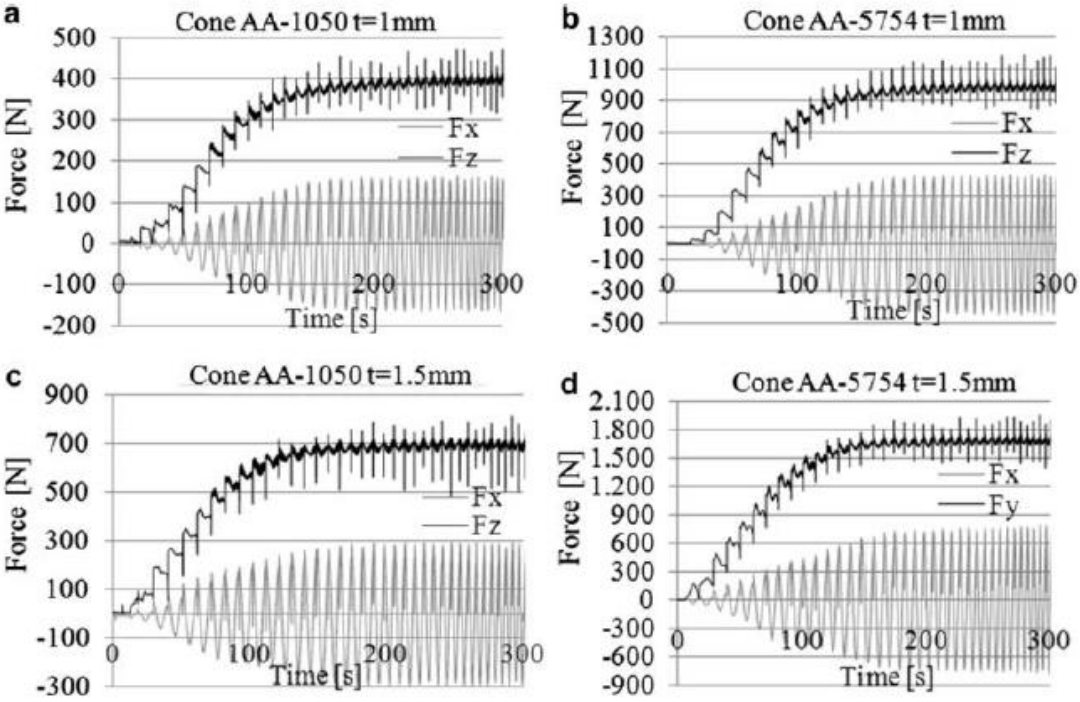


Figure 3.7. Forces distributions during the manufacture of a frustum of cone: a) material AA 1050, thickness 1 mm; b) material AA 5754, thickness 1 mm; c) material AA 1050, thickness 1.5 mm; b) material AA 5754, thickness 1.5 mm.

The forces distributions shown in **Figure 3.7** are refered to a truncated cone, for both 1 mm and 1.5 mm thick sheets. Comparing **Figure 3.7a** and **Figure 3.7b**, it is important to underline that, due to the different material properties, the forces trends are similar, but the magnitude is significantly different; it is also evident that while the AA 1050 reaches a stationary around 400 N for the normal component and ±150N for the planar component, the AA 5754 exceeds more than twice these values. Same conclusion is derived if **Figure 3.8a** is compared to **Figure 3.8b:** in both, the obtained shape is a frustum of pyramid. For the same material and the same thickness (see for instance **Figure 3.7a)** and **Figure 3.8a**), even varying the part geometry, the average values of the force components are not significantly different.

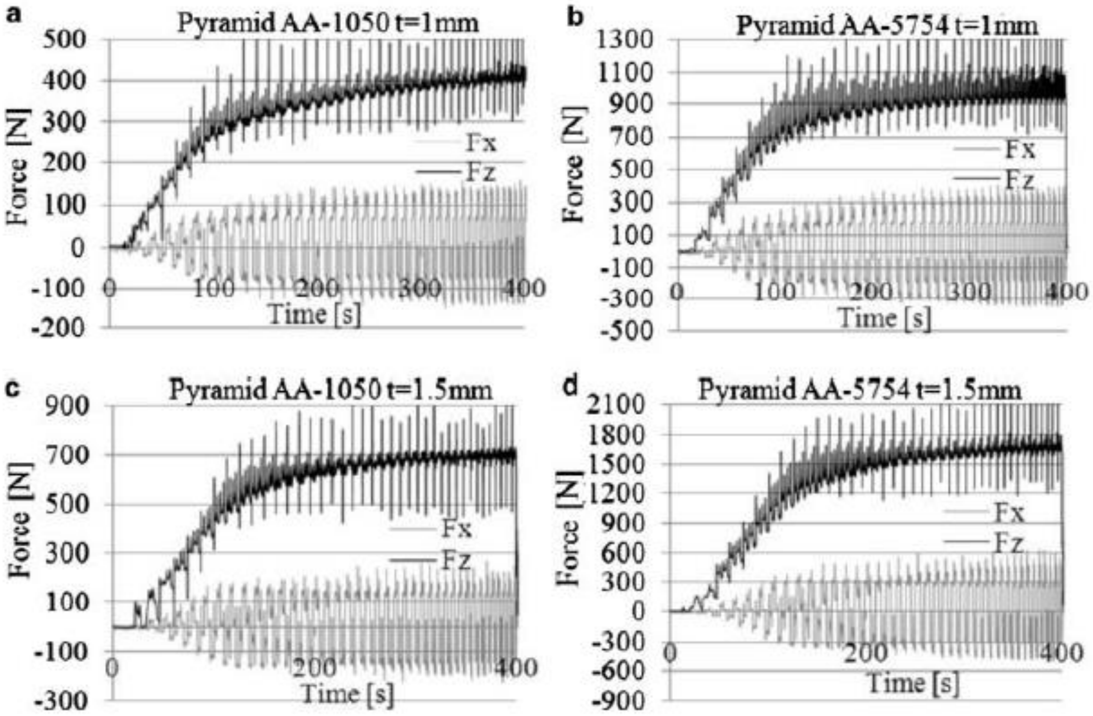


Figure 3.8. Forces distributions during the manufacture of a frustum of pyramid: a) material AA 1050, thickness 1 mm; b) material AA 5754, thickness 1 mm; c) material AA 1050, thickness 1.5 mm; b) material AA 5754, thickness 1.5 mm.

It is possible to calculate the energy necessary for the ISF processes, starting from the above forces diagrams. In particular, **Figure 3.9** shows a zoom of the forces curves along a particular spire in test A (see **Table 3.13**). Energy (Ez) is calculated knowing the force value along z-direction and the entity of the z-direction displacement. Following the same procedure, since the geometry of the part and the tool path are known, the x-component (y-component) of the displacement is known, and also the Fx (Fy) component value, thus the energy component Ex (Ey) absorbed while the punch moves along the spire can be easily calculated.

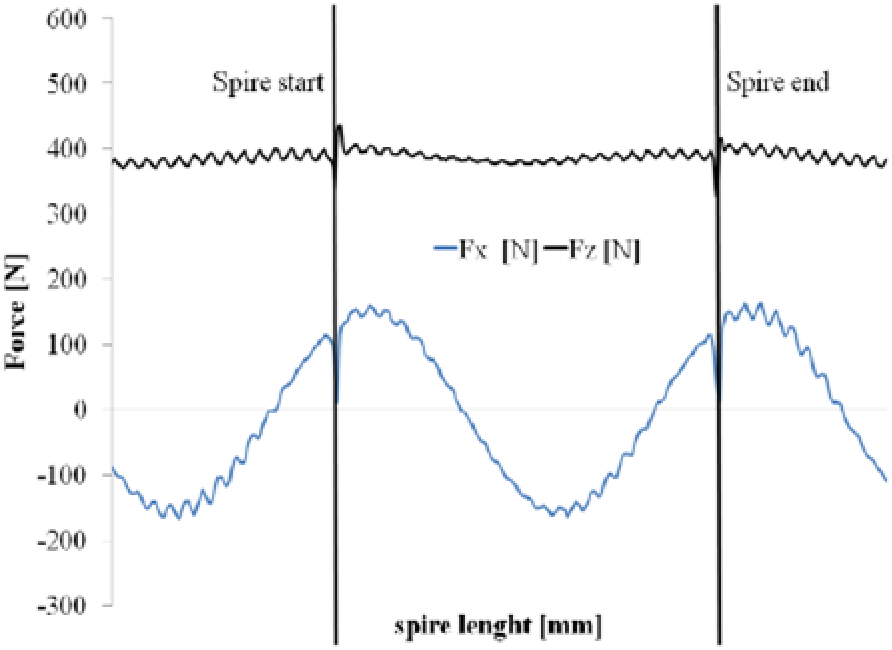


Figure 3.9. Forces components versus spire length for test A: zoom for a single spire.

Similarly, **Figure 3.10** shows a zoom of the forces curves along a certain spire in test D. As above mentioned, the energy is thus calculated.

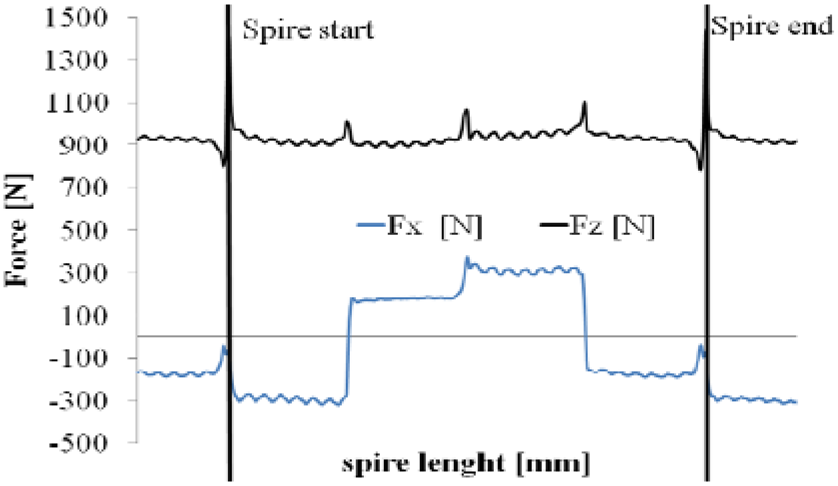


Figure 3.10. Forces components versus spire length for test D: zoom for a single spire.

The energy required for the ISF operations is only a fraction of the total energy consumption for the deformation process. Anyway, as far as a comparison between two processes is necessary, it is quite correct to compare two theoretical energy values. The ideal energy has been finally calculated by summing its three directions components. Similar considerations can be developed for each one of the four tests reported in **Table 3.13**. **Table 3.15** reports the values of the planar (Ex+Ey) and normal energy (Ez) components. As already known, working the AA 5754 requires much more energy. The pyramid part shape requires major total displacement (the major part of it is related to the displacement over the planar directions), and consequently, also higher energies.

Table 3.15. Energy components and relative values.

Test	**Shape**	**Material**	**(Ex+Ey)**	**Ez**
A	Truncated Cone	AA-1050	760.99 Joule	13.21 Joule
B	Truncated Cone	AA-5754	2018.03 Joule	34 Joule
C	Truncated Pyramid	AA-1050	1237.17 Joule	14.90 Joule
D	Truncated Pyramid	AA-5754	2917.93 Joule	38.17 Joule

3.3.3 Stamping process: numerical simulations and load curves

To evaluate the stamping process energy, numerical simulation was used. The model used to simulate the deep drawing process was previously optimized and validated by means of a comparison between numerical and experimental results (Marretta et al., 2010).

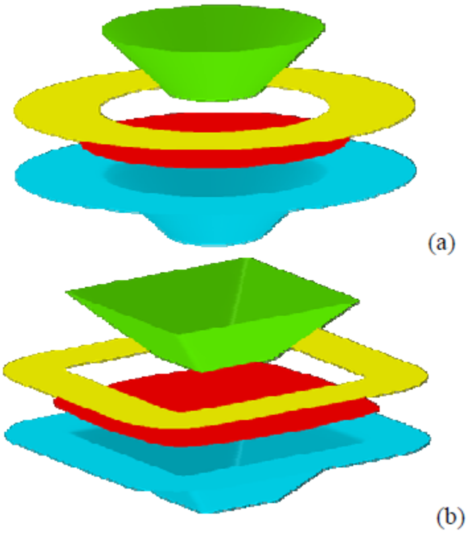


Figure 3.11. Sketch of the stamping operations: a) truncated cone and b) truncated pyramid.

The starting blank shapes have been designed in order to minimize the wasted (trimmed out) material after the forming processes: for the frustum of pyramid, a trial and error approach was developed to find the most suitable starting blank shape, whereas for the cone shape a circular starting blank was selected due to the symmetry of the process. Starting from the CAD model, the other necessary tools were built as illustrated in **Figure 3.11**.

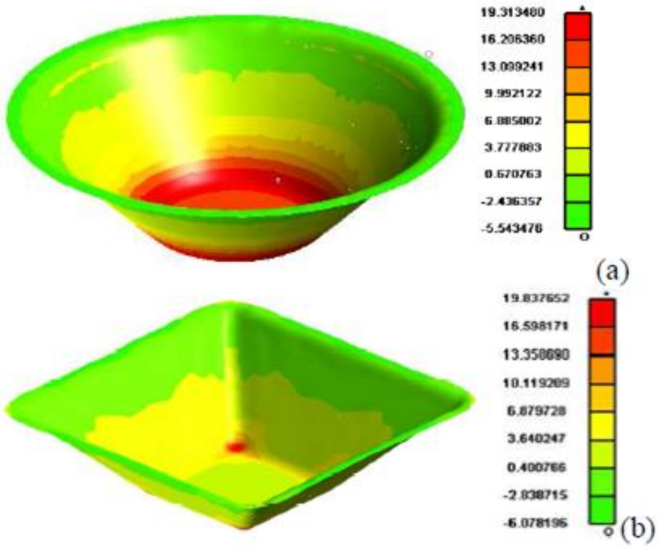


Figure 3.12. Thinning distributions for the stamping operations: a) truncated cone and b) truncated pyramid.

Figure 3.12 reports two thinning numerical maps, and it is evident that the initial blank shapes allow to cover just the die fillet radii. Without getting into the details, as numerical simulation the commercial code Dynaform was utilized.

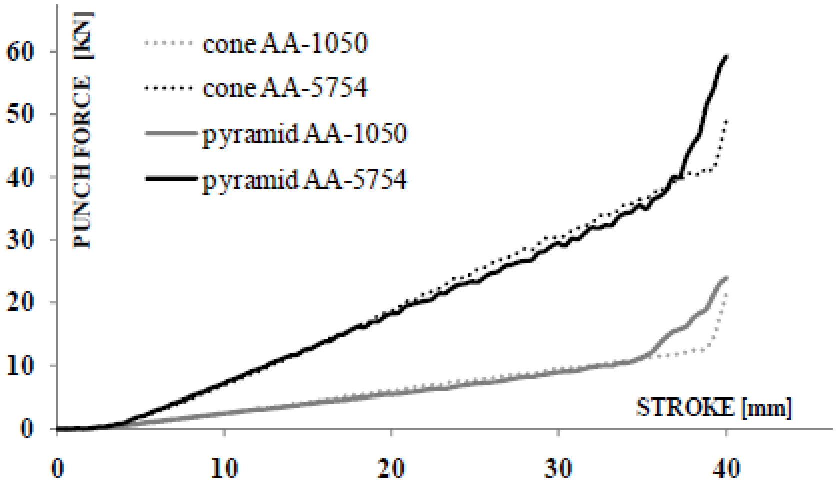


Figure 3.13. Load versus stroke curve for all the developed tests.

As soon as the punch load versus punch stroke curve was determined, after each numerical simulation, in order to obtain the deformation energy, it is necessary to calculate the area under the load curve (see **Figure 3.13**).

As foreseeable, load curves trends are quite different at the varying of the material (AA 5754 versus AA 1050). The same occurrence is, as explained below, for ISF operations. The load curves, once fixed the material, are not significantly affected by the part geometry (a slight difference at the end of the stroke can be explained by the different part shape).

3.3.4 Comparison between ISF and stamping operations

The results of the process energy calculated either for stamping operations or for ISF (see **Table 3.15**), are summarized in **Figure 3.14**.

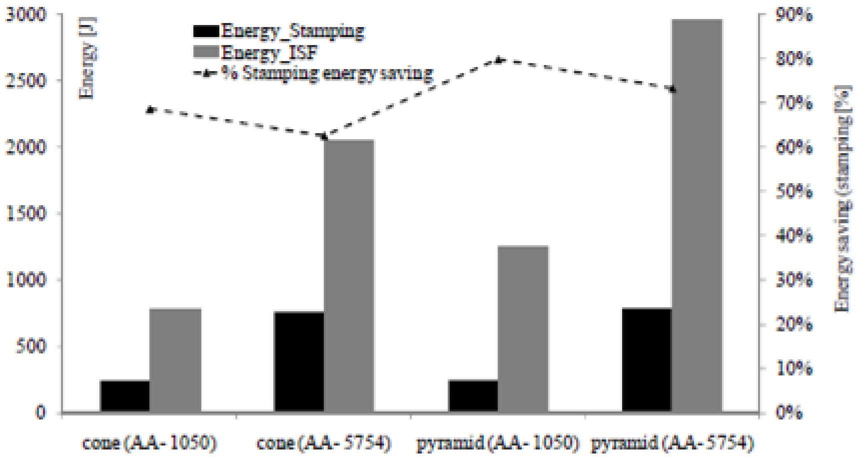


Figure 3.14. Energy comparison.

It is possible to derive some assessments from the analysis of the energy requirements:

- the energy consumption in ISF is significantly higher than the one in stamping operations, and that is for all the examined cases;

- as far as stamping operations are concerned, the final shape does not influence an increasing in energy, but only the different type of material does;

- the variations in energy for ISF operations are related either to material variation or to geometry variation;

- the major difference in energy, and consequently the major savings that happen in stamping operations, come from pyramid shaped final part and this is probably due to the major displacement affecting ISF;
- the AA-1050 alloy always guarantees higher savings in stamping, regardless.

Material waste

A comparison of the initial blank shapes for both the analyzed processes are presented in **Figure 3.15**.

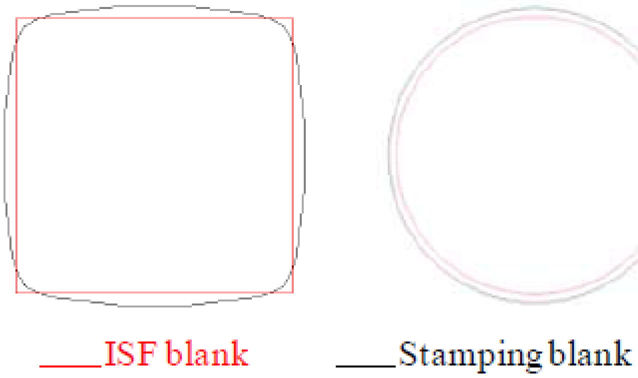


Figure 3.15. Blank shapes.

It is important to highlight that the material quantity implies different weight and also different energy necessary to produce the sheets. As already affirmed, the initial blank shape for ISF process has to be larger than the largest spire (in order to allow a proper clamping). For these particular shapes a frame dimension equal to 10 mm was considered all along the sheet outline. As mentioned before, in stamping operation, the initial blank shape was optimized in order to minimize material wasting. In **Table 3.16** the corresponding area values thus calculated, together with the material saving allowed by ISF, are shown.

Table 3.16. Material saving.

Shape	Operation	Area [mm^2]	Material saving [%]
Truncated Cone	Stamping	21124	-
Truncated Cone	ISF	18870	10.67
Truncated Pyramid	Stamping	26336	-
Truncated Pyramid	ISF	24025	8.78

3.3.5 Final considerations

Analysing **Table 3.16** and **Figure 3.14** content, a first remarkable conclusion is that even if higher forces act during stamping operations with respect to ISF, the total displacement during ISF is much higher than the one occurring in stamping. Force and displacement are the two factors contributing to energy and their proportion determine the differences of the total energy. As far as material waste is concerned, ISF allows a certain saving. To be incisive, this case study was done in relation to a process point of view; it can be expanded to a plant level, but in this case the difficulty of modelling strongly increases. The next case study will show an enlargement of this first point of view. Confining to a sheet forming point of view, this case study confirms that conclusions are strictly dependent on the particular investigated cases and that the question about which forming process is more “environmental friendly” remains open.

3.4 Case study 3: a comparative cradle to gate analysis applied to deep drawing and to incremental forming processes

In this case study, a comparison between a traditional Deep Drawing (DD) process and an ISF one is done. The desired output is a truncated pyramid component manufactured in an Aluminium alloy. Those processes environmental impact was evaluated taking into account the following parameters: energy consumptions, material use and lubrication. As method, using LCA software Gabi4, a comparative cradle-to-gate life cycle analysis was proposed. More in detail, the whole process flow, starting from raw material extraction phase to the final forming phase, was evaluated. The two processes data useful for the analysis come from respectively experimental tests (ISF process) and numerical simulations (DD process). Furthermore, results from Gabi4 were compared to an alternative method, that is faster and cheaper than a full LCA, but less accurate. As alternative to LCA methodology, the Carbon Emission Signature (CES) method was applied (Ashby, 2009; Jeswiet and Kara, 2008; Nava et al., 2010) together with an end-of-life perspective (see section 3.2).

3.4.1 Problem modelling

The specimen profile was a frustum of pyramid, the same shape that represented the object of the study described in the previous sections. The forming material was AA 5754

Aluminium alloy, 1 mm thick. The dimensions of the truncated pyramid are: a base dimension of 120 mm, a final depth of 40 mm and a wall inclination angle of 45°. The simple equipment used to realize the experimental tests for ISF consists of a 4-axis vertical CNC machine and a clamping frame that has the function to block the sheet (Jeswiet et al., 2005). A dynamometer positioned under the clamping frame was placed in order to measure the energy dissipated during the process, and two force components were acquired. Following the same procedure described in the previous section, the energy required for the ISF process was then calculated (Ingarao et al., 2011c). To assure a proper lubrication, 0.64 g of a conventional mineral oil was utilised. As already explained, the initial blank was oversized (dimensions 155×155 mm). Energy data necessary for the DD process analysis (Ingarao et al., 2011c) come from FEM numerical simulations (by LS-DYNA). This deformation energy, required just for the forming process, was calculated by considering the area below the punch load curve as function of the stroke, as shown in **Figure 3.16**. Both **Figure 3.16** and **Figure 3.17** display the forces distribution experimentally and numerically derived for ISF and DD respectively. The mineral oil based lubricant quantity was 0.079 g. The initial blank shape design, made by a trial and error approach, took into account to minimize material wastes.

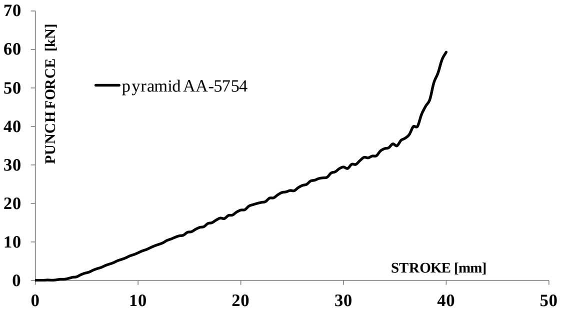


Figure 3.16. DD process load curve.

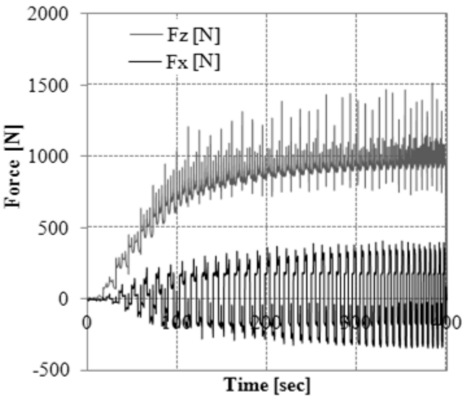


Figure 3.17. ISF test load curve.

According to the forces distributions shown in **Figure 3.16** and **Figure 3.17**, it is quite evident that the required force during DD is much larger than the one consumed by ISF. However, the DD process is much faster than the ISF process. On the other hand, DD process requires initial blank dimensions bigger than the ones necessary for ISF, as reported in **Figure 3.18** and in **Table 3.17**.

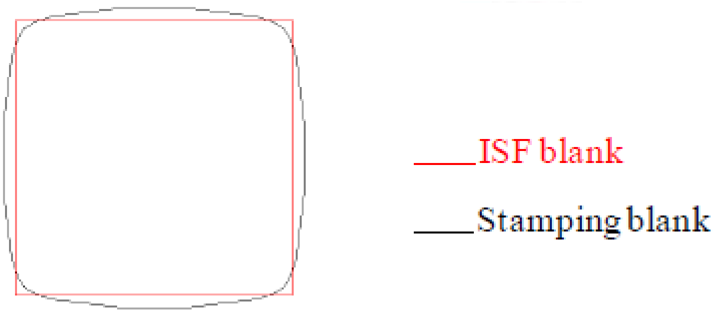


Figure 3.18. Initial blank shapes for ISF process (red colour) and DD process (black colour).

All the differences between the two processes in terms of deformation energy (+74% by ISF), lubricant quantity and required material area (material saving up to 10%), are summarized in **Table 3.17.**

Table 3.17. Investigated processes: data relative to deformation energy, lubrication and shape area.

Frustum of pyramid manufacturing: ISF versus DD			
	ISF	DD	Δ [%] = 1-DD/ISF
Deformation energy [J]	2998.2	770.339	74%
Lubricant [g]	0.64	0.079	88%
Initial shape area [mm^2]	24025	26336	-10%

3.4.2 Life cycle assessment model by using Gabi4

As already touched on in section 1.2.1, the definition of the system boundaries is the first step of any LCA. The approach followed in this research is a cradle-to-gate analysis of the two forming technologies, that takes into account different phases: raw material extraction, Aluminium primary production, primary shaping processes and finally manufacturing processes. The data were analyzed in Gabi by using as Life Cycle Impact Assessment method CML2001 (Cml, 2010). The following impact categories were considered: Abiotic

Depletion (ADP [kg Sb-eq]), Acidification Potential (AP [kg SO2-eq]), Eutrophication Potential (EP [kg Phosphate-eq]), Global Warming Potential (GWP 100 years [kg CO_2-eq]), Ozone Layer Depletion Potential (ODP, steady state [kg R11-eq]), and Photochemical Ozone Creation Potential (POCP [kg Ethene-eq]). In order to obtain a global environmental score (in this case, CML2001 score), data were aggregated by normalization and weighting operation. Gabi4 diagrams of the DD and the ISF processes are respectively shown in **Figure 3.19** and **Figure 3.20**. In this analysis, the impact coming from used material and waste, the manufacturing energy and the lubricant quantity were also considered. Furthermore, the environmental impact from dies and tooling systems was neglected.

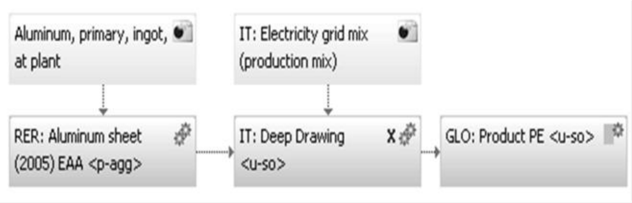


Figure 3.19. GaBi4 diagram of the DD process.

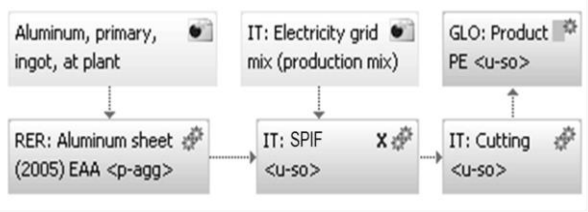


Figure 3.20. GaBi4 diagram of the ISF process.

As energy aspect is regarded, the power grid location is supposed to be in Italy, being the environmental impact from energy location dependent. **Figure 3.21** details the environmental balance of the two processes by the impact categories aforementioned. As it can be derived from **Figure 3.21**, DD has totally higher environmental impact than ISF. This can be easily explained because ISF allows in fact material saving, and that has the biggest impact on the environment, as demonstrated by the lowest CML2001 score.

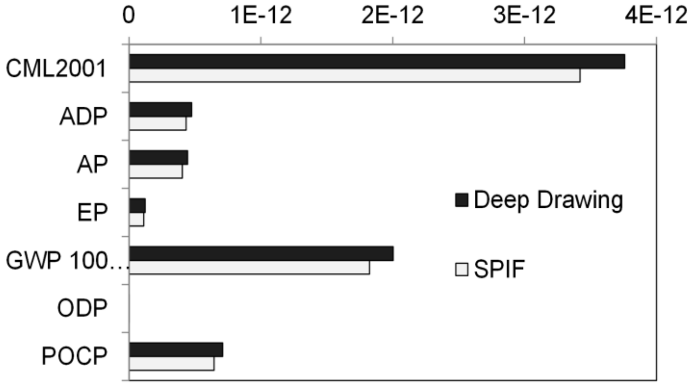


Figure 3.22. DD versus ISF environmental balance.

As extra confirmation, **Figure 3.22** shows the environmental balance splitted in each life cycle phase: the forming phase has lower environmental impact than material primary production and shaping processes. As direct consequence, **Table 3.18** reports the data, which are neither normalized nor weighted, about the carbon emissions (as kg of CO_2) from the two analysed processes.

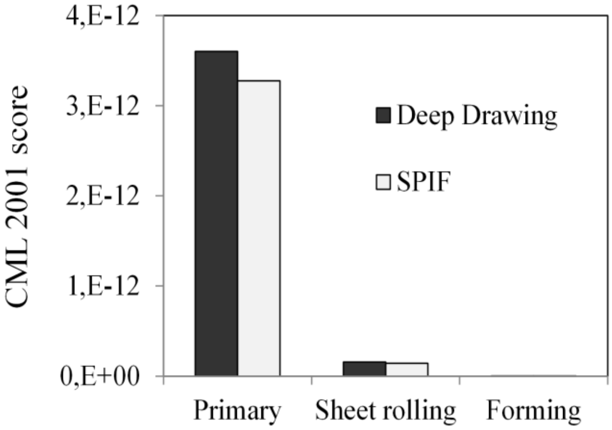


Figure 3.2 CML 2001 score by life cycle phase.

Table 3.18. Kg CO_2 emitted during each life cycle phase taken into account.

kg CO_2				
Process	Total	Primary production	Sheet Rolling	Forming Phase
ISF	0.94	0.91	0.04	0.000499
DD	1.04	0.99	0.045	0.00013

This comparative cradle to gate analysis indicated the material saving strategy as effective choice to pursue sustainability purposes in sheet forming applications.

3.4.3 Environmental analysis by alternative methods

As alternative method to do environmental analysis, the input/output model, already presented in a previous case study, has been applied to the ISF and the DD processes. The aim of this alternative method is to analyse and to quantify lubricant, material and energy consumption, as well as outputs into environment. The functional scheme of the investigated processes is presented in **Figure 3.23**, following Kellens et al. (2011). **Figure 3.23a** and **Figure 3.23b** show respectively the scheme utilised for ISF process (split into two sub-unit processes) and for DD process (where the trimming phase is neglected).

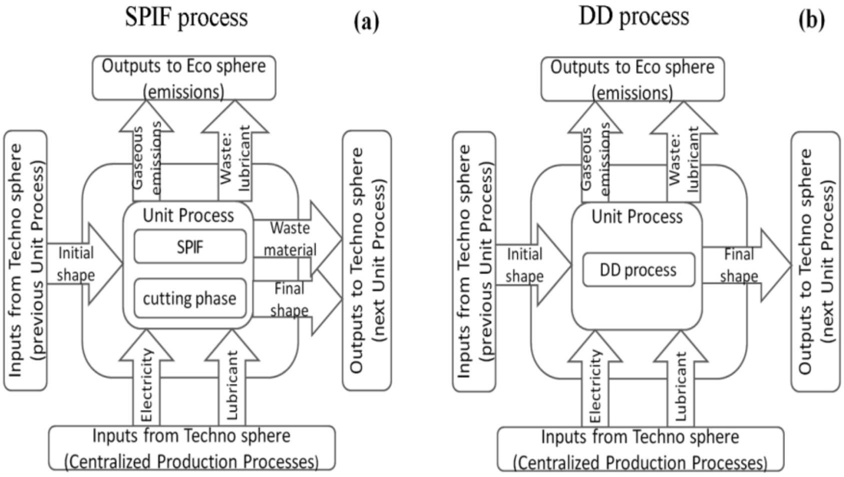


Figure 3.23. Functional scheme for ISF (**a**) and DD (**b**) reporting inputs and outputs (Kellens et al., 2011).

Alternative approaches applied to ISF

Process inputs are shown in **Table 3.17**; in particular, the inputs from techno sphere (centralised production processes) are: a) theoretical energy consumption (Ingarao et al., 2011c) related to both sub-unit processes, b) the used lubricant, c) initial shape. Material wasting is unavoidable in ISF processes, as already stated. On the other hand, an attractive peculiarity of Aluminium alloys is their recyclability (nearly 100% as recycling rate); therefore waste material impact on the environment is not considered in the present analysis (Gronostajski and Matuszak, 1999; Ingarao et al., 2011b; Kellens et al., 2011). In order to calculate the CO_2 emissions, two approaches were followed: the Carbon Emission Signature (CES^{TM}) method (Jeswiet and Kara, 2008) and the end-of-life perspective already proposed (see section 3.2). The CES^{TM} method allows to calculate CO_2 emissions from electric energy (Jeswiet and Kara, 2008) by considering the power grid location. For the proposed anlysis the location is in Italy, thus the amount of CO_2 emitted per Joule of the energy consumed during a process, such as the Italian CES^{TM} index is 0.114 mg/J (see section 3.2). In **Table 3.19** the CO_2 emissions are calculated. As lubricant is regarded, an end-of-life perspective was followed considering 0.400 grams of CO_2 emitted per gram of lubricant; thus, the CO_2 emissions due to the lubricant are also shown in **Table 3.19** (see section 3.2).

Table 3.19. Outputs to techno and eco sphere for ISF process.

	Output	**Entity**		**CO_2 [grams]**
Outputs to eco-sphere (emissions)	Energy	2998.2	Joule	0.343
	Lubricant	0.64	G	0.256
	Total emissions			0.599
Output to techno sphere	Waste material	0.026	Kg	-

Alternative approaches applied to DD

The above described input/output model was applied to the DD process as well. The outputs are shown in **Table 3.20** and the CO_2 emissions are calculated either for energy consumption or for lubricant use, following respectively the CES^{TM} method and the end-of-life perspective.

Table 3.20. DD process: outputs to techno and eco sphere.

	Output	**Entity**		**CO_2 [grams]**
Outputs to eco-sphere (emissions)	Energy	770.339	Joule	0.088
	Lubricant	0.079	g	0.032
	Total emissions			0.120
Output to techno sphere	Waste material	0	g	-

Comparing outputs data for ISF process and DD process (**Table 3.19** versus **Table 3.20**) and taking into account that there is not waste material for the DD process, it is evident that the ISF, being higher energy demanding, is more impactful over DD as far as just the forming phase.

3.4.4 Final remarks

The analysis just presented revealed that incremental forming processes, although having higher energy consumptions, result more eco-friendly than traditional stamping operations.

In fact, the ISF process enables a more efficient use of the input material, which represents the most significant cause of impact onto the environment. A cradle to gate approach in the evaluation of forming technologies pointed out efficient material use strategies as priority in sheet forming processes. Therefore, in conclusion, it can be drawn that a comprehensive cradle to gate approach would suggest efficient material use strategies as priority in sheet forming process design.

3.5 Case study 4: tools coatings in ISF as alternative to oils and emulsions use

3.5.1 Tool coatings

Lubricants use, nowadays, is very common (see chapter 1) both in manufacturing and in machining operations. However, the high environmental impact of oils (Hermann et al., 2007; Dettmer, 2006) drives the industry attention on reduction and, if possible, on complete suppression of the lubricant use (Wang, 2004). This case study investigates the tool coatings use as alternative to oils and emulsions.

The tool coatings are not an innovation in industry, since they are widely used in machining fields, because they guarantee a better tool performance both in terms of duration and final component surface quality (Sokovic et al., 2006). Two kinds of coatings were analyzed (AlSiTiN and AlSiCrN) in manufacturing processes, in particular in ISF: these innovative coatings were deposited onto the classical punch substrate through an arc Physical Vapor Deposition (PVD) process, which is an innovative technology developed in the nano-technological field. PVD is fundamentally a vaporisation coating technique that involves transfer of material on an atomic level. In order to vapor the material that must be deposited, the methods can be several: in this case study a new coating technology based on rotating arc cathodes, named LARC® (Lateral Arc Rotating Cathodes), was developed. The PVD process was realized at the Clean NT Lab, in Turin (Italy). The tools, after being washed, have been inserted into Platit Pi55, which is shown in **Figure 3.24**. The two coatings AlSiTiN (built-up by a matrix of nanometrical crystal of nc-TixAl1-xN, immerged in a thin amorphous film of Si_3N_4) and AlSiCrN (built-up by a matrix of nanometrical crystal of nc-CrxAl1-xN, immerged in a thin amorphous film of Si_3N_4) have a multilayer structure: the role of this kind of structure is either to resist to mechanical and thermal strains or to limit the crack propagation.

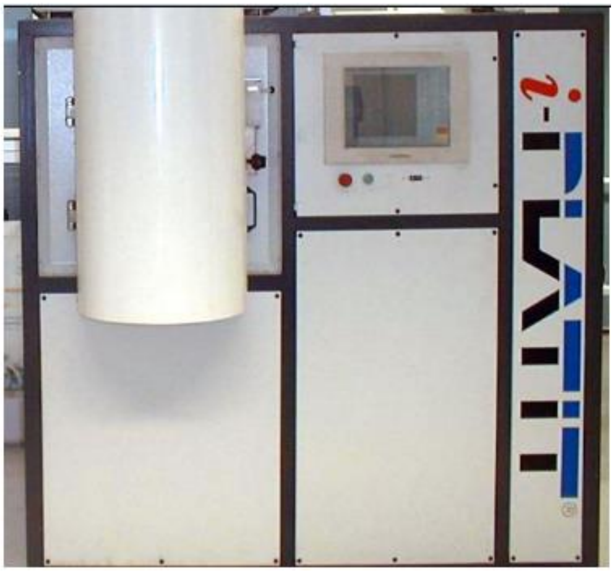


Figure 3.24. Platit Pi55 unit, at the Clean NT Lab, in Turin (Italy).

The multilayer part, as shown in **Figure 3.25,** has a sequence of five layers A + B, with a total thickness of 3 μm.

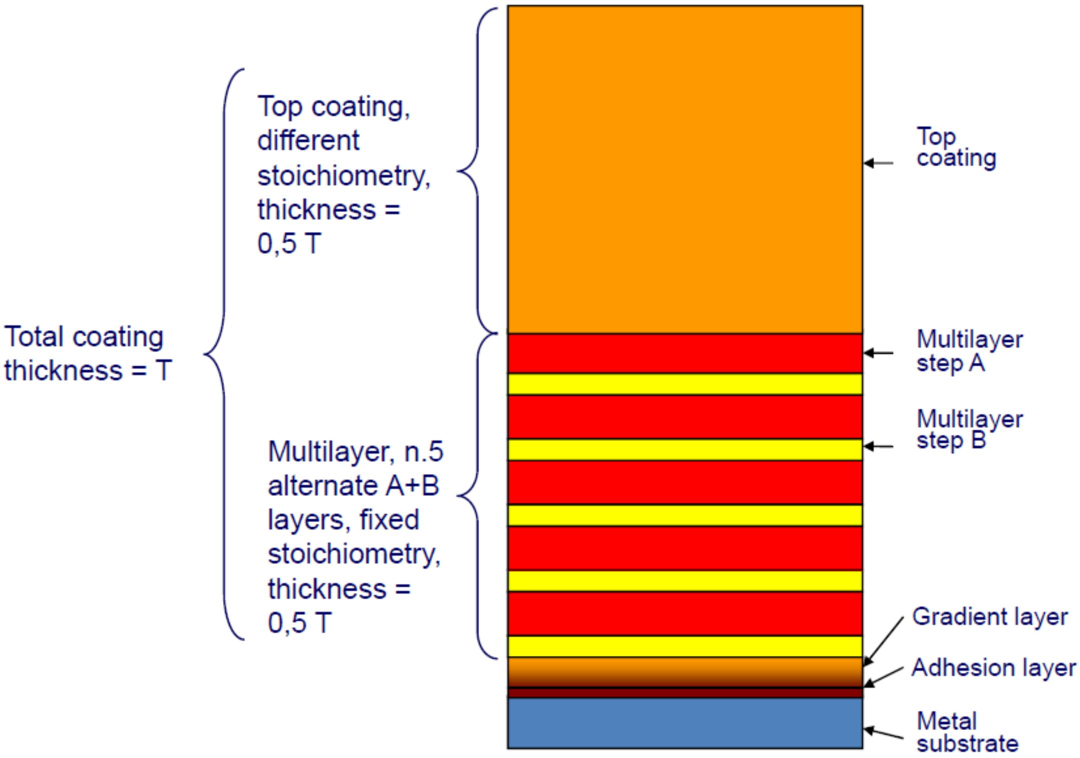


Figure 3.25. Scratch of the coatings structure.

3.5.2 Experimental evidences

The experimental plan, that is summarized in **Table 3.21**, takes into account a comparative evaluation between processes realized through naked tools or with coating tools (where coating A is AlSiTiN and coating B is AlSiCrN), either lubricated or not (dry). Each condition was evaluated in terms of tool wear and in terms of surface quality. The above mentioned conditions have been evaluated on both coatings types. All the tests were executed on AISI 304 blank material, 0.5 mm thick. The choice of this material type is not casual; on the contrary, this steel has been chosen for its strength in order to emphasize the wear phenomenon on the tool.

The final shape used for this experimental investigation is a truncated pyramid. Dimensions of the truncated pyramid, with a square base, are the following ones: it has a side of 100 mm and a final depth of 40 mm. Process parameters are reported in **Table 3.22**. More in detail, tool feed and speed were fixed in order to keep the local velocity between punch and sheet close to zero.

Table 3.21. Experimental plan.

Test number	Tool conditions	Lubrificant use?
1	Coating A	Yes
2	Coating B	Yes
3	Naked	Yes
4	Coating A	No
5	Coating B	No
6	Naked	No

Table 3.22. Process parameters related to the experimental tests.

Process parameters	
Tool diameter	15 mm
Tool depth step	0.5 mm
Wall angle of the truncated pyramid	40°
Feed rate	1445 mm/min
Tool rotation	50 revolutions per minute

Each test was executed with a new tool, so that at the end of each one it was possible to make measurements of the tool wear and of the roughness on the final component. Independently from the specific type of tool (if naked or with coating A or B), some conclusions can be derived just observing the final components:

- the lubricant absence does not cause component failure during the manufacturing phase; the failure is caused by other process conditions such as the tool depth step and the forming angle;
- the lubricant absence causes an increased tool wear and, as a consequence, a progressive increase of the surface roughness (**Figure 3.26**) of the final component.

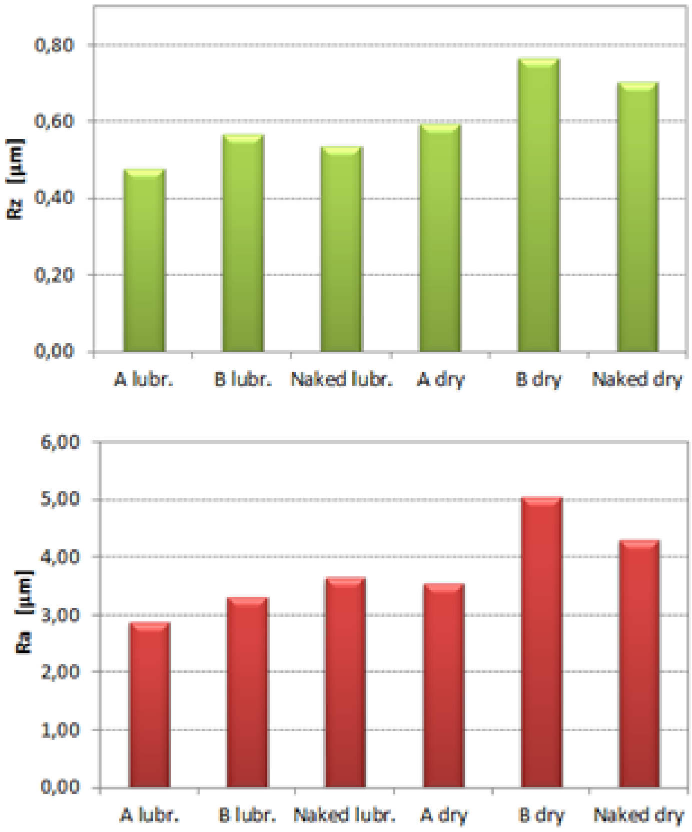
Since lubricant absence determines a gradual deterioration of the tool characteristics and of the surface, in order to make measurements comparable, the roughness was conventionally evaluated at a depth of 30 mm from the larger base.

Figure 3.26. Test number 5 – without the lubricant and with the coating type B.

3.5.3 Surface roughness

In **Figure 3.27** values of average medium (R_a) and maximum (R_z) roughness are synthesized, where the final result was obtained as medium value of the measures taken on the 4 lateral faces of the truncated pyramid.

As expected, the tests confirm that lubricant use improves surface quality. However, the most interesting results concern “dry” tests (tests number 4, 5 and 6). The conclusion of this research is that it is possible to work a material such as AISI 304 and to obtain good performance also without lubricant, but providing a suitable tool coating.



legend	
Test 1	Coating A - lubricant
Test 2	Coating B - lubricant
Test 3	Naked - lubricant
Test 4	Coating A - dry condition
Test 5	Coating B - dry condition
Test 6	Naked - dry condition

Figure 3.27. Medium values of medium (R_a) and maximum (R_z) roughness measurements.

As shown in **Figure 3.27**, the coating type A is not only better in normal lubrication condition (test number 1), but provides some satisfying results also without lubricant use. Last condition is comparable, in terms of surface roughness, to what it can be obtained with conventional "naked" tool and conditions of lubricated process (test 4 versus test 3). Final components, with and without lubricant, are directly compared in **Figure 3.28**.

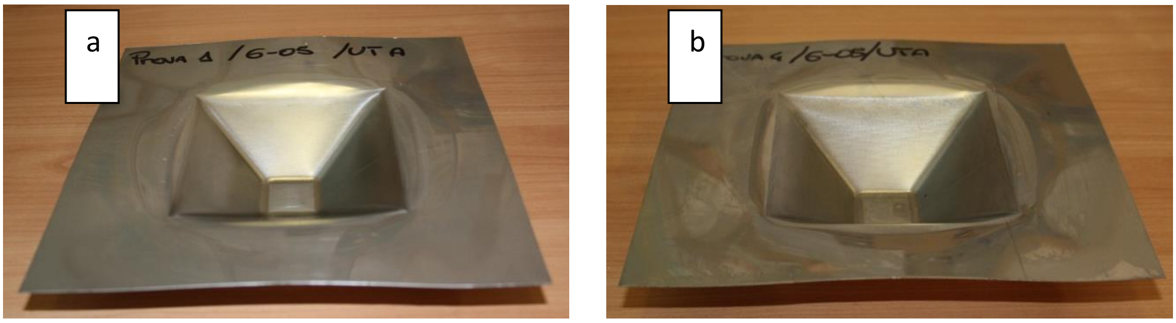


Figure 3.28. Final component, worked by using coating type A, during a test executed with lubricant (a) and without (b).

3.5.4 Tool wear

In order to measure the tool wear resistance, after each test some roughness measurements have been done by means of a profilometer (**Figure 3.29**). A Form Talysurf 120 (Taylor-Hobson) PC-controlled contact profilometer, with a laser interferometer able to measure vertical peaks and a tip radius of 2μm, has been used.

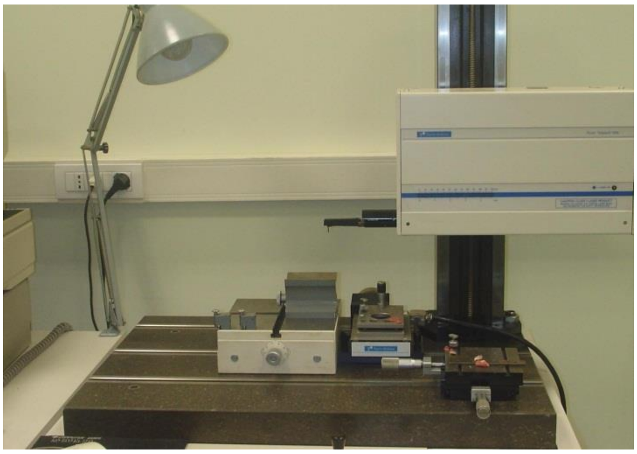


Figure 3.29. The profilometer employed to measure the tool wear.

As it can be deducted comparing tools profiles with coating type A, as shown in **Figure 3.30** and **Figure 3.31**, lubricant absence determines a greater wear; more in detail, the more important flattening of the profile in case of dry process is evident in **Figure 3.31**.
In every condition, coating type A behavior is better than others. In fact, tool wear, in this case, is the lowest one: that is due either to the coating type A better contact or to the coating type A higher strength.

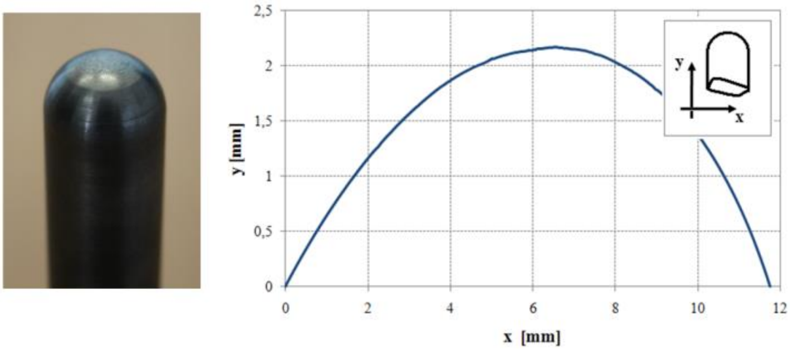


Figure 3.30. Tool profile at the end of the test 1, with coating type A, in standard lubrication conditions.

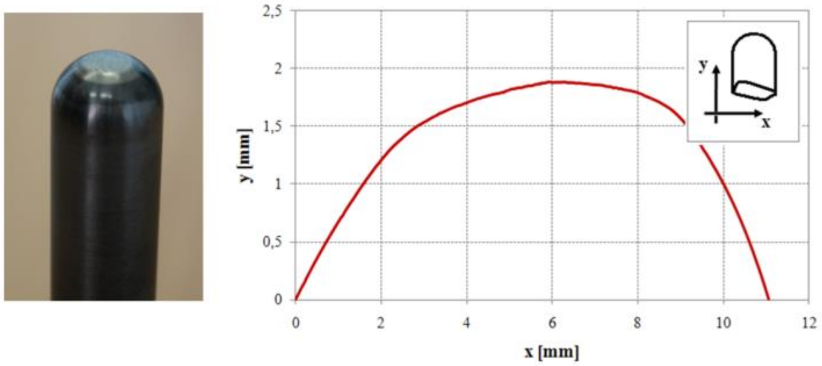


Figure 3.31. Tool profile at the end of the test 4, with coating type A, without lubricant use.

A quantitative analysis of the profile wear is done by measuring the height reduction (h) after the manufacturing process (see **Figure 3.32**).

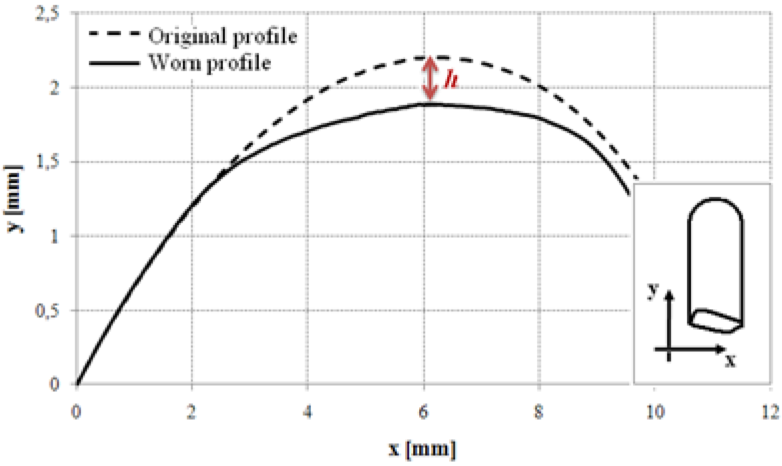
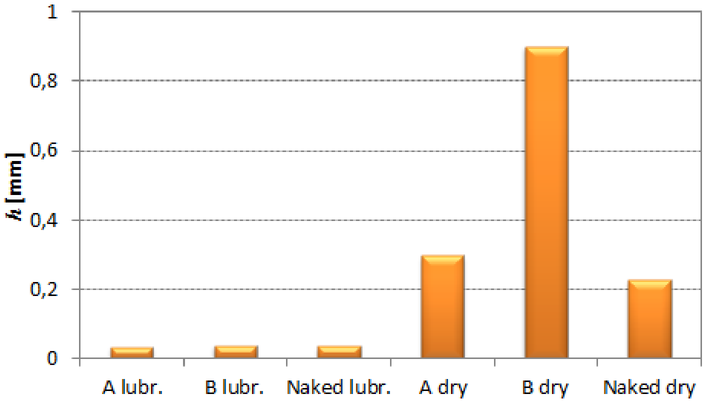


Figure 3.32. Tool wear (h) measurements.



legend

Test 1	Coating A - lubricant
Test 2	Coating B - lubricant
Test 3	Naked - lubricant
Test 4	Coating A - dry condition
Test 5	Coating B - dry condition
Test 6	Naked - dry condition

Figure 3.33. Tool wear (h) measurements for each test.

Looking at values reported in **Figure 3.33**, the following conclusions can be derived:

- in lubrication conditions, wear phenomenon is significantly reduced and coating presence does not contribute to this phenomenon reduction;
- in lubrication conditions, the height h (defined as difference between the initial profile and the eroded one) has the same reduction, either without coating or with any coating;
- without lubricant, the bigger wear is with coating type B, thus the coating B seems to be the worst;
- on the contrary, the best performance is provided by the coating A: in fact, even if the tool wear is higher than that of the naked tool, the manufactured component results to be better (**Figure 3.28**).

3.5.5 Final remarks

Principles inspired to sustainability disapprove lubricant use because of its impact on the environment. Based on these guide lines, in this case study the coatings use on conventional tools utilized in ISF has been analyzed in order to reduce lubricant use. The experimental campaign and measurements done showed the good performance of the coating type A (AlSiTiN), both in terms of tool wear and surface quality. Even if the analysis done has a validity strictly dependent on the material and on relative coatings utilized, gives new optimization ideas about ISF process from a sustainable perspective. In fact, a sustainable modification of forming processes, that abstains from lubricants use, is pursuable through the use of a suitable coating. It has been shown that the coating AlSiTiN deposited on carbon steel tools, guarantees satisfying results also in dry conditions.

Chapter 4

ENERGY EFFICIENCY ANALYSIS IN INCREMENTAL SHEET FORMING OPERATIONS

4.1 Towards energy efficiency

Since 1987 (year of “Our common future”), in part the consideration that much of our electricity is still generated from carbon based sources (coal, oil and gas) which are responsible for the world’s greenhouse gas emissions (which drives to the search of green sources of power generation), in part the recent rise in the energy cost, in part the increasing number of social and legislative requirements, highlight how crucial is an “energy efficient approach” in all technologies domains, and thus in machining and manufacturing applications. Believing in the necessity of energy efficiency, a worldwide consortium of universities and research institutes launched the CO2PE! – Initiative (Cooperative Effort on Process Emissions in Manufacturing), that has conceived a methodology used to analyze manufacturing unit processes and which allows to identify some improvement potential (Kellens et al., 2011). The aspect related to energy has a great importance, due to the high impact of energy consumption of the various analyzed processes total impact (Duflou et al., 2011a; Duflou et al., 2011b). An interesting research made by Rahimifard et al. (2010) highlights the need for appropriate methods within manufacturing businesses, that can assess the efficiency of the energy consumption: this research proposes a modeling framework able to represent the total energy necessary to manufacture a unit product. In the embodied product energy framework, the energy consumed by various activities is categorized into two groups (Rahimifard et al., 2010): direct energy (the energy consumed by various processes required to manufacture a product, like casting, machining, etc.) and indirect energy (the energy used by various activities, like lightning, heating, etc.). The total embodied product energy during the manufacturing phase of a certain product life-cycle is thus calculated as the sum of the direct energy for *n* processes together with the indirect energy for *m* zones within a production system. An energy simulation model, that includes various processes and manufacturing zones, has been proposed in order to evaluate energy consumption during the manufacturing phase of a certain product life-cycle. This simulation model enables a more efficient monitoring and control of energy, in order to optimize the activities at “plant” level (Rahimifard et al., 2010). In literature, with the exception of the research lines mentioned, most of the data available are incomplete and do not take into account energy consideration, or at least their focus is often limited to theoretical energy consumption (Steiner and Frischknecht, 2007). Subsequently, an energy efficiency analysis is proposed at the varying of different process parameters within the sheet metal forming processes, with the aim of giving a contribution to find energy efficiency solutions.

4.2 Case study 5: an energy efficiency analysis at the varying of the process parameters

Following this line of research, the attention has been focalized on the ISF process in order to evaluate the required energy and how it changes for changing process conditions. A wide experimental investigation has been executed taking into account different process parameters (5 tests for each parameters setting) and the energy consumption has been monitored during all the experiments.

4.2.1 Experimental equipment

An experimental investigation was performed at the Laboratory of Mechanical, Energy and Management Engineering of the University of Calabria. The experiments were carried out through the vertical milling machine Mazak Nexus 410, that is a 3-axis CNC work center, with a maximum feed speed of 36000 mm/min. The vertical milling machine used during the experiments is shown in **Figure 4.1**.

Taking into account the aim of the study, the work center was equipped with an Efergy power meter directly connected to the machine cable and linked with a wireless data acquisition system.

Figure 4.1. The vertical milling machine Mazak Nexus 410, placed at the Laboratory of Mechanical Engineering, University of Calabria.

Actually, the utilized measurement instrument is able to measure the instantaneous power with a precision of 7%, while the energy is evaluated at the end of each test as the integral of the power distribution on the time.

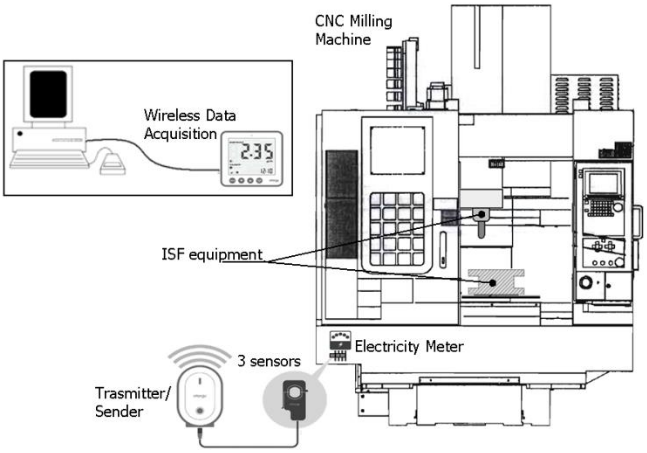


Figure 4.2. Utilized equipment scheme.

Clamping equipment which ensures a high rigidity during the experiments was mounted on the machine. An hardened steel tool completed the equipment and an emulsion of mineral oil was used as lubricant to reduce the friction related phenomena. Further details of the utilized equipment are displayed in **Figure 4.2**. A sketch of Efergy power meter is shown in **Figure 4.3**.

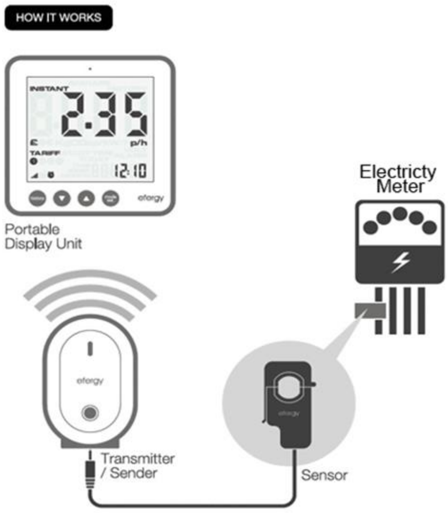


Figure 4.3. Efergy power meter scheme.

4.2.2 Time study

As first step, a time cycle analysis during the entire production cycle, following Kellens et al. (2011) model, was done. Initially, the process was divided into ten different phases:

1. Starting tool;
2. Tool set-up;
3. Zero tool;
4. Loading new sheet;
5. Zero workpiece;
6. Preparation (program preparation on PC, lubricant administering, etc.);
7. Program start;
8. Forming (since the axes initial movement);
9. Unloading;
10. Shut down.

An example of the percent incidence of the time for each phase on total time necessary to complete an entire ISF cycle (data shown in **Figure 4.4** are the average calculated for all the tests executed) is shown in **Figure 4.4**.

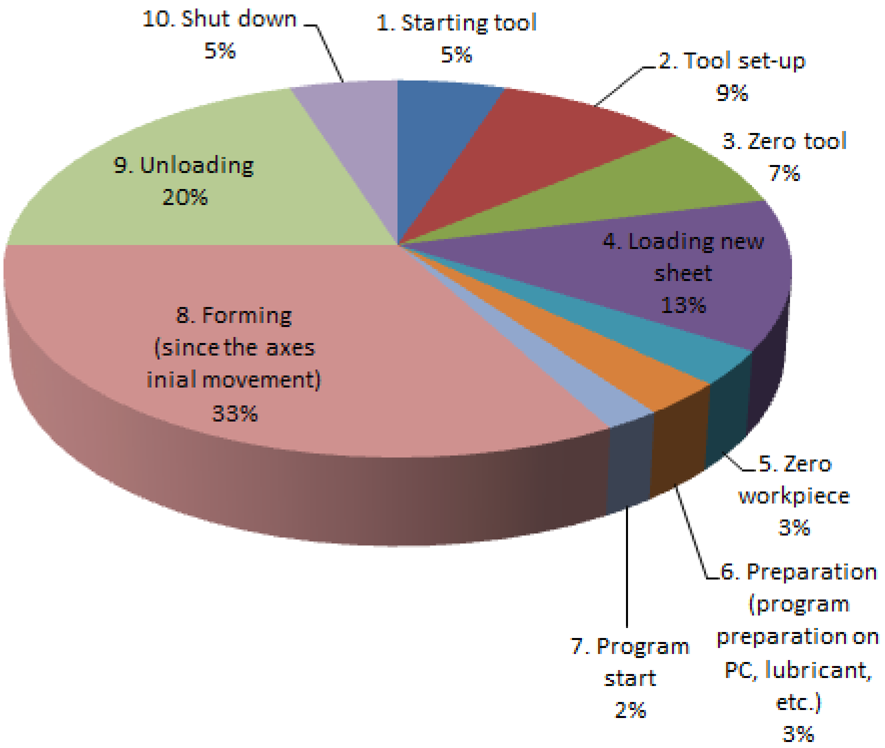


Figure 4.4. Percent influence of each phase on total time during an ISF process.

The forming phase is related to the manufacturing of a frustum of pyramid, made by AA 1050 (1.5 mm thick), characterized by a major base of 140 mmm and a final depth of 40 mm. Furthermore, a punch speed and a punch feed equal to 200 r.p.m. and 2000 mm/min were chosen respectively.

In reference to the ten phases, it is important to make a distinction between recurring and not recurring operations. Machine start-up, tool set-up and shut-down are typically steps that have day or batch repetition; on the contrary, there are other sub-steps which are repeated for each produced part and can be associated to the production phase. For the sake of simplicity, the not recurring steps are not considered in the following analysis and the attention is focalized only on the repetitive operations for each manufactured part. The production phases, in which a single ISF process can be split, are identified as follows:

- tooling, that comprehends the new sheet loading and the PC set-up;
- forming operations, that consists of starting program on PC and workpiece forming;
- disassembly, that consists of removing the workpiece and cleaning the milling machine.

Both tooling and disassembly phases are semi-automatic operations, whose time depends on operator efficiency. **Figure 4.5** shows the percent incidence of each one of the three principal phases for an entire ISF process, executed in the same experimental conditions (average calculated for 5 tests), already highlighted.

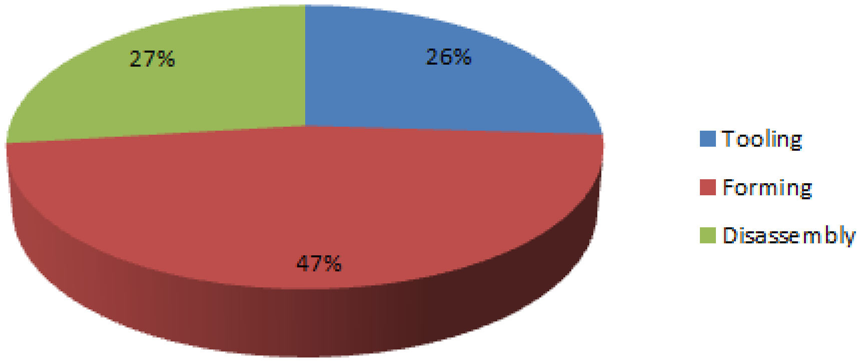


Figure 4.5. Percent influence of each principal phase on total time for an ISF process.

As it can be easily deducted from **Figure 4.4** and **Figure 4.5**, the forming phase has the biggest influence on total time, whereas tooling and disassembly are comparable.

4.2.3 Experimental plan

A screening approach, as presented by Kellens et al. (2011) was utilized during the investigation. Naturally, in order to reduce the number of experiments, some factors were kept constant, i.e. the material (an Aluminium alloy: AA-1050), the tool speed rotation, etc..

Table 4.1. Values either kept constant or not constant, during the experiments.

Parameters	Unit	First value [min]	Second value [max]
Tool feed	[mm/min]	2000	2000
Tool speed rotation	[rpm]	200	200
Tool pitch, p	[mm]	0.5	1.0
Tool diameter, D	[mm]	10	18
Wall inclination angle, α	[°]	45	65
Sheet thickness	[mm]	1.0	1.5
Shape	---	Truncated pyramid	Truncated cone

All the parameters kept constant and those ones that varied during the experiments are summarized in **Table 4.1**.

As shapes, respectively a frustum of pyramid, having a major base of 140 mm and a final depth of 40 mm, and a frustum of cone with a maximum diameter of 140 mm, and a final depth of 40 mm, were chosen as benchmark geometry. On the other hand, taking into account the knowledge base on the investigated process (Duflou et al., 2005; Filice et al., 2006; Duflou et al., 2007a), the experiments were repeated varying the wall inclination angle (α), according to the specific material formability limit.

As already stated, each experiment, determined by a proper combination of the investigated parameters, was repeated five times, due to the variability of work-center conditions (i.e. auxiliary motors cycles) and semi-automatic operations. The whole experimental plan is shown in **Table 4.2**.

Table 4.2. The complete experimental plan.

Test number	Shape	Diameter punch [mm]	Pitch [mm]	Wall inclination angle [α]	Thickness [mm]
1/32	Pyramid	10	1	45	1
2/32	Pyramid	10	1	65	1
3/32	Pyramid	10	0.5	45	1
4/32	Pyramid	10	0.5	65	1
5/32	Cone	10	1	45	1
6/32	Cone	10	1	65	1
7/32	Cone	10	0.5	45	1
8/32	Cone	10	0.5	65	1
9/32	Pyramid	10	1	45	1.5
10/32	Pyramid	10	1	65	1.5
11/32	Pyramid	10	0.5	45	1.5
12/32	Pyramid	10	0.5	65	1.5
13/32	Cone	18	1	45	1.5
14/32	Cone	18	1	65	1.5
15/32	Cone	18	0.5	45	1.5
16/32	Cone	18	0.5	65	1.5
17/32	Pyramid	18	1	45	1
18/32	Pyramid	18	1	65	1
19/32	Pyramid	18	0.5	45	1
20/32	Pyramid	18	0.5	65	1

21/32	Cone	18	1	45	1
22/32	Cone	18	1	65	1
23/32	Cone	18	0.5	45	1
24/32	Cone	18	0.5	65	1
25/32	Pyramid	10	1	45	1.5
26/32	Pyramid	10	1	65	1.5
27/32	Pyramid	10	0.5	45	1.5
28/32	Pyramid	10	0.5	65	1.5
29/32	Cone	18	1	45	1.5
30/32	Cone	18	1	65	1.5
31/32	Cone	18	0.5	45	1.5
32/32	Cone	18	0.5	65	1.5

Since data related to duration and to instantaneous power were quite the same for the five tests, with a variation of less than 5%, power, duration and energy necessary for the test were referred as mean value and reported in the **Table 4.3** for the three main phases.

Table 4.3. Energy per hour requested by the machine in stand-by and by the auxiliary motors.

	Medium power [W]	Energy per hour [J]
Stand-by	2064	7430400
Auxiliary motors	3388	834120
Total		8264520

Table 4.3 shows how much energy per hour is consumed both by the machine in stand-by mode and by the auxiliary motors: the last ones cause an increase of about the 10% in energy consumption.

However, before showing the experiments results in term of power consumption, duration and energy, some notes about the presence of auxiliary motors and their influence on total energy consumption must be done.

4.2.4 Auxiliary motors and their impact on total energy consumption

The experiments were carried out through the vertical milling machine Mazak Nexus 410 shown in **Figure 4.1**.

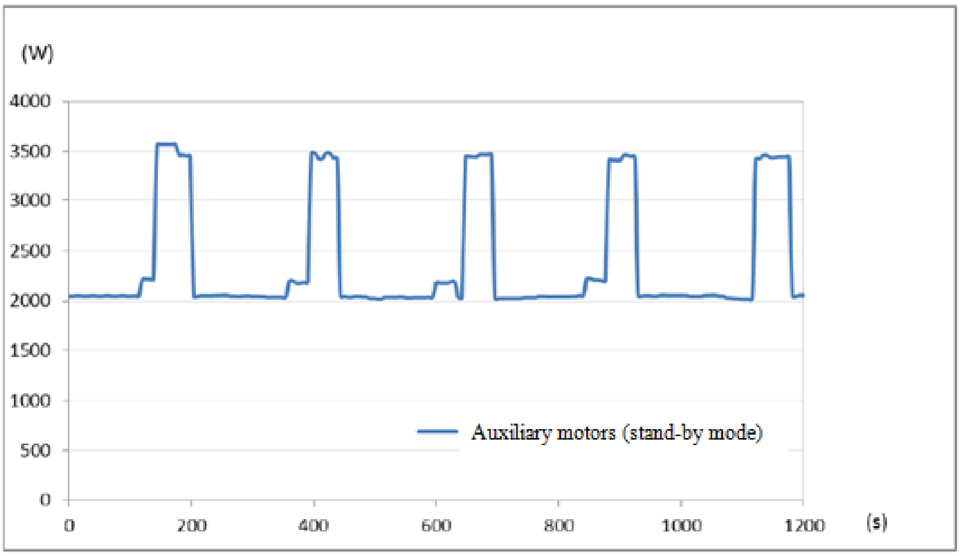


Figure 4.6. Power consumption due to the auxiliary motors (machine in stand-by mode).

Some auxiliary motors guarantee the correct functioning of the work centre, such as provide the correct functioning of its refrigerating system. In order to quantify how much power these auxiliary motors need, the machine stayed in stand-by mode for 20 minutes: the relative results are shown in **Figure 4.6**.

From **Figure 4.6** (which corresponds to the average distribution calculated on 5 tests), it is evident that the auxiliary motors turn on each 157 seconds and need a power 1500 W bigger than the power relative to the machine starting, and stay in operation for about 42 seconds. In 20 minutes auxiliary motors stay on 5 times; which means that the auxiliary motors stay on 15 times in 1 hour.

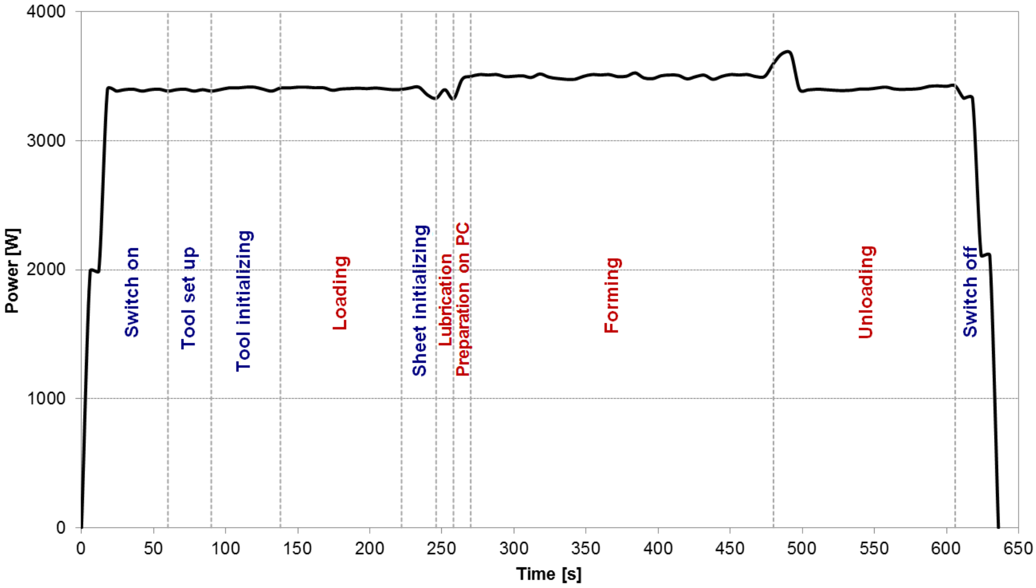


Figure 4.7. Power consumed during each one of the sub-phases.

Taking into account the cycle time analysis made before, **Figure 4.7** shows the power consumed during an entire cycle of ISF splitted into the various sub-phases, in the same experimental conditions highlighted previously.

4.2.5 Power consumption, duration and energy consumed

Power, duration and energy necessary for the tests were referred as mean value and reported in **Table 4.4** for the three main phases and for all the test conditions.

Table 4.4. Mean values for power, duration and energy measured during the a) tooling analysis; b) the process analysis; c) the disassembly analysis.

				Tooling	a)		Forming	b)		Disassembly	c)
P	D_p	α	Power [W]	Duration [s]	Energy [J]	Power [W]	Duration [s]	Energy [J]	Power [W]	Duration [s]	Energy [J]
1.0	10	45	2060	90	185400	2207	228	503196	2085	138	287730
1.0	10	65	2083	78	162474	2136	276	589536	2088	156	325728
1.0	18	45	2090	84	175560	2143	156	334308	2144	156	334464
1.0	18	65	2111	72	151992	2173	270	586710	2104	96	201984
0.5	10	45	2077	84	174468	2173	480	1043040	2097	144	301968
0.5	10	65	2080	90	187200	2181	558	1216998	2100	108	226800
0.5	18	45	2128	78	165984	2191	414	907074	2109	66	139194
0.5	18	65	2119	78	165282	2194	508	1114552	2172	90	195480

Actually, the results displayed in **Table 4.4** refer to the only set of experiments carried out considering the final shape equal to a frustum of pyramid and changing the other process parameters. In order to make the analysis easier and accurate, auxiliary engines that randomly starts when the work centre temperature increases was neglected during the experimental analysis.

Some preliminary considerations on the investigation can be easily derived for the semi-automatic phases (i.e. tooling and disassembly). The tooling and the disassembly steps were independent from the process parameters: the required power was quite constant whereas the duration was more variable and influenced by the manpower efficiency.

However, it is possible to refer to absolute mean values for this semi-automatic operations and consider the data reported in **Table 4.5**. Small differences were detected between the two phases both for mean power and duration: a larger mean power was measured during the disassembly due to the engines inertia after the manufacturing step; in the same way, longer duration was observed during the disassembly due to the worse ergonomic positions that the operator assumed during the operation.

On the other hand, the processing phase cannot be considered in terms of mean value, since both power and duration were affected by the process parameters. For this reason, a comparative analysis resulted necessary. The details for each parameter are summarized in the next subsections.

Table 4.5. Absolute mean values for the semi-automatic operations.

Phase	Power [W]	Duration [s]	Energy [J]
Tooling	2094	82	171045
Disassembly	2112	119	251669

Tool depth step influence

Varying the tool depth step from 1 mm to 0.5 mm the process duration doubled, such as the energy as consequence. However, having a look to the power distribution reported in **Figure 4.8**, no differences were visible on the steady state value and were dependent from the tool trajectory.

Taking into account the whole set of experiments (**Table 4.2**), it was possible to asses that changing the tool depth step, from 0.5 mm to 1.0 mm, the total energy decreased in the range of [47.3 ÷ 63.1]% at the varying of the other process parameters.

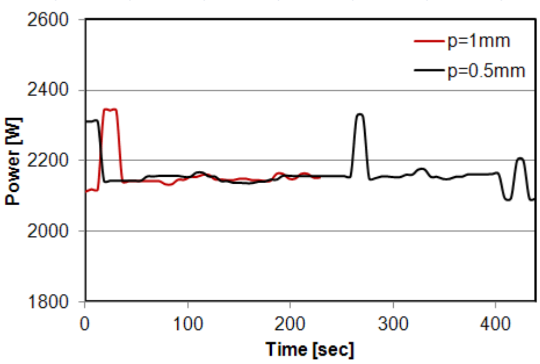


Figure 4.8. Tool depth step influence (D_p=18mm, α=45°).

Tool diameter influence

Changing the tool diameter into the considered range changed the trajectory length whereas no differences were visible in terms of required power. A larger tool did the shape profile by a short trajectory; for this reason, the variation of the total energy (see **Table**

4.4) was dependent on the process duration, rather than the instant power. The last one, instead, was quite constant in terms of distribution during the process time, as can be observed in **Figure 4.9**. All the tests were compared for changing tool diameter only; this comparison highlighted a reduction of the total energy up to 33.5% at the increase of the tool diameter from 10 mm to 18 mm (see **Table 4.4**).

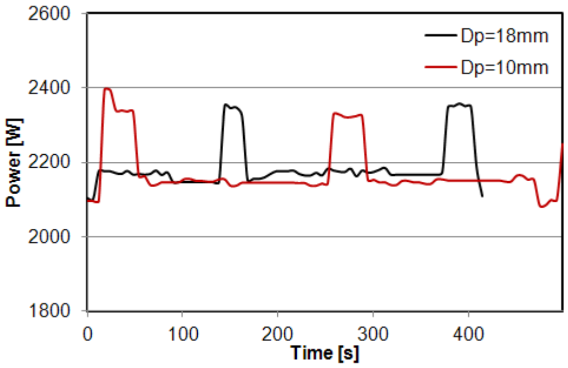


Figure 4.9. Comparison between the tool diameter (p=0.5mm, α=45°).

Wall inclination angle influence

No differences in the instant power were observed changing the wall inclination angle; the steady state value, in fact, was the same even if the larger wall inclination angle (α=65°) was close to the forming limit for the investigated material. On the other hand, a deeper angle implied a larger lateral surface of the pyramid and, as a consequence, a longer trajectory. This determined a longer process and, subsequently, higher value of energy (see **Table 4.4**). A comparison between the power distribution during the process for changing wall inclination angle is reported in **Figure 4.10**. Tests for changing wall inclination angle and fixed parameters values were compared and a reduction up to 43.0% of the total energy required was observed.

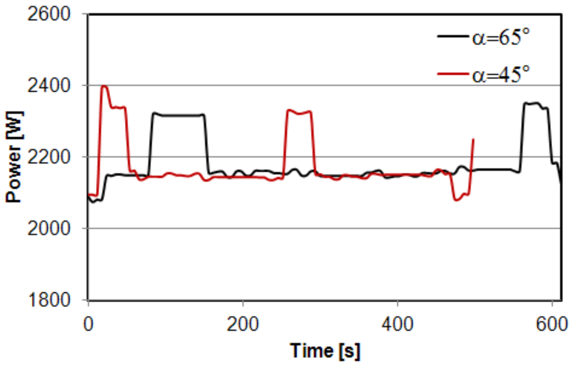


Figure 4.10. Comparison between the wall inclination angles (p=0.5mm, D_p=10mm).

Other parameters variation: shape influence

Looking at the data in **Table 4.6**, it is evident the power difference in the case of a frustum of pyramid and truncated cone. The **Table 4.6** shows the results related to two tests (mean values), but the same results were obtained for all the other tests. The **Figure 4.11** shows with evidence that the frustum of pyramid needs more power than the truncated cone: that can be explained by the bigger resistance that the material incrementally formed requires; moreover, the process duration in the case of frustum of pyramid is bigger, also because of the longer trajectory covered by the tool punch.

Table 4.6. Example of the different power and duration during the process phase for the pyramid shape and the cone one.

Test number	Shape	Dp [mm]	P [mm]	A [°]	thickness [mm]	power process [W]	duration process [s]
3/32	Frustum of pyramid	10	0.5	45	1.0	2173	498
7/32	Frustum of cone	10	0.5	45	1.0	2112	354

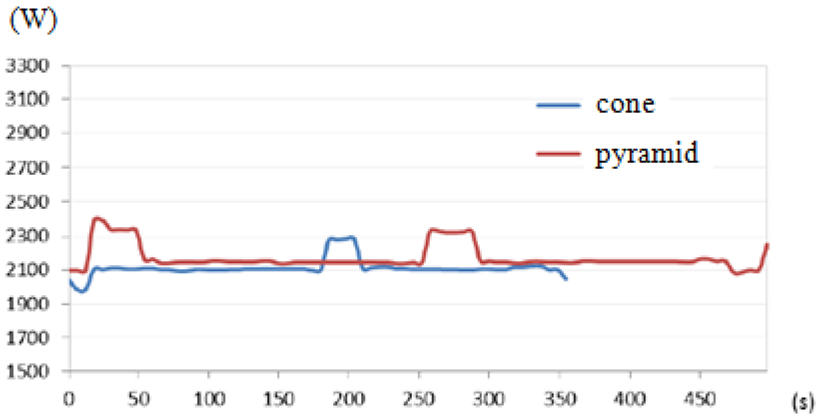


Figure 4.11. Power tendency at the varying of the component geometry.

Other parameters variation: sheet thickness

Finally, two different thicknesses (1 mm and 1.5 mm) have been compared. Both **Table 4.7** and **Figure 4.12** show the comparison between two tests, the 16 and the 20, but the same results can be displayed for all the tests.

Table 4.7. Example of the different power and duration during the process phase for the thickness of 1.5 mm and 1.0 mm, respectively.

Test number	Shape	Dp [mm]	P [mm]	A [°]	thickness [mm]	power process [W]	duration process [s]
16/32	Frustum of pyramid	18	0.5	65	1.5	2249	564
20/32	Frustum of pyramid	18	0.5	65	1.0	2194	558

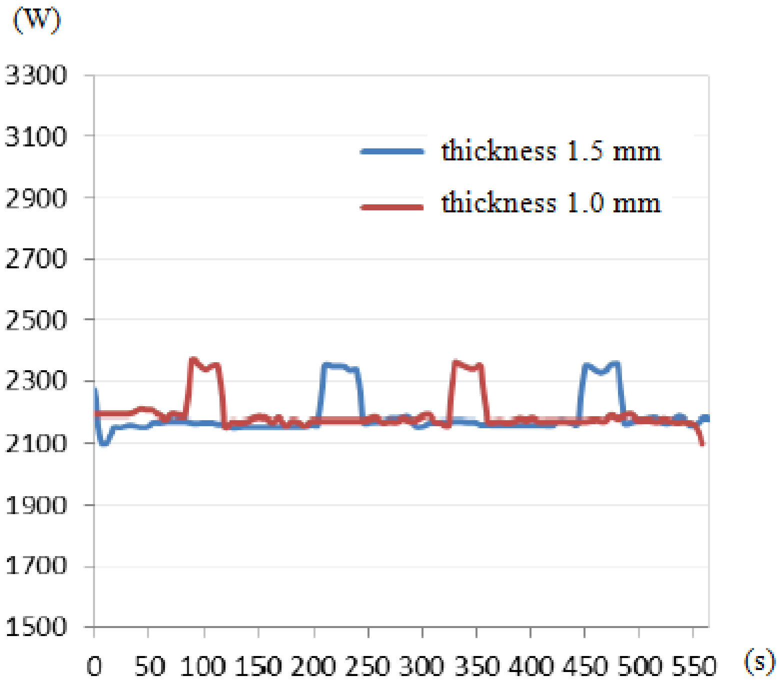


Figure 4.12. Power tendency at the varying of the component thickness.

If the thickness increases, both the duration and the power consumed during the process are unvaried. That can be explained by the particular material utilized, that has a low yield strength and it has been subjected to the heat-treating of annealing.

4.2.6 Final remarks

Some general conclusions can be derived:

- the energy related to the tooling and disassembly phases represents a small part of the overall consumption;
- the energy required for ISF process is strongly related to the tool trajectory and the process duration;

- accordingly, the tool depth step is the most significant factor and a proper choice of this determines a reduction of about 60% of the energy consumption.

Chapter 5

INNOVATIVE INCREMENTAL FORMING

5.1 Incremental forming innovative variants

In the last 20 years, many papers have been published taking into account different aspects of Incremental Forming processes, such as the process mechanics and, in particular, the analysis of formability, in comparison to traditional stamping process (Ambrogio et al., 2008; Jakson and Allwood, 2009). As stated in chapter 2, Incremental Sheet Forming processes present two relevant limitations, the one related to dimensional accuracy and the other one related to process slowness. As far as process accuracy is concerned, several studies can be traced by the state of the art (Filice et al., 2001; Hirt, 2004; Yoon and Yang, 2004; Bambach et al., 2005). On the other hand, the process slowness is still an open point of the research that penalizes the ISF process both from an industrial applicability and a sustainability point of view. Furthermore, industries interest towards the processing of new materials, in particular lightweight alloys, has increased. Due to that, for instance, Ji and Park (2008) investigated the single point incremental forming of Magnesium alloys, as well as Franzen et al. (2009) presented a study focused on the Single Point Incremental Forming of Polyvinyl chloride. Finally, in the last years, the literature showed an increasing interest towards the research of Incremental Forming innovative variants, which either solve the issue of the process slowness safeguarding the process accuracy, or allow different heating methods into the process itself.

Regarding the hot incremental forming and limiting the attention on the Titanium, different equipment were proposed, each one distinguishable also for the energy source. In the research done by Duflou et al. (2007b), the hot incremental sheet forming of Ti6Al4V was introduced and a Nd-YAG laser supplying a power of 500W was used as heat source; the experimental set-up required a 6-axis robot, equipped with a tool spindle mounted on a strain gauge based force/torque sensor. The machine structure is shown in **Figure 5.1**.

Even if the results were encouraging, a point of weakness was represented by the tooling cost and the complexity.

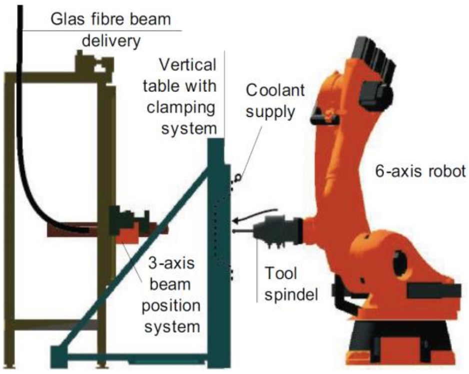


Figure 5.1. Single point incremental forming machine structure with dynamic, laser supported heating equipment (Duflou et al., 2007b).

A simpler technique based on the Joule's effect was, instead, introduced by Fan et al. (2008). An electric current was supplied by a DC power source while a closed circuit was built through the forming tool and the blank. Either the maximum drawing angle or the part accuracy were investigated in this paper (Fan et al., 2008). Later, Fan et al. (2010) used the same technique to work the Ti6Al4V alloy and demonstrated that the material can be formed by electric hot incremental forming in a range of 500°- 600°C, with a slight surface oxidation. Ambrogio et al. (2012a) followed the same approach and, besides, they created a workability map for the Ti6Al4V (**Figure 5.3**). This map determines the optimal energy to supply depending on the desired inclination angle (**Figure 5.3**). More recently, a thermo-mechanical approach to heat the Titanium blank was proposed by Palumbo et al. (2011).

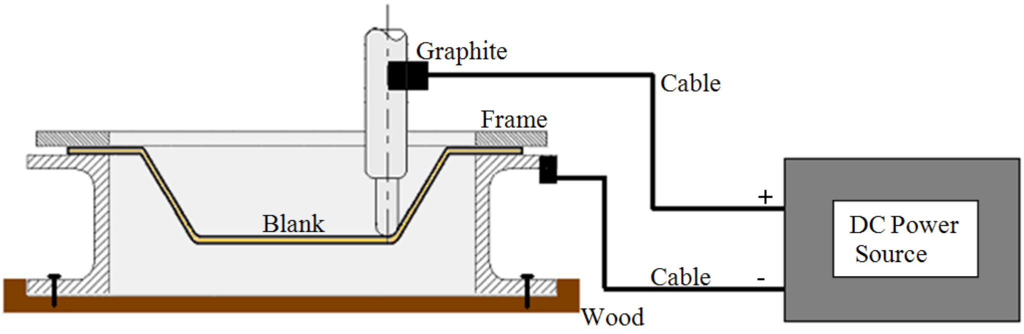


Figure 5.2. Sketch of the equipment used for electrical heating ISF (Ambrogio et al., 2012a).

This research consisted in using some heater bands that were mounted on both the flange and the blank holder. The results discussed in the above mentioned studies are different from each other in terms of formability. This is justified by several reasons: the utilized tool path, the punch dimension, the distance between the first coil and the clamping frame, the heating system.

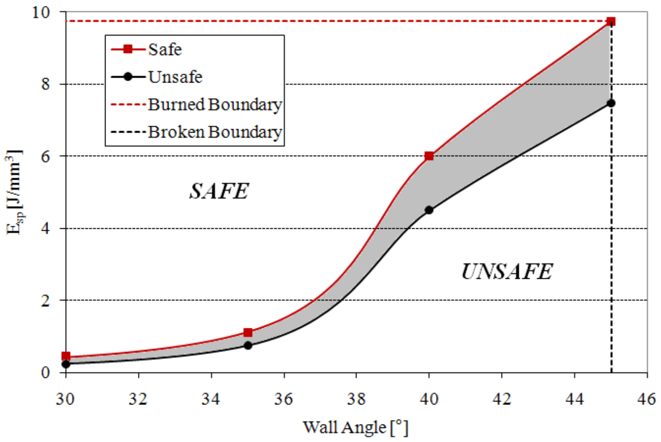


Figure 5.3. Hot Incremental Sheet Forming of Ti6Al4V: workability window (Ambrogio et al., 2012a).

According to that, the last part of the PhD research activity has been addressed in this direction and two studies have been executed aimed at completing the sustainability analysis of ISF. First of all (see case study 6) an high speed variant of ISF process has been designed and evaluated from the environmental impact point of view. This study allows to quantify the improvements obtainable by reducing the process duration. Secondly, a comparison between different equipment (which realize the hot incremental forming process) has been investigated (see case study 7) in terms of energy efficiency of the heating system.

5.2 Case study 6: high speed Incremental Forming

5.2.1 Materials and experimental apparatus

For the present investigation, two kinds of materials were used for the ISF experiments at high speed: Titanium Ti 6Al4V and Aluminium Alloy 6082 T6. The Ti 6Al4V is the most utilized Titanium alloy. It contains 6wt% Al and 4wt% V. Titanium Ti 6Al4V has a good corrosion resistance and presents an excellent combination of strength and toughness, with tensile strength up to 1000 MPa and elongation at fracture up to 13%. If cold formed, Ti6Al4V presents a reduced formability and excessive springback, thus it requires to be formed at elevated temperatures. The AA 6082 T6 presents a good formability and high strength. The Ti6Al4V and the AA 6082 T6 were provided in sheets of 1.0 mm thickness.

The experimental campaign was carried out by means of a Mazak™ QTurn 1000 CNC lathe. It is worth pointing out that a traditional milling machine allows transverse speeds of about 2000 inches per minute, equivalent to about 50 m/min, whereas the machine spindle allows a rotating speed up to 4500 r.p.m., with a theoretical relative velocity between the sheet and punch, of about 2500 m/min for the investigated geometry. This choice of the CNC lathe as a Single Point Incremental Forming machine, was done in order to increase the process speed: in fact, the tests were executed at two different orders of magnitude of feed rate. Due to the machine peculiarities, just axisymmetric shapes were analyzed: as shape, a frustum of cone with the major diameter of 180 mm and height of 25 mm was manufactured for Ti6Al4V and a frustum of cone with the major diameter of 180 mm and height of 40 mm was manufactured for AA 6082 T6.The wall inclination angle (α) was selected according to safe conditions (20° for Ti6Al4V and 42° for AA 6082 T6), since the issue of material formability is not of interest in this investigation (Duflou et al., 2007b).

As forming tool, an hemispherical punch of 15 mm diameter was used. In order to reduce friction, the molykote lubricant (Molybdenum disulfide) was sprayed on the sheet. As far as the tool speed is concerned, it ranged between 3 and 300 m/min for the AA 6082 T6 and between 5 and 500 m/min for the Ti6Al4V. It is worth to note that ISF processes are normally run at a speed of the order of 1 m/min. The experimental conditions for AA 6082 T6 and those ones for Ti6Al4V are shown in **Table 5.1**.

Table 5.1. Summary of the experimental conditions.

Experimental conditions – AA 6082 T6			
Pitch [mm]	0.1	0.55	1
Feed [m/min]	3	30	300
Experimental conditions – Ti6Al4V			
Pitch [mm]	0.1	0.3	0.5
Feed [m/min]	5	50	500

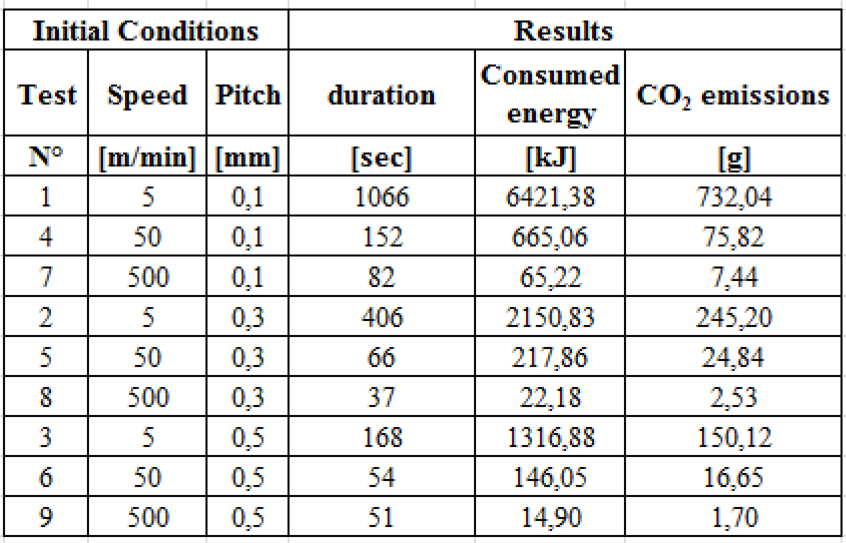
The tool pitch ranged between 0.1 mm and 1.0 mm for AA 6082 T6 and between 0.1 mm and 0.5 mm for Ti6Al4V during the whole investigation.

Each experiment, determined by a proper combination of the investigated parameters, was repeated five times. Since data related to duration and to power were quite the same for the five tests, with a variation of less than 5%, power, duration and consequently energy necessary for the experiments were referred as mean value in the following tables and charts.

5.2.2 Discussion of the results

The most relevant results of the above described experimental campaign, with particular attention to the consumed energy and consequently to the CO_2 emissions, at the varying of speed and pitch are here presented. In order to highlight the effect of the speed, one and two orders of magnitude characterize the tests at lower and higher feed.

Table 5.2. Energy consumed values, CO_2 emissions at the varying of pitch and speed for Ti6Al4V.

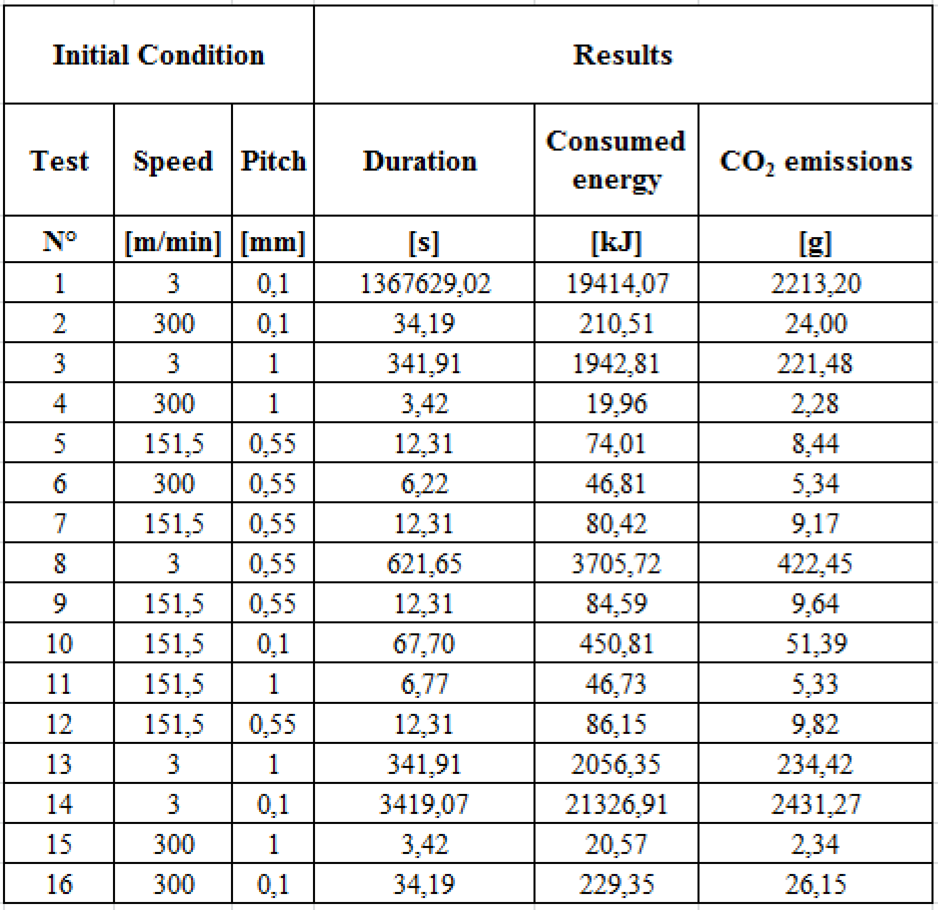


Initial Conditions			Results		
Test	Speed	Pitch	duration	Consumed energy	CO_2 emissions
N°	[m/min]	[mm]	[sec]	[kJ]	[g]
1	5	0,1	1066	6421,38	732,04
4	50	0,1	152	665,06	75,82
7	500	0,1	82	65,22	7,44
2	5	0,3	406	2150,83	245,20
5	50	0,3	66	217,86	24,84
8	500	0,3	37	22,18	2,53
3	5	0,5	168	1316,88	150,12
6	50	0,5	54	146,05	16,65
9	500	0,5	51	14,90	1,70

Table 5.2 summarizes the results for the Titanium alloy, **Table 5.3** those ones for the Aluminium alloy: the calculation of CO_2 emissions is made following the CES^{TM} method, which was already discussed in chapter 3. In **Table 5.3**, the effect of the variation of the different thicknesses is also shown.

If the speed increases, it is evident from **Table 5.2** the time reduction for target components made in Titanium alloys; the same results occur in **Table 5.3** for components made in Aluminium alloy. Considering just the working time for the test carried out on the Ti6Al4V sheets, a reduction from about 17 minutes to less than 1 minute was reached from the slowest experimental condition (V=5 m/min, p=0.1 mm) to the fastest one (V=500 m/min, p=0.5 mm).

Table 5.3. Energy consumed values, CO_2 emissions at the varying of pitch and speed for AA 1082 T6.



Initial Condition			Results		
Test	**Speed**	**Pitch**	**Duration**	**Consumed energy**	**CO_2 emissions**
N°	**[m/min]**	**[mm]**	**[s]**	**[kJ]**	**[g]**
1	3	0,1	1367629,02	19414,07	2213,20
2	300	0,1	34,19	210,51	24,00
3	3	1	341,91	1942,81	221,48
4	300	1	3,42	19,96	2,28
5	151,5	0,55	12,31	74,01	8,44
6	300	0,55	6,22	46,81	5,34
7	151,5	0,55	12,31	80,42	9,17
8	3	0,55	621,65	3705,72	422,45
9	151,5	0,55	12,31	84,59	9,64
10	151,5	0,1	67,70	450,81	51,39
11	151,5	1	6,77	46,73	5,33
12	151,5	0,55	12,31	86,15	9,82
13	3	1	341,91	2056,35	234,42
14	3	0,1	3419,07	21326,91	2431,27
15	300	1	3,42	20,57	2,34
16	300	0,1	34,19	229,35	26,15

A reduction in duration has consequences in energy consumption and the energy consumption in CO_2 emissions, as it is evident from **Table 5.2** and **Table 5.3** and also from **Figure 5.4**, where the CO_2 emissions are displayed at the varying of some parameters (speed and pitch).

It is remarkable how the execution time and consequently energy consumed and CO_2 emitted become very small using the high speed. In order to diffuse its use in industries, the single point incremental forming technique, high performance machines must be available, whereas nowadays they are not.

As far as high speed is regarded, Hamilton and Jeswiet (2010) proposed a study on the forming of AA3003-H14 alloy at high feed rates and rotational speeds: the goal of their research is to evaluate how the increase of the working speed affects the quality of components produced by ISF.

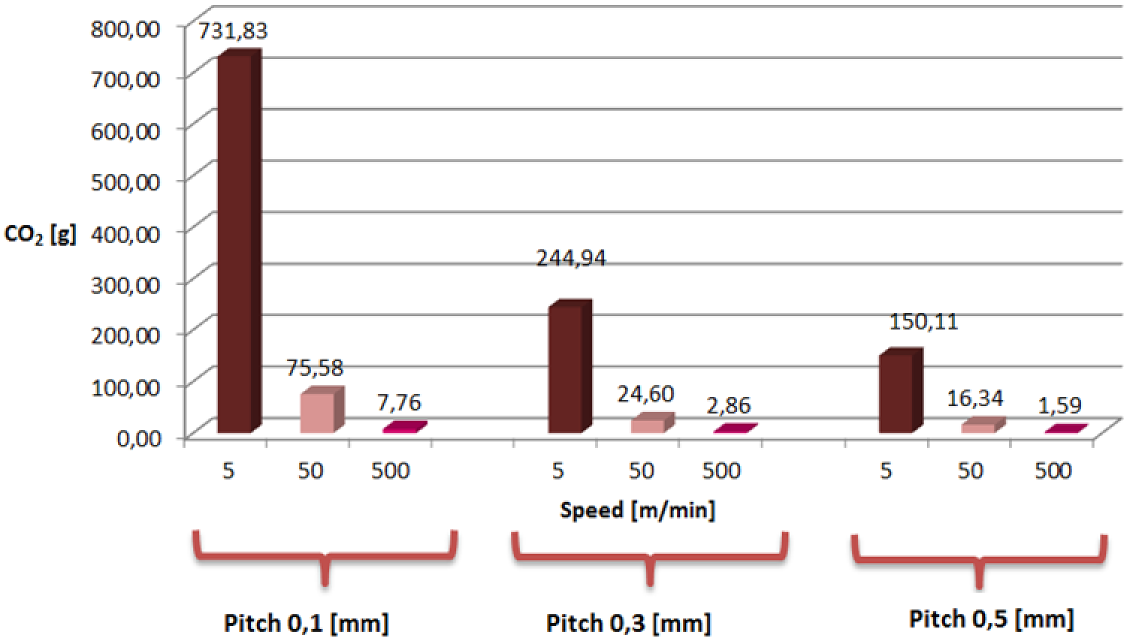


Figure 5.4. Ti 6Al4V: CO_2 emissions at the varying of the speed and of the pitch.

Only recently, this issue was discussed taking into account some Aluminium alloys (Ambrogio et al., 2012b). Following the results of this case study, an interesting research (Ambrogio et al., 2013) investigated how the increase of the process speed does not alter neither the material microstructure nor the micro-hardness, thus pushing to realize ISF processes at a rate of two orders of magnitude higher than the one currently utilized.

5.3 Case study 7: sustainable process feasibility for lightweight materials

5.3.1 Hot incremental sheet forming

The advantages that ISF presents have been already discussed (see chapter 2). A new advantage not yet discussed is that ISF could be a suitable alternative to manufacture some “hard to work materials”. Among them, Titanium plays a relevant role. As well-known, lightweight materials (such as Aluminium, Magnesium and Titanium alloys) have a great interest. These allow a strong mass reduction which directly impacts CO_2 emissions. For instance, 50 kg of a car mass saving corresponds to a reduction of about 5 grams of CO_2 each kilometer (Habashi, 1997; Ingarao et al., 2011b). Thanks to its excellent mechanical characteristics, Titanium rises above the others lightweight alloys (Ambrogio et al., 2010; Stainless steel, 2010). It is mainly used in aircraft, naval ships, spacecraft and missiles due to the fuel consumption reduction. Moreover, the biocompatibility allows a safe use in human bone and tissue replacement. Titanium scrap can be recyclable and for these reasons is one of the most environmentally friendly metals (Stainless steel, 2010). However, Titanium alloys have a huge environmental impact: the current production of Titanium is exclusively done by the Kroll process (Habashi, 1997; Ingarao et al., 2011b), with a very huge environmental impact. As a matter of fact, the LCA methodology, related to "cradle to gate" stage in metal production, shows the environmental impacts concerning Titanium ingot production (Norgate et al., 2007). As a consequence, the importance of saving energy in the stages of life cycle that follow the raw material extraction and refining (product manufacturing, product use, recycling and disposal) is easily discernible.

In spite of all advantages presented previously, Titanium shows a low cold workability (Ambrogio et al., 2010). Today Titanium is usually worked by superplastic forming or hot forming in case of simple shapes. In case of hot workability, the importance of analyzing energy consumption and, thus, of reaching energy efficiency increases. Furthermore, both the processes are very slow and expensive. In a previous work, Ambrogio et al. (2012a) showed how it is possible to form Titanium alloys using ISF combined with a local heating. The process does not require large forces but is really slow. Thus, the different heating sources can have a deep impact on the global energy performance. This case study is a first attempt to consider the process in a wider view, looking at the energy consumption as a primary issue.

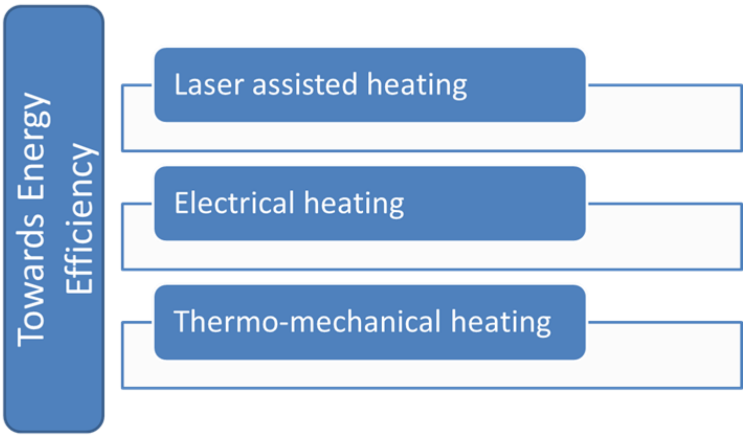


Figure 5.5. Alternatives investigated in the present case study, from an energy consumption point of view.

In particular, a comparison among different heating methods was carried out: the goal is to roughly highlight the differences among laser assisted heating, electrical heating and thermal heating in ISF of Ti6Al4V alloy, as summarized in **Figure 5.5**: these methods, in fact, are those comparable from the literature overview, as introduced at the beginning of this chapter (Duflou et al., 2007b; Fan et al., 2008; Palumbo et al., 2011).

Summing up, the aim of this case study has been to compare some heating methodologies only from the energy consumption point of view. In order to evaluate the energy consumption for each strategy, a coupled numerical/experimental approach was adopted. A specific case study was used to make the comparison.

5.3.2 Experimental and numerical evidences for the electrical heating source

As far as the electrical heating source is concerned, the equipment used in the experiments is already shown in **Figure 5.2**. A steel frame was utilized to clamp the blank along its perimeter. A HSS (high strength steel) steel punch with a diameter of 12 mm was used in order to ensure a good mechanical resistance at high temperature. A DC power unit EA-PS1000 was able to supply a current intensity in the range 0-6000 A, applying the required voltage (V) at the ends of the closed circuit composed by the blank and the tooling. The electrical connection with the punch was accurately designed and made by using a graphite slider forced against the rotating tool. A wood support was placed at the bottom of the equipment for the electrical insulation. A thin layer of molybdenum bisulfate (MoS_2) was applied on the sheet surface before the test. A frustum of cone, which is conventionally recognized as a benchmark shape (Habashi, 1997), was produced: the major base and the final depth were fixed to 120 mm and 40 mm, respectively. According to the previous investigation and the workability map obtained for the 1 mm thick Ti6Al4V blank (Ambrogio et al., 2012a), a wall inclination angle equal to 45° was manufactured supplying a specific energy of 10 J/mm^3. Taking into account the contact area and the tool feed, this corresponds to a power of about 400 W. As expected, the test was completed leading to a sound component.

Starting by this result, a numerical analysis was performed to evaluate the temperature field in the specimen and, as a consequence, the temperature arising in the working volume. This is the key variable since it directly influences the material ductility.

A thermal Finite Element simulation based on the discretization of Fourier’s equation was performed to evaluate the temperature evolution in the blank. The model was implemented in SFTC Deform 3D environment; all the material data are available by literature and the room temperature (20°C) was imposed on the perimeter as boundary condition.

The heat flux supplied during the experimental test was set in the numerical model; in particular, a constant heat flux was locally applied to a small area which matches the interface surface. The temperature increasing was calculated up to reach the stationary condition, which corresponds to 500°C approximately (see **Figure 5.6**).

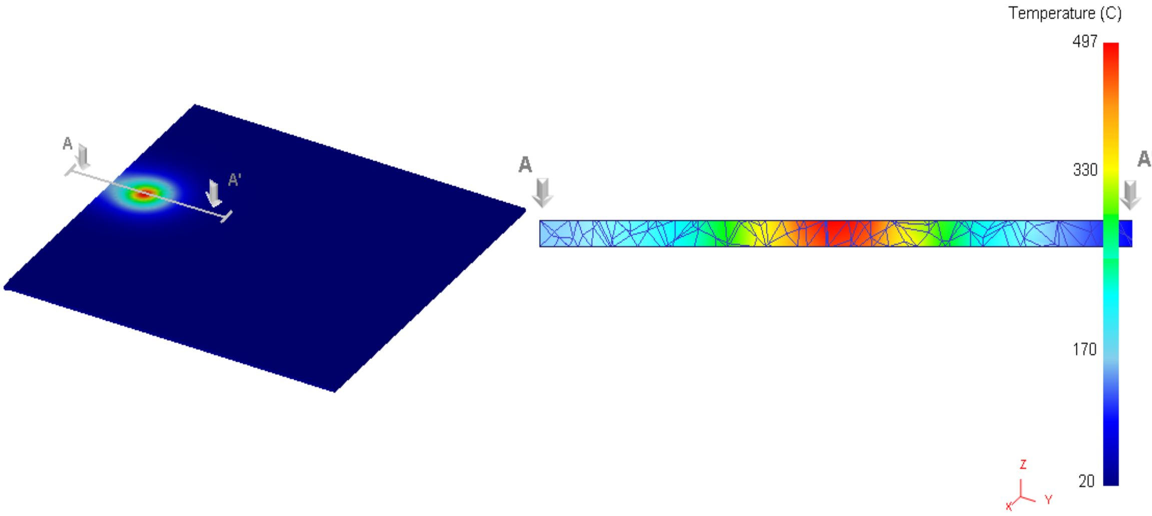


Figure 5.6. Temperature map due to the sheet local heating.

The obtained temperature was chosen according also to Fan’s experiments (Fan et al., 2008). The above introduced numerical model was then used to estimate the required thermal flux able to heat the whole blank, modeling an approach based on a diffuse heating (heater band).

Fixing 497°C as target temperature, an inverse approach was implemented to predict the required heat flux. The convergence was obtained imposing about 4600 W on the sheet. In practice, the heated surface increases by a factor 100, the specific power reduces by a factor 10.

5.3.3 Energy efficiency analysis

A global energetic analysis has to take into account also the machine electric consumption (axis movement, mandrel rotation, lubrication pump, machine devices) but since this value does not depend on the heating system, a differential analysis has been here executed.

As far as the local heating systems are regarded, in this paper both a Joule’s effect device and a laser source are considered. Experimental tests demonstrated that the circuit resistance in the first equipment is about the half (47%) of the total electrical resistance.

This means that half of the power is dissipated in the circuit, the other part (53%) is supplied to the sheet. In other words, taking into account the electric machine efficiency, equal to 86%, 878 W are required at the power line to supply 400 W at the working material.

On the other hand, a reference laser source (IPG-photonics YLS series) presents a global efficiency of about 10%, taking into account both wall plug efficiency and material reflectance, than about 4000 W are required to execute the forming operation.

As far as the diffuse heating is regarded, it was calculated in 4600 W the required power on the sheet. In this case, due to the layout and the limited energy loss on the cables and toward the environment, the efficiency has been estimated equal to 93%. Thus, 4946W are required to heat the sheet.

For the considerations above reported, as it was expected, a local heating is preferable in terms of energy absorption. However, Joule’s effects allows to obtain the same effect using an electric power about 4-5 times less than laser or heater bands system. Laser and heater bands absorb more or less the same power and this is the reason why sometimes a global heating is preferable, also due to the tooling simplicity.

However, some other considerations can be taken into account:

1. moving system. Systems based on external source like laser or lamps require a moving device to allow a proper tooling following. This system is expensive and increases the equipment complexity;
2. temperature controlling. Localized sources allow a better temperature control in order to reduce oxidation and lead a proper formability;
3. Joule’s effect heater is probably the most efficient from the energetic point of view and very easy to build up since it integrates the normal tooling. On the other hand, the continuous sparkling on the sheet may cause local overheating which tends to decrease the surface quality.

5.3.4 Final remarks

Implementation of sustainability concepts in manufacturing passes through a wider analysis which takes into account a number of variables. Considerations based only on the energy consumption may lead to quick solutions that can affect the product performance in use. In this analysis it has been demonstrated that a good formability of Ti6Al4V is obtained when the temperature reaches about 500°C. The absorbed electric power required to reach this result ranges between 900 W and 5000 W. A quick data analysis suggests the use of Joule’s effect heating because of the significant power saving. On the other hand, more detailed investigations related to the effects on the material have to be executed.

As a general results, it is possible to claim that system based on diffuse heating are simple but really costly from an energetic point of view. Local heating systems probably will be the best solutions of the next years but systems more efficient than laser sources have to be preferred. Among them, Joule’s effect based equipment could play a relevant role.

CONCLUSIONS

Manufacturing field and, in particular, incremental sheet metal forming processes, have not widely explored from the environmental impact point of view. The aim of these years of research has been to study the sustainability principles and then to apply them to a set of manufacturing processes, such as the incremental sheet forming processes. Central in this research has been a specific innovative process: the Single Point Incremental Forming (SPIF), which is very flexible and cheap presenting practically the only disadvantage of a long duration. The goal of this research is to investigate and to give a little contribution to explore this process into the wide scenario of the manufacturing field, from a sustainable point of view. As methodology, in some case studies the life cycle assessment methodology has been followed either as general approach or as software (using Gabi), such as in case study 1, 2 and 3. The originality of the work consists in investigating the ISF process (the generic ISF acronym has been used instead of SPIF, during the whole PhD thesis) from a new perspective, that one of sustainability, and in exploring all the aspects related to it, such as materials consumption, lubricant use, energy and CO_2 emissions. Of all the sustainability factors taken into account, in this research energy represents the most important one, because of its importance as factor able to generate development and because of the energy resources scarcity. The theoretical energy consumption has been counted in case study 1, 2 and 3, by comparing the ISF technology with the more conventional Deep Drawing one in order to fully highlight the points of strength and weakness of both processes. The result was that ISF process is the best one, if only the material quantity is considered, but ISF is the worst one because of the high energy consumption. Subsequently, after starting the research with the theoretical energy consumption, the real energy consumption for ISF was determined executing an experimental investigation at the laboratory of mechanical, energy and management engineering department (as detailed in case studies 5 and 6), which allowed to determine both the influence of all the process parameters and the inefficiencies that need to be solved in order to make the process more competitive. The result was that process is highly time and trajectory dependent; while the last one is strongly related to the product shape and needed quality, the time can be reduced by working at high speed. The last issue, finally, represent the point of start of new lines of research. As far as the energy aspect is concerned, the duration of the process is very important (see case study 5). Dealing with energy problems, the innovation degree of this research consisted from one hand in overcoming the issue of process slowness by proposing the high speed incremental forming (see case study 6), and from the other hand by addressing industries attention towards new machines dedicated to incremental forming processes. The high speed incremental forming is a new technique able to overtake a big disadvantage of the ISF process, the process duration: this technique reduces drastically the process duration, without compromising the surface quality and thus industries can include the ISF process as new innovative and profitable technique. Always in energy field, the comparison between different ways of heating the sheets in order to hot form different lightweight materials, in particular Titanium alloys, as detailed in case study 7, was done: the objective was to establish the best one, that means that one less energy consuming. The comparison was done between laser assisted heating, electrical heating and thermo-mechanical heating and the best one resulted to be the electrical heating. Dealing with lubrication problem, the innovation degree of this work consisted also in proposing an appropriate tool coating (AlSiTiN), as detailed in case study 4. This sustainable solution for the ISF process allows to completely avoid the use of lubricant. In conclusion, the goal of the present PhD thesis was to investigate incremental sheet metal forming processes from a new perspective, that one of sustainability, and to propose some environmental friendly ideas in order to make the process itself more profitable for manufacturing industries.

REFERENCES

Ambrogio, G., Filice, L., Micari, F., 2004. Verso il Dieless: la Formatura Incrementale. Lamiera, Tecniche Nuove, Novembre 2004, pp. 74-80.

Ambrogio G., Filice L., Micari F., 2006. A force measuring based strategy for failure prevention in incremental forming. Journal of Materials Processing Technology 177, pp. 413-416.

Ambrogio G., Filice L., Manco G.L., Forcellese A., Simoncini M., 2007. A FE approach to design warm deep drawing operations of magnesium alloys. Proc. 8th A.I.Te.M. Conference (2007), pp. 109-110.

Ambrogio, G., Filice, L., Manco, G.L., 2008. Considerations on the Incremental Forming of Deep Geometries, Int. J. of Metal Forming 1, pp. 1143-1146.

Ambrogio, G., Filice, L., Gagliardi, F., Manco, G.L., Lazzaro, S., 2010. Manufacturing of an Aircraft Component by Hot Forming of Titanium Alloy. 7th CIRP International Conference on Intelligence Computation in Manufacturing Enginnering. In. Cogn. Prod. Tech. Syst., 23 - 25 June 2010, Capri (Gulf of Naples), Italy.

Ambrogio, G., Filice, L., Gautier, G., Rizzuti S., 2011. Influence of tool coating on the process performance of AISI 304 Incremental Sheet Forming. Proc. 10th Int. Conf. Techn. Plast. (ICTP 2011).

Ambrogio, G., Filice, L., Gagliardi, F., 2012a. Formability of lightweight alloys by hot incremental forming. Materials and Design 34, pp. 501-508.

Ambrogio, G., Filice, L., Gagliardi, F., 2012b. Improving industrial suitability of incremental sheet forming process, Int. J. Adv. Manufacturing Technology, DOI 10.1007/s00170-011-3448-6.

Ambrogio, G., Gagliardi, F., Bruschi, S., Filice, L., 2013. On the high-speed Single Point Incremental Forming of Titanium alloys. CIRP Annals - Manufacturing Technology, Volume 62, Issue 1, pp. 243-246.

Ashby, M.F., 2009. Materials and the Environment: Eco-Informed Material Choice. Elsevier.

Badurdeen, F., Jayal, A.D., Jawahir, I.S., 2009. Towards a System Approach for Developing Sustainable Products from Sustainable Manufacturing. Bangalore Workshop, Bangalore India.

Badurdeen, F., Goldsby, T.J., Iyengar, D., Metta, H., Gupta, S., Jawahir, I.S., 2010. Extending Total Life-cycle Thinking to Sustainable Supply Chain Design. International Journal of Product Lifecycle Management, 4/1/2/3, pp. 49–67.

Bambach, M., Hirt, G., Junk, S., 2003. Modelling and Experimental Evaluation of the Incremental CNC Sheet Metal Forming Process, VII International Conference on Computational Plasticity, COMPLAS 2003, Barcelona 7-10 April 2003.

Bambach, M., Hirt, G., Ames, J., 2005. Quantitative Validation of FEM Simulations for Incremental Sheet Forming Using Optical Deformation Measurement. In: Proceedings of the 11th International Conference on Sheet Metal, SheMet 2005, Erlangen, Germany.

Bambach, M., 2008, Process Strategies and Modelling Approaches for Asymmetric Incremental Sheet Forming, Umformtechnische Schriften Band 139, Shaker Verlag, Aachen.

Bare, J.C., 2002. Developing a Consistent Decision-Making Framework by Using the U.S. EPA's TRACI, AIChE (2002).

Bay, N., Olsson, D.D., Andreasen, J.P., 2005. Testing Environmentally Friendly Lubricants for Sheet Metal Forming; Proc ICTP Conference.

Boden, T.A., Marland, G., Andres, R.J., 2010. Global, Regional, and National Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2010.

Chee, W.P., Shi, F.R., Zhiquan, Y., Kenneth, H.K.G., Ruisheng, N., Bin, S., 2011. Identifying Carbon Footprint Reduction Opportunities through Energy Measurements in Sheet Metal Part Manufacturing. Glocalized Solutions for Sustainable Manufacturing, pp. 389-394.

Chen, F. K., Chiu, K. H., 2005. Stamping formability of pure Titanium sheets. Journal of Materials Processing Technology 170, pp. 181–186.

Cml, 2010. Information in http://www.cml.leiden.edu (2010).

Coou, 20010. Information in http://www.coou.it (2010).

Davis, J.R., 1998. Metals Handbook, 2nd Edition. The Materials Information Society.

Dettmer, T., 2006. Nichtwassermischbare Kühlschmierstoffe auf Basis nachwachsender Rohstoffe, Vulkan-Verlag, Essen.

Duflou, J. R., Szekeres, A., Vanherck, P., 2005. Force Measurements for Single Point Incremental Forming: An Experimental Study. In: Proceedings of the 11th International Conference on Sheet Metal (2005) April 5-8; Erlangen, Germany.

Duflou, J., Tunckol, Y., Szekeres, A., Vanherck, P., 2007a. Experimental study on force measurements for single point incremental forming. Journal of Materials Processing Technology 189, pp. 65-72.

Duflou, J.R., Callebaut, B., Verbert, J., De Baerdemaeker, H., 2007b. Laser assisted incremental forming: formability and accuracy improvement. Cirp Annals-Manufacturing Technoly 56/1, pp. 273–276.

Duflou, J.R., Callebaut, B., Verbert, J., De Baerdemaeker, H., 2008. Improved SPIF performance through dynamic local heating. International. Journal of Machine Tools & Manufacture, pp. 543–549.

Duflou, J.R., Kellens, K., Devoldere, T., Deprez, W., Dewulf, W., 2010. Energy Related Environmental Impact Reduction Opportunities in Machine Design: Case Study of a Laser Cutting Machine. International Journal of Sustainable Manufacturing, 2/1, pp. 80–98.

Duflou, J.R., Clarke, R., Merklein, M., Micari, F., Shirvani, B., Kellens, K., 2011a. Environmental Performance of Sheet Metal Working Processes. Key Engineering Materials 473, pp. 21-26.

Duflou, J.R., Kellens, K., Dewulf, W., 2011b. Unit process impact assessment for discrete part manufacturing: A state of the art. CIRP Journal of Manufacturing Science and Technology 4, pp. 129–135.

Eoearth, 2013. Information in http://www.eoearth.org/article/United_Nations_Conference_on_the_Human_Environment_(UNCHE)%2C_Stockholm%2C_Sweden

Fan, G., Gao, L., Hussain, G., Wu, Z., 2008. Electric hot incremental forming: a novel technique. International Journal of Machining Tools and Manufacturing 48, pp. 1688-1692.

Fan, G., Sun, F., Meng, X., Gao, L., Tong, G., 2010. Electric hot incremental forming of Ti-6Al-4V Titanium sheet. Int Journal of Advanced Manufacturing Technology 49, pp. 941-947.

Filice, L., Fratini, L., Micari, F., 2001. New Trends in Sheet Metal Stamping Processes. Proc. of 1th Int. Seminar of Progress in Innovative Manufacturing Engineering, Sestri Levante, Italy.

Filice, L., Fratini, L., Micari, F., 2002. Analysis of material formability in incremental forming, Annals of the CIRP, 51/1, pp. 199-202.

Filice, L., Ambrogio, G., Micari, F., 2006. On-line control of Single Point Incremental Forming Operations through punch force monitoring. CIRP Annals – Manufacturing Technology 55(1), pp. 245-248.

Franzen, V., Kwiatkowski, L., Martins, P.A.F., Tekkaya, A.E., 2009. Single point incremental forming of PVC. Journal of Material Proc. Technology 209, pp. 1810-1815.

Fratini, L., Ambrogio, G., Di Lorenzo, R., Filice L., Micari, F., 2004. Influence of mechanical properties of the sheet material on formability in single point incremental forming. CIRP Annals – Manufacturing Technology 53(1), pp. 207-210.

Gantar, G., Šehič, E., Kuzman, K., 2005. Reduction of the environmental burden caused by household appliances. Proceedings of ICTP Conference.

Goedkoop, M., Müller-Wenk, R., Hofstetter, P., Spriensma, R., 1998. The Eco-Indicator 99 explained, International Journal of Life Cycle Assessment, 3/6, pp. 352–360.

Gronostajski, J., Matuszak, A., 1999. The recycling of metals by plastic deformation: an example of recycling of Aluminium and its alloys chips. Journal of Materials Processing Technology 92-93, pp. 35-41.

Gutowski, T., 2004. Design and Manufacturing for the Environment. Handbook of Mechanical Engineering, Springer-Verlag.

Gutowski, T., Dahmus, J., Thiriez, A., 2006. Electrical Energy Requirements for Manufacturing Processes; 13th CIRP Int Conf LCE, Leuven, Belgium.

Habashi, F., 1997. Handbook of Extractive Metallurgy. Wiley-VCH.

Hamilton, K., Jeswiet, J., 2010. Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences. Annals of CIRP 59/1, pp. 311-314.

Hauschild, M., Jeswiet, J., Alting, L., 2005. From Life Assessment to Sustainable Production: Status and Perspectives. CIRP Ann – Manuf Tech, pp. 1-21.

Hermann, C., Hesselbach, J., Bock, R., Zein, A., Öhlschläger, G., Dettmer, T., 2007. Ecologically Benign Lubricants – Evaluation from a Life Cycle Perspective. Clean - Soil, Air, Water, vol. 35(5), pp. 427-432.

Hermann C., Thiede, S., 2009. Process Chain Simulation to Foster Energy Efficiency in Manufacturing. CIRP J Manufacturing Sci Technol 1, pp. 221-229.

Hirt, G., Junk, S., Witulski, N., 2002. Incremental Sheet Forming: Quality Evaluation and Process Simulation. 7th ICTP International Conference on Technology of Plasticity, October 27-November 1, 2002, Yokohama, Japan, paper no. 343.

Hirt, G., 2004. Tools and Equipment used in Incremental Forming. 1st Incremental Forming Workshop, University of Saarbrucken, 9 June 2004. On Cdrom.

Hirt, G., Ames, J., Bambach, M., Kopp, R., 2004. Forming Strategies and Process Modelling for CNC incremental Sheet Forming. Annals of the CIRP, 52/1, pp. 203-206.

Hirt, G., Ames, J., Bambach, M., 2005. A New forming strategy to realise parts designed for deep drawing by incremental CNC sheet forming. Steel research, 71/2, pp.160-166.

Ingarao, G., Ambrogio, G., Di Lorenzo, R., Micari, F., 2011a. On the Sustainability Evaluation in Sheet Metal Forming Processes. Key Engineering Materials 473, pp. 824-829.

Ingarao, G., Di Lorenzo, R., Micari, F., 2011b. Sustainability Issues in Sheet Metal Forming Processes: an Overview. Journal of Cleaner Production 19, pp. 337-347.

Ingarao, G., Gagliardi, F., Anghinelli, O., Di Lorenzo, R., 2011c. A Sensitivity Analysis on Enviromental Sustainability in Sheet Metal Forming. The 10th International Conference on Technology of Plasticity, 25-30 October 2011, Aachen –Germany.

International Energy Agency, 2011. CO_2 emissions from fuel combustion.

IPCC, 2001. Third Assessment Report.

Iseki, H. Kato, K., Kumon, H., Ozaki, K., 1992. Flexible and Incremental Sheet Metal Bulging Using a Few Spherical Rollers. Trans JSME 59-565, pp. 2849-2854 (in Japanese).

International Standards Organisation, 2006a. ISO 14040 Life Cycle Assessment – Principles and Framework. International Standards Organisation: ISO 14044 Life Cycle Assessment Requirements and Guidelines.

International Standards Organization (ISO), 2006b. ISO 14044 Life cycle assessment Requirements and guidelines.

Iucn, 2013. Information in http://www.iucn.org (Jun-2013).

Iwanaga, K., Tashiro, H., Okamoto, H., Shimizu, K., 2004. Improvement of Formability from room temperature to warm temperature in AZ31 Magnesium Alloy. Journal of Materials Processing Technology, 155-156, pp. 1313-1316.

Jadhav, S., Goebel, R., Homberg, W., Kleiner, M., 2003. Process Optimization and Control for Incremental Sheet Metal Forming. In: Proceedings of the International Deep Drawing Research Group Conference, IDDRG, pp. 165-171, Bled, Slovenia, May 2003.

Jadhav, S., 2004. Basic investigation of the incremental sheet metal forming process on a CNC milling machine. Universität Dortmund, Germany, Diss..

Jakson, K., Allwood, J., 2009. The mechanics of incremental sheet forming. Journal of Materials Processing Technology 209, pp.1158-1174.

Jawahir, I.S., Dillon Jr O.W., 2007. Sustainable Manufacturing Processes: New Challenges for Developing Predictive Models and Optimization Techniques. In: Proceedings of the 1st International Conference on Sustainable Manufacturing (SM1) (Montreal, Canada).

Jawahir, I.S., Baburdeen, F., Rouch, R.E., 2013. Innovation in Sustainable Manufacturing Education. 11th Global Conference on sustainable Manufacturing, 23rd-25th September, Berlin - Germany.

Jayal, A.D., Badurdeen, F., Dillon Jr., O.W., Jawahir, I.S., 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology, Volume 2, Issue 3, pp. 144–152.

Jeswiet J., Micari, F., Hirt, G., Bramley, A., Duflou, J., Allwood, J., 2005. Asymmetric Single Point Incremental Forming of Sheet Metal. CIRP Annals – Manufacturing Technology 54/2, pp. 88-114.

Jeswiet, J., Kara, S., 2008. Carbon Emissions and CES^{TM} in Manufacturing. CIRP Annals – Manufacturing Technology 57, pp. 17-20.

Ji, Y.H., Park, J.J., 2008. Formability of magnesium AZ31 sheet in the incremental forming at warm temperature. Journal of Materials Processing Technology, 201, pp. 354-358.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. International Journal of Life Cycle Assessment 10, pp. 324-330.

Joshi, K., Venkatachalam, A., Jawahir, I.S., 2006. A New Methodology for Transforming 3R Concept into 6R Concept for Improved Product Sustainability. In: Proceedings of the IV Global Conference on Sustainable Product Development and Life Cycle Engineering (São Carlos, Brazil.

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Z., Duflou, J.R., 2011. Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) —CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description, Int J Life Cycle Assess, 17/1 (2011), pp. 69-78.

Kim, Y.H., Park, J.J., 2003. Fundamental studies on the incremental sheet metal forming technique. Journal of Materials Processing Technology 140, pp. 447–453

Kiron, D., Kruschwitz, N., Haanaes, K., Reeves, M., Goh, E., 2013. The innovation bottom line. MIT Sloan Management Review Research Report Winter 2013.

Kitazawa K., Nakajima A., 1999. Cylidnrincal incremental drawing of sheet metals by CNC incremental forming process. Proc. of the 6th ICTP Conference, Nuremberg, pp. 1495-1500.

Leszak, E., Patent US3342051A1, published 1967-09-19. Apparatus and Process for Incremental Dieless Forming.

"Marretta, L., Ingarao, G., Di Lorenzo, R., 2010. Design of sheet stamping operations to control springback and thinning: A multi-objective stochastic optimization approach. International Journal of Mechanical Sciences, Volume 52, Issue 7, July 2010, pp. 914-927.

Matsubara, S., 1994. Incremental Backward Bulge Forming of a Sheet Metal with a Hemispherical Tool. J. of the JSTP, vol. 35, pp. 1311-1316.

McAuley, J. W., 2003. Global Sustainability and Key Needs in Future Automotive Design. Environmental Science Technology 37, pp. 5414-5416.

Micari F., Ambrogio G., Filice L., 2007. Shape and dimensional accuracy in Single Point Incremental Forming: state of the art and future trends, International Journal of Material Processing Technology, Vol.191, pp. 390-395.

Nava, P., Jeswiet, J., Kim, I. Y., 2010. Calculation of Carbon Emissions in Metal Forming Manufacturing Processes with Eco-Benign Lubrication. Transaction of Namri/Sme 38, pp. 751-758.

Neugebauer, R., Altan, T., Geiger, M., Kleiner, M., Sterzing, A., 2006. Sheet Metal Forming at elevated temperatures, Annals of the CIRP, 55/2, pp. 793-816.

Nidumolu, R., Prahalad, C.K., Rangaswami, M.R., 2009. Why sustainability is now the key driver of innovation. Harvard Business Review, pp. 3-10.

Norgate, T.E., Jahanshahi, S., Rankin, W.J., 2007. Assessing the environmental Impact of Metal Production Processes. Journal of Cleaner Production 15 pp. 838-848.

Palumbo, G., Montemurro, M., Fracchiolla, M., Brandizzi, M., 2011. Single point incremental forming of a Titanium car body component superimposing a temperature increase. Proceedings of the 10th International Conference on Technology of Plasticity, 25-30 October 2011 Aachen –Germany), pp 525- 530

Petek, A., Gantar, G., Pepelnjak, T., Kuzman, K., 2007. Economical and Ecological Aspects of Single Point Incremental Forming versus Deep Drawing Technology. Key Engineering Materials 344, pp. 931-938.

Pusavec, F., Krajnik, P., Kopac, J., 2010a. Transitioning to Sustainable Production Part I: Application on Machining Technologies. Journal of Cleaner Production 18, pp. 174-184.

Pusavec, F., Krajnik, P., Kopac, J., 2010b. Transitioning to Sustainable Production Part II: Evaluation of Sustainable Machining Technologies. Journal of Cleaner Production 18, pp. 1211-1221.

Rahimifard, S., Seow, Y., Childs, T., 2010. Minimising Embodied product energy to support energy efficient manufacturing. CIRP Annals - Manufacturing Technology 59, pp. 25-28.

Schmoekel, D., 1992. Developments in Automation, Flexibilization and Control of Forming Machinery. Annals of CIRP 40/2/1992, pp. 615-622.

Semiatin, S.L., Seetharaman, V., Weiss, I., 1998. Hot workability of Titanium and Titanium aluminide alloys—an overview. Materials Science and Engineering A243, pp. 1–24.

Sokovic, M., Kopac, J., Dobrzanski, L.A., Mikula, J., Golombek, K., Pakula, D., 2006. Cutting Characteristics of PVD and CVD - Coated Ceramic Tool Inserts. Tribology in industry 28, No. 1&2.

Sondergard, S. E., 2009. Climate Balance, a balanced and realistic view of climate change. Tate Publishing & Enterprises.

Spahni R., Chappellaz, J., Stocker, T.F., Loulergue, L., Hausammann,G., Kawamura,K., Flückiger, J., Schwander, J., Raynaud, D., Masson-Delmotte, V., Jouzel, J., 2005. Atmospheric Methane and Nitrous Oxide of the Late Pleistocene from Antarctic Ice Cores. Science, 310, pp. 1317-1321.

Stainless steel, 2010. Information in http://www.stainless-steel-word.net (2010).

Steiner R, Frischknecht, R., 2007. Ecoinvent report number 23.

Sustainablemeasures, 2013. Information in http://sustainablemeasures.com/Training/ Indicators/Def-Br1.html (Jun-2013).

Sutherland, J., Gunter, K., 2004. A global perspective on the environmental challenges facing the automotive industry: state-of-the-art and directions for the future, International Journal of Vehicle Design, 35 (2004), 86-110.

Terna, 2010. Information in http://www.terna.it (Jan-2010)

Ueda, K., Takenaka, T., Vancza, J. and Monostori, L., 2009. Value creation and deicision making in sustainable society. CIRP Annals – Manufacturing Technology, 58/2, pp. 681-700.

United Nations World Commission on Environment and Development, 1987. Our common future. Oxford University Press, New York, Oxford.

Varady T., Martin R., Cox J., 1997. Reverse engineering of geometric models – an introduction. Computer-Aided Design, Vol. 29/4, pp. 255-268.

Veleva, V., Hart, M., Greiner, T., Crumbley, C., 2001. Indicators of Sustainable Production. Journal of Cleaner Production, pp. 447-462.

Vijayaraghavan, A., Dornfeld, D., 2010. Automated Energy Monitoring of Machine Tools. CIRP Ann Manuf Technol 59, pp. 21-24.

Wang, Z.G., 2004. Tribological approaches for green metal forming. Journal of Materials Processing Technology 151, pp. 223–227.

Yoon, S. J., Yang, D.Y., 2004. Development of a highly flexible incremental roll forming process for the manufacture of a doubly curved sheet metal. Annals of the CIRP 52/1, pp. 201-204.

Zhang, K.F., Yin, D.L., Wu, D.Z., 2006. Formability of AZ31 magnesium alloy sheets at warm working conditions. International Journal of Machine Tools & Manufacture 46, pp. 1276-1280.