MINISTRY OF EDUCATION AND RESEARCH
National University of Science and Technology
POLITEHNICA Bucharest
Doctoral School of Industrial Engineering and Robotics
Doctoral School of Industrial Engineering (Pitești)

BĂDULESCU V. Emanuel

DOCTORAL THESIS

-EXTENDED ABSTRACT-

Contributions to the study, modeling, and innovative development on the incremental plastic deformation forming process and system, the experimental research of process characteristics and the quality of manufactured parts

***Scientific coordinators*,**
Prof. Eng. Marian GHEORGHE, PhD
Prof. Eng. Eduard Laurențiu NIȚU, PhD

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Foreword

The development of an innovative tool for incremental plastic deformation, as well as the analysis and improvement of the quality of AA6061-T6 aluminum alloy truncated cone-shaped parts obtained by single-point incremental plastic deformation, represent *the motivation* and direction of the doctoral studies, completed by this doctoral thesis.

The doctoral program consisted, in its first phase, of analyzing scientific literature in the field of incremental plastic deformation, preparing, presenting, and defending exams and scientific reports. In the second phase of these doctoral studies, a modular device for orienting and fixing the metal sheet and an innovative tool were designed, developed, and tested, which offer numerous advantages when used in the incremental plastic deformation process. Subsequently, an in-depth study of the phenomena occurring during incremental plastic deformation processing was carried out, and the quality of parts processed with tools with different geometries was evaluated using experimental and numerical investigation methods, in accordance with the research and development methodology developed. Thus, the influence of process parameters on certain resulting quantities was analyzed, an experimental methodology for determining the geometric accuracy of parts using three-dimensional scanning was developed, and numerical models were developed for in-depth investigation of the incremental plastic deformation process.

With deepest gratitude, I would like to express my sincere thanks to Prof. Eng. Marian GHEORGHE, PhD, and Prof. Eng. Eduard Laurențiu NIȚU, PhD, for their scientific guidance and coordination of my entire doctoral program, as well as for their support, complete trust, and total availability throughout this period.

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I am grateful to my family and colleagues at the company where I work for their moral support and understanding throughout my doctoral studies.

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Emanuel Bădulescu

Introduction

Current industry trends toward customizing products to customer requirements have contributed to the development of flexible manufacturing technologies that enable specific configurations. One such technology is single-point incremental plastic deformation.

The research and development activity within the doctoral program focuses on developing an incremental plastic deformation system by creating a device for orienting and fixing the metal sheet, developing a new innovative tool, and validating innovative aspects.

* * *

In the first part of the doctoral thesis, based on an analysis of the current state of research and development, relevant data on single-point incremental plastic deformation processes and systems are presented, along with their advantages and disadvantages.

In the second part of the doctoral thesis, based on the data and conclusions drawn from the analysis of the current state, the directions of research and development regarding incremental plastic deformation processes are defined, and the main research and development objective within the doctoral program is determined: the development of the process and system for single-point incremental plastic deformation of AA6061-T6 aluminum alloy parts through theoretical and experimental research and numerical simulation.

urthermore, the research and development methodology represents the reference point for achieving the main objective of the doctoral activity. The theoretical and experimental research carried out has resulted in:

- Development of a configurable technological device for orienting and fixing the metal sheet for processing by incremental plastic deformation at a single point. It brings new features in that it allows simultaneous measurement of forces and temperatures during the process, has high rigidity, and can be configured according to the dimensions of the processed parts.
- Design and manufacture of an innovative tool with an eccentric head and variable radius (ETVR), which significantly reduces deformation forces and improves the quality of the surfaces obtained through its use.
- Performing machining operations by incremental plastic deformation at a single point using the innovative tool and tools with a hemispherical head, and evaluating the quality of the machined parts to highlight the characteristics of the innovative tool compared to those of tools with a hemispherical head.

Research into the incremental plastic deformation process was furthered by developing numerical models using ABAQUS software and simulating the incremental plastic deformation process.

The final part of the doctoral thesis presents the general conclusions and main contributions made by the doctoral thesis to the achievement of the main objective of the doctoral research and development activity, the scientific importance of the doctoral thesis, the practical importance of the doctoral thesis, and the directions for development regarding the improvement of the incremental plastic deformation process using the innovative tool developed.

Part I

Current state of research, development, and industrial applications of incremental plastic deformation machining

Chapter 1. General characteristics of incremental plastic deformation processes

1.1. Incremental plastic deformation processes

Incremental plastic deformation developed from a simple technical idea, which was presented in a patent by Edward Leszak in 1967 [S14], [L01], but which did not have any real implementation. Spin forming and stretch forming processes [N01], [G03] are considered to be the precursors of incremental plastic deformation.

Incremental plastic deformation with a punch uses a punch-shaped tool with relatively small dimensions. Contact between the tool and the semi-finished product is continuous and occurs over a small area [B14]. A specific working diagram for the incremental plastic deformation process with a punch is shown in Fig. 1.5 [N01].

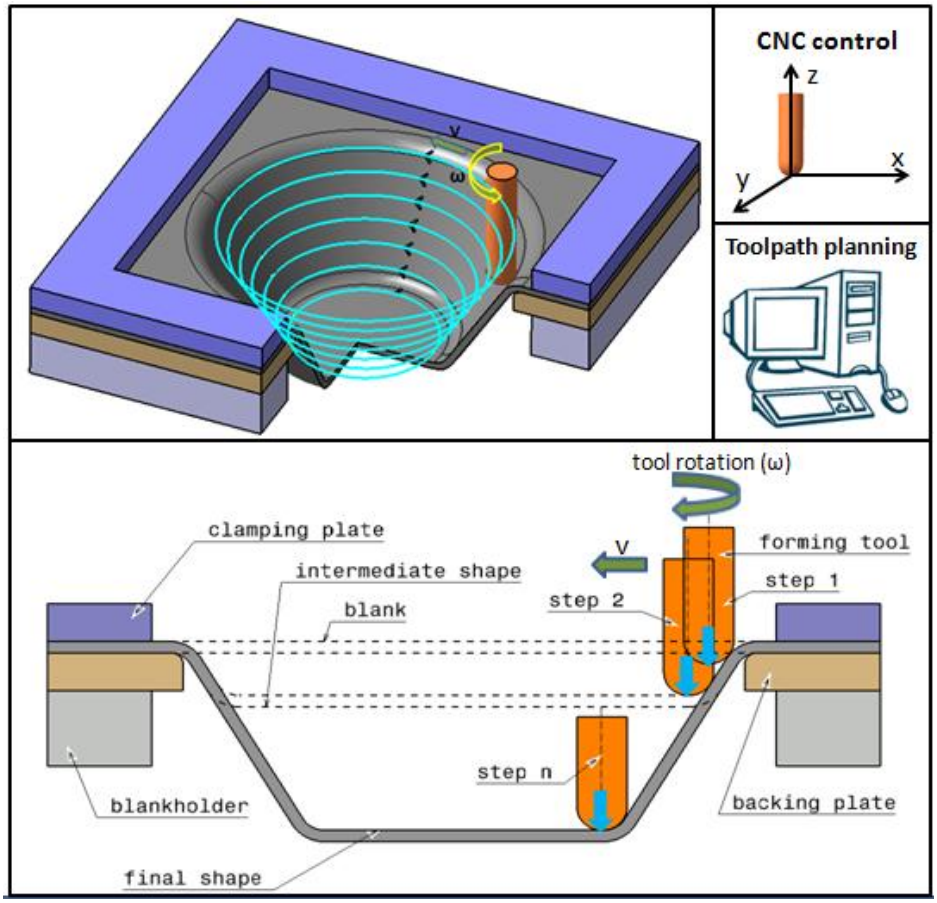


Fig.1.5. Work diagram specific to the incremental plastic deformation process with a punch [N01]

The tool (punch) moves along a programmed trajectory using numerical control, depending on the shape of the part to be made, and the technological parameters are: tool speed - n [rpm], tool feed rate - Va [mm/min], and incremental step - Δz [mm], defined as the distance between two successive levels [N01].

1.2. Materials for parts processed by incremental plastic deformation

The materials used in incremental plastic deformation are generally the same as those used in conventional plastic deformation, but specific materials may also be used. The choice of materials used in these processes is determined primarily by the functional requirements of the part to be

manufactured, but also by the requirements imposed by the manufacturing process. The functional requirements of the part depend on the product/industry to which they belong: automotive, aeronautics, biomedical, or other industries.

1.3. Types of parts processed by incremental plastic deformation

Through incremental plastic deformation, a relatively wide variety of parts can be processed, with simple or complex geometric shapes, with or without axes of symmetry. Their shape and dimensions are determined by the purpose of their research or use and by the processing method used. The main types of parts processed by incremental plastic deformation, identified in the studied bibliography, are: parts with simple geometric shapes, parts with medium complexity geometric shapes, and parts with high complexity geometric shapes.

1.4. Technological systems for incremental plastic deformation processing

Machine tools for incremental plastic deformation

Incremental plastic deformation processes can be applied with high efficiency on machine tools designed for mechanical machining by cutting, which develop sufficiently high forces and have high rigidity. To generate complex geometric shapes of parts, these machines must be equipped with numerical control (CNC) equipment.

The most commonly used machine tools for incremental plastic deformation processes are numerically controlled milling machines [B14], [A09], [B11]. These machines can be used to produce simple parts and parts with complex geometries, as they are numerically controlled in at least three directions of tool movement [N01]. Also, their high rigidity, flexible programming, and the possibility of using related research equipment during machining, such as force and temperature measurement systems, are advantages in their use.

Devices for orienting and fixing the metal sheet

With the development of incremental plastic deformation processes, several types of devices for orienting and fixing metal sheets products have been developed and manufactured, ranging from simple to complex, using various solutions depending on the machine tool used, the shape of the part to be produced, or the requirements imposed by process research.

Tools for incremental plastic deformation

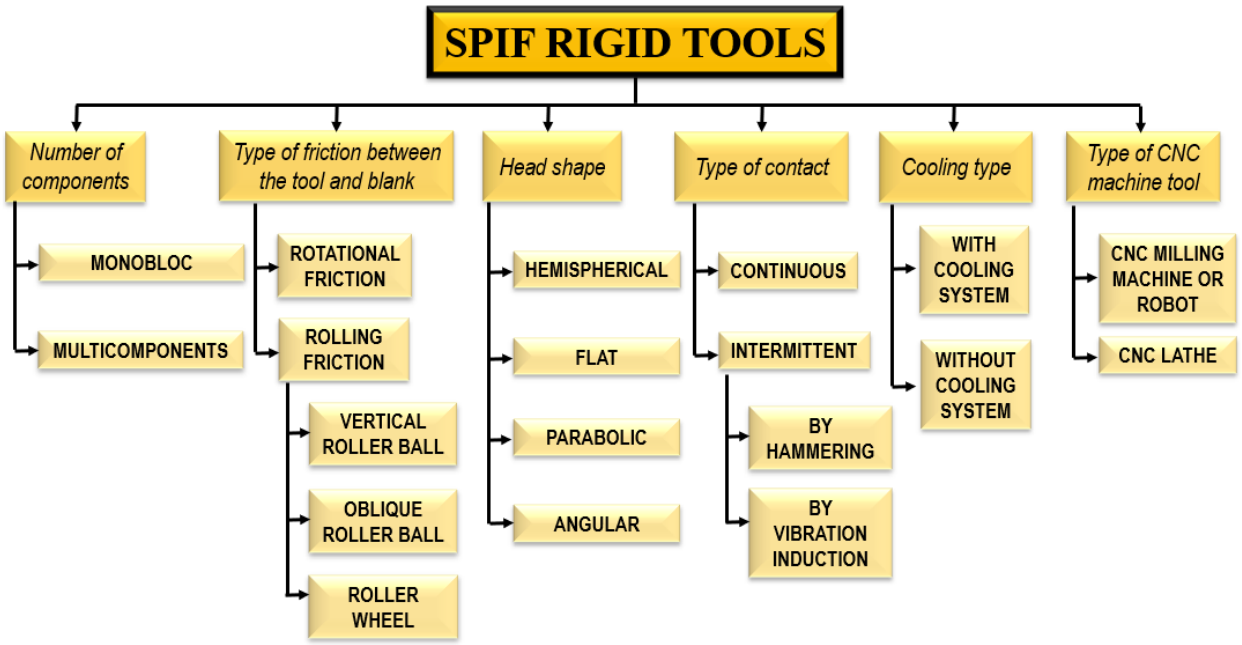


Fig.1.22. Classification of tools used in single-point incremental plastic deformation (SPIF) processing [B04]

The tools most commonly used in SPIF processes are punch-type tools. In general, researchers and users design and manufacture the type of tool according to the clamping system on the machine tool used, as there are no suppliers that deliver standardized tools [J05], [N06]. A classification of the tools used in SPIF, based on an analysis of the literature using criteria such as number of components, type of friction between the tool and the semi-finished product, head shape, type of contact, type of cooling, and type of machine tool used, is presented in Fig. 1.22.

The main types of tools used in SPIF, along with the advantages and disadvantages of their use, are presented below.

Rigid tools with a hemispherical head are the most commonly used punches and the most diverse in terms of design.

Flat-head rigid tools are simple punches and very similar to those with a hemispherical head. They consist of a circular rod with a diameter "D", and the flat surface at the end of the rod is connected with a connecting radius "r".

Ball tools are more complex than monoblock tools, consisting of a body and a moving part, usually a ball or roller. The main difference between these and monoblock tools is the way friction is created between the tool and the semi-finished product: when deforming with a rigid tool, such as one with a hemispherical head, the friction is sliding; when deforming with a ball tool, the friction is rolling.

1.5. Applications of incremental plastic deformation

Due to their high flexibility and low manufacturing costs, incremental plastic deformation processes can be used for a wide range of applications, from rapid prototyping in the automotive, aerospace, or naval industries to the production of components in the medical and household appliance sectors [M14], [C01], [K04], [T07], [L06], [S04], [A01], [B08], [G07], [A04]. Some relevant examples are presented below.

Automotive parts

The applications of incremental plastic deformation in the automotive industry are related to a wide range of parts manufactured in limited series, in small batches, either as spare parts or as customised parts.

A prime example is that of highly complex parts, such as the optical block and the exhaust manifold.

Several applications in the automotive industry have been developed by Amino Corporation. One of these, developed in collaboration with Honda Motors, involved the reproduction of a limited number of spare parts for a classic car model that has not been manufactured since 1970, namely the hood panel for the HONDA S800.

Medical partsl

The use of incremental plastic deformation is also found in the medical field, for the manufacture of several types of prostheses used in different areas of the human body. The characteristics of these parts are that they are unique, being customized according to the patient who will use them.
Materials used in the medical field must meet certain specific requirements in order to be used, such as: biocompatibility, ease of shaping, mechanical strength, but low weight, low electrical and thermal conductivity, low manufacturing costs, etc. Synthetic materials such as metals, polymers, and ceramics can be used in medical implants [B05].

Parts from other industrial fields

In practice, incremental plastic deformation processes can be applied to manufacture sheet metal parts in all industrial sectors.

Chapter 2. Elements regarding the state of knowledge of single-point incremental plastic deformation machining processes

2.1. Studies on the formability of workpiece materials and machining forces

The formability of a material represents its ability to be plastically deformed without the occurrence of undesirable conditions [H07]. Undesirable conditions include: cracking or breaking of the material during the plastic deformation process, poor surface quality (macro- asperities), the appearance of defects (cuts, waves, etc.) or other commercially imposed conditions. In general, the factors that influence deformability depend on the characteristics of the processed material (chemical composition, structure, mechanical properties) and the deformation process (stress and strain state, temperature and deformation speed, friction between the tool and the metal sheet, etc.) [M02].

The processing forces in SPIF reflect the stress-strain state that occurs during the deformation process and can indicate areas at risk of breakage or excessive thinning of the semi-finished product. Their analysis represents another direction of research into SPIF processes, as they are considered very important for ensuring the integrity of the part, the selection of processing equipment, and the energy consumption of the process.

Studies in the specialized literature highlight that the axial force, in the direction of the symmetry axis of the workpiece - Fz, is the main component of the deformation force, having the largest magnitude. This causes plastic elongation of the material, while the radial force - Fr and the tangential force - Ft, which are much smaller, cause the redistribution of the material in the plane of the semi-finished product.

2.2. Studies on tool path

When deforming on CNC lathes, where the rotational movement is performed by the semi-finished product, the tool's movement trajectory is simple, being a generating curve that corresponds to the interior or exterior profile of the part. When forming on milling machines, specialized machines, or industrial robots, the trajectory is much more complex because the semi-finished products oriented and fixed in the device mounted on the machine table do not move at all, and the tool performs all the movements necessary to carry out the incremental plastic forming process. Programming these trajectories is quite laborious and, in most cases, specialized software is used.

The tool path is an essential element in the incremental plastic deformation process, as it influences the deformation mode of the material, the mechanical stresses, and the quality of the part (wall thickness uniformity, dimensional deviations, roughness) [N01], [J05]. Therefore, research in this area has analyzed several types of tool trajectories.

The tool path on levels consists of a sequence of curves in the plane, which follow the contour of the part at each level into which the part is divided vertically [L05], [N01]. The distance between two levels represents the incremental step Δz.

The helical tool path consists of a single helical curve that starts at the level of the undeformed semi-finished product and ends at the bottom of the part when the part is completely deformed [L05], [N01].

Multiple pass tool paths were developed as alternatives to single pass trajectories in order to eliminate their disadvantages. Incremental deformation of the workpiece is achieved by repeated passes of the tool, with the final shape of the workpiece resulting from successive passes of the tool, which are performed using one of the two trajectories mentioned above.

2.3. Studies on the quality of machined parts

The quality of parts processed using SPIF is a critical factor for validating the technology used and its industrial application. Therefore, the specialized literature presents many studies on the main parameters that characterize the quality of these parts and the challenges related to them. The main parameters that characterize the quality of parts processed by SPIF are: geometric accuracy, surface roughness, microstructural changes, and defects specific to SPIF processing.

Geometric accuracy of parts

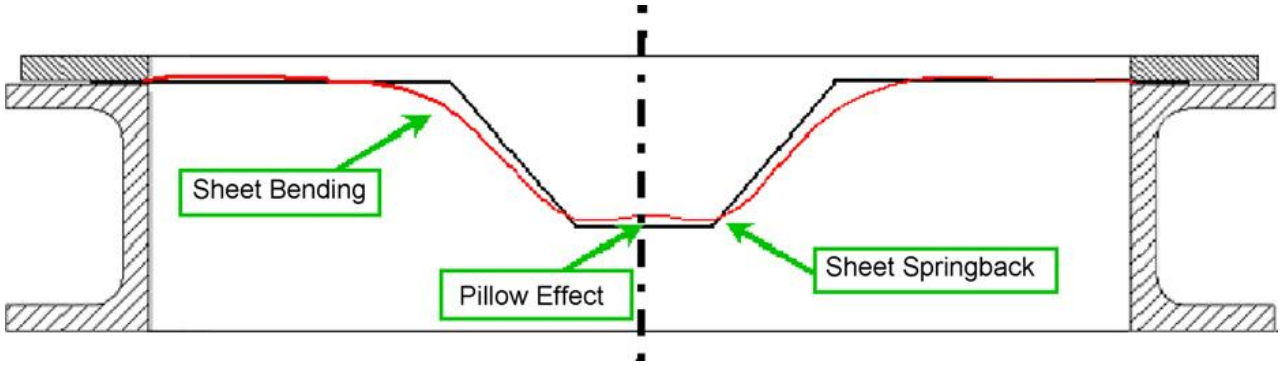


Fig.2.10. Errors during the SPIF process that cause geometric deviations in the machined part [M07]

Micari and colleagues [M07] classified the errors that occur during the SPIF process, which cause geometric deviations in the machined parts, into three categories, Fig. 2.10:

- bending of the sheet metal near the fastening element of the semi-finished product; such an error can be resolved by using a support plate;
- elastic recovery of the semi-finished product at the end of the deformation process;
- the appearance of a "cushion" effect at the bottom of the part, in the form of a concave surface of the undeformed material.

Another important indicator of the quality of SPIF-machined parts is the wall thickness deviation. This, frequently referred to in the literature as "wall thinning," determines not only the mechanical strength of the part, but also the limits of the part's deformability, being directly correlated with the appearance of cracks. Therefore, numerous experimental studies have analyzed the influence of process parameters, material, and active tool shape on the wall thickness of parts machined by SPIF. The conclusions of some of these studies are presented below.

Surface roughness

The roughness of the machined surface represents the set of small irregularities (scratches, grooves, tool marks, voids, pores, etc.), whose pitch is relatively small in relation to their depth, and appear due to the oscillatory movement between the tip of the tool machining it and the surface of the part that has been machined [C03].

Achieving low roughness of surfaces machined by SPIF is another challenge in the design of SPIF processes. The aim of most research studies is to determine the effect of process parameters on the quality of the machined surface so that the machining process can be controlled in the desired direction. In these studies, the main process parameters that are varied are the shape or size of the active part of the tool, the rotational speed of the tool, the feed rate of the tool, the size of the incremental step, and the use of a suitable lubricant.

Microhardness and microstructural changes

The SPIF process causes work hardening of the material, which leads to an increase in microhardness and microstructural changes, such as grain refinement and the appearance of areas of intense deformation. Therefore, microhardness and microstructural changes in the processed surface layer

are relevant indicators for evaluating the effect of plastic deformation on the local mechanical properties of parts.

Akhavan Farid A. and colleagues [A04] studied SPIF machining of a truncated cone-shaped part using a tool with a hemispherical head. The part was made of AA6061 aluminum alloy in a recrystallized state, with an initial hardness of 48 HV. During the SPIF process, the material underwent intense and localized plastic deformation, which led to a significant increase in hardness, with values reaching up to 85.2 HV. The maximum hardness was obtained for the set of technological parameters, incremental step of 1 mm and feed rate of 1000 mm/min, while the lowest surface roughness, with a Ra value of 4.55 µm, was obtained for the set of technological parameters, incremental step of 1 mm and feed rate of 1500 mm/min. These results highlight the pronounced sensitivity of the AA6061 alloy to process parameters, demonstrating the importance of deformation conditions in simultaneously improving surface properties and structural integrity in the SPIF process.

Specific defects of SPIF parts

SPIF processing can lead to defects, which can have multiple causes. In addition to cracks, which are mainly caused by low material ductility, unfavorable part geometry, intense friction, material anisotropy, or inadequate technological parameters, other specific defects may also occur in the SPIF process, such as extruded wall, corner folds or bulging.

2.4. Studies on modeling and numerical simulation of the SPIF process

SPIF machining process simulation is used both in research and industrial practice before the actual part is produced [S13], [W03], [Y01], [Z05]. The most commonly used method for this purpose is the finite element method, although it has a major disadvantage, namely very long calculation times. The long and complex trajectories of the deformation tools and the fine discretization of the numerical model, which is necessary due to the small contact surface between the tool and the metal sheet, are the main causes of the long simulation times [Z02].

Stages of numerical modeling

Numerical modeling aims to create a numerical model on which numerical simulations can be performed. The main stages of numerical modeling specific to SPIF machining processes are: (1) choosing integration methods; (2) choosing the type of finite element and constructing the geometry of the elements specific to the machining process; (3) establishing boundary conditions; (4) establishing the friction behavior and thermomechanical behavior of the processed material; (5) validating the numerical models.

Simulation of numerical models

Validated numerical models are subsequently used to gain a deeper understanding of the incremental deformation process, to obtain additional information, or to optimize the machining process. Several examples of this are presented below.

Chang and colleagues [C06] investigated the influence of friction and vibration on surface quality in SPIF for aluminum alloys such as AA5251 and AA6082. Analytical models and simulations demonstrated that high-amplitude vibrations reduced the coefficient of friction and improved surface microhardness.

Advanced numerical simulations using multi-tool systems, multi-point systems with layered plates, or adaptive mesh concepts reduced part formation time and minimized cushioning and springback defects in aluminum parts, improving dimensional accuracy [U01] [Z03], [N07].

Chapter 3. Conclusions on the current state of research – development and industrial applications of incremental plastic deformation

The analysis of the current state of research, development, and industrial applications of incremental plastic deformation, presented in the first two chapters of the doctoral thesis, has allowed for the drawing of relevant and important conclusions. This assessment of recent studies and research highlights the current needs and trends in the field of incremental plastic deformation, emphasizing the importance of continuing research in this area. The main conclusions are presented below..

• There is a relatively wide variety of incremental plastic deformation processes, including incremental plastic deformation with a punch. One or more relatively small punch-shaped tools are used. Contact between the tool and the metal sheet is continuous and takes place over a small area.

• Single Point Incremental Forming (SPIF) is one of the incremental plastic forming processes using a punch, in which a single tool is used. The process is widely used because its kinematics are relatively easy to apply (see §1.1).

• Through incremental plastic deformation, a relatively wide variety of parts can be processed, with simple or complex geometric shapes, with or without axes of symmetry, whose shapes and dimensions are determined by the purpose of their research or use (see §1.3).

• The most commonly used shapes of parts in research into the incremental plastic deformation process are those with a simple, axially symmetrical geometric shape, such as cones, truncated cones, and spherical caps, as these can be produced on most universal or specialized machining equipment, with or without numerical control (see §1.3).

• Other types of parts with simple geometric shapes used in researching the incremental plastic deformation process are those based on truncated pyramids or those derived from truncated cones or pyramids, but with variable wall angles (see §1.3).

• Parts with a geometric shape of medium complexity in terms of incremental plastic deformation are considered to be those whose geometric shape is a combination of several simple geometric shapes, such as a stepped cone and cylinder – sphere, or those that have two or more axes of symmetry, which can only be processed on machines that provide specific kinematics (see §1.3).

• Incremental plastic deformation processes can be applied with high efficiency on machine tools designed for mechanical machining by cutting, which develop sufficiently high forces and have high rigidity. Incremental plastic deformation processing can be performed on CNC lathes for revolving (axially symmetrical) parts with simple or moderately complex geometric shapes. Numerically controlled milling machines are most commonly used, as they can be used to produce both simple parts and parts with complex geometries (see §1.4).

• Incremental plastic deformation processes can also be performed on specialized machines, which are cheaper than CNC milling machines but harder to find on the market, or with the help of industrial robots, but these have lower rigidity (see §1.4).

• The devices for orienting and fixing semi-finished products for incremental plastic deformation processing have been developed in various simpler or more complex designs, using different solutions depending on the machine tool used, the shape of the part to be produced, or the requirements imposed by process research (see §1.4).

• The tool used in the incremental plastic deformation process plays an important role during the process because, through direct contact with the semi-finished product, it significantly influences the

quality of the obtained part. The tools most commonly used in SPIF processes are punch-type tools (see §1.4).

• Rigid tools with hemispherical heads are the most commonly used in SPIF processes, with a wide variety of designs. The main design variants of these tools are: tools with a constant cross-section hemispherical head, tools with a conical cross-section hemispherical head, and tools with a multi-conical cross-section hemispherical head. The radius of the active area is the geometric parameter of the tool that differentiates hemispherical head punches (see §1.4).

• Rigid flat-head tools are simple tools and very similar to those with a hemispherical head, but they have a larger contact surface with the semi-finished product compared to the hemispherical head tool. The main advantages of using them are: the precision of the parts obtained is higher and the unfavorable cushioning effect that occurs at the end of machining is reduced (see §1.4).

• Ball tools are more complex than monoblock tools, but they have the advantage of replacing the sliding friction encountered in deformation with monoblock tools with rolling friction, which leads to a reduction in machining forces, increased material deformability, and improved quality of the machined part (see §1.4).

• Applications of incremental plastic deformation in the automotive industry relate to a wide range of parts manufactured in limited series, in small batches, either as spare parts or as customised parts. These parts are of simple or complex shapes, made of steel or aluminium alloys (see §1.5).

• In the medical field, incremental plastic deformation is used to manufacture certain types of prostheses for different areas of the human body. These parts are unique, being customized according to the patient who will use them, and are made of metallic, polymeric, and ceramic materials that are biocompatible, lightweight, have low electrical and thermal conductivity, and low deformability (see §1.5).

• Parts processed by incremental plastic deformation are also used in other fields, such as the railway industry, the aerospace industry, the food industry, and the decorative elements industry (see §1.5).

• Although incremental plastic deformation processing, including that using a single punch (Single Point Incremental Forming – SPIF), has been studied and used for several decades, SPIF is still considered a developing process due to several challenges. These include: modeling the stress-strain state in the tool-workpiece contact area, modeling the processing forces, and controlling the quality of the processed part (see §2.1).

• The deformation mechanisms in SPIF are stretching, which is the dominant mode of deformation, and shearing, determined by the friction between the tool and the semi-finished product. Shearing occurs across the thickness of the sheet, in the plane generated by the local direction of the tool and the direction of the metal sheet normal, as well as in a plane perpendicular to the machined semi-finished product (see §2.1).

• There are numerous studies on the characterization of the behavior of materials processed by SPIF, with different objectives, such as: establishing the influence of tool geometry, processing parameters, heat treatment applied to the part, the geometry of the part to be made, etc. on the deformability of the material (see §2.1).

• The processing forces in SPIF reflect the stress-strain state that occurs during the deformation process and can indicate areas at risk of breakage or excessive thinning of the semi-finished product. The axial force, in the direction of the symmetry axis of the workpiece - Fz, is the main component of the deformation force, having the largest magnitude. It determines the plastic elongation of the material, while the radial force - Fr and the tangential force - Ft, which are much smaller in magnitude, determine the redistribution of the material in the plane of the semi-finished product (see §2.1).

• The tool trajectory is an essential element in the incremental plastic deformation process, as it influences the deformation of the material, the mechanical stresses, and the quality of the part.

Research in this area has analyzed several types of tool paths, such as: level tool paths, helical tool paths, or tool paths with multiple passes (see §2.2).

• The level trajectory consists of a sequence of curves in the plane that follow the contour of the part at each level into which the part is divided vertically. The helical tool path consists of a single helical curve that starts at the level of the undeformed blank and ends at the bottom of the part when the part is completely deformed (see §2.2).

• The multiple pass tool path consists of the incremental deformation of the part through repeated passes of the tool, which is achieved through one of the two tool paths mentioned above. There are several variants of such trajectories that have been studied, such as: the two-pass tool path, the successive pass trajectory, and the compensation pass trajectory (see §2.2).

• The quality of parts processed using SPIF is a critical factor for validating the technology used and its industrial application. The main parameters characterizing the quality of SPIF-machined parts are: geometric accuracy, surface roughness, microstructural changes, and defects specific to SPIF machining. The influence is determined through experimental research or numerical modeling and simulation (see §2.3).

• Geometric accuracy is one of the most important quality indicators in SPIF. This is mainly caused by three categories of errors that occur during the SPIF process: bending of the sheet metal near the fastening element of the metal sheet; elastic recovery of the semi-finished product at the end of the deformation process; the appearance of a cushion effect at the bottom of the part, in the form of a concave surface of undeformed material (see §2.3).

• Wall thickness deviation or "wall thinning" is another important indicator of the quality of SPIF machined parts, as it determines the mechanical strength of the part and its deformability limits, being directly correlated with the occurrence of cracks (see §2.3).

• Achieving low surface roughness of parts machined by SPIF is another objective in the design of SPIF processes. Most research aims to determine the effect of process parameters (shape or size of the active part of the tool, tool rotation speed, tool feed rate, incremental step size, and use of a lubricant) on the roughness of the machined surface (see §2.3).

• Microhardness and microstructural changes in the machined surface layer are relevant indicators for evaluating the effect of plastic deformation on the local mechanical properties of parts. Therefore, many studies analyze the influence of process parameters (tool rotation speed, tool feed rate, incremental step size) on these properties (see §2.3).

• SPIF processing can lead to defects, which can have multiple causes. Specific defects that can occur in the SPIF process are: extruded wall, corner fold, or bulging (see §2.3).

• The main stages of numerical modeling specific to SPIF machining processes are: choosing integration methods; choosing the type of finite element and constructing the geometry of elements specific to the machining process; establishing boundary conditions; establishing the friction behavior and thermomechanical behavior of the machined material; validating numerical models (see §2.3).

• The validation of numerical models is based on several criteria, such as deformation forces, wall thickness, or the profile of the machined part, by comparing the results obtained through numerical simulation with those determined experimentally (see §2.3).

• Numerical simulations are used to gain a deeper understanding of the incremental deformation process, to obtain additional information, or to improve the SPIF machining process. A particular problem in simulating SPIF processes is the long duration of the calculations, especially when high calculation accuracy is desired and/or the semi-finished product is large (see §2.3).

Part II

Contributions to theoretical-experimental research and numerical modeling of the incremental plastic deformation process

Chapter 4. Directions, main objective and research and development methodology of the incremental plastic deformation process and system

4.1. Research and development directions

Based on the data and conclusions drawn from the analysis of the current state, the following research and development directions regarding the process and systems of incremental plastic deformation at a single point are considered to be relevant:

(1) increasing the range of materials used in researching the process and systems of incremental plastic deformation at a single point.

(2) developing new tools for incremental plastic deformation, leading to increased material deformability and geometric precision of deformed parts.

(3) deepening and expanding knowledge about the phenomena specific to the single-point incremental plastic deformation process by analyzing the interdependencies between process parameters (stresses/forces, temperature, etc.) and the parameters that define the quality of the deformed parts (roughness, geometric precision, elastic recovery, wall thinning, etc.) and the characteristics of the deformed material, technological parameters, the geometry of the part to be produced, and the type of trajectory used.

(4) developing numerical models for simulating single-point incremental plastic deformation processes in order to deepen knowledge about the phenomena specific to the deformation process, optimize it, and reduce research and manufacturing costs.

4.2. The main objective of research and development activity

Considering the research and development directions of single-point incremental plastic deformation processes, the main objective of the doctoral activity was established: **the development of the single-point incremental plastic deformation process and system for AA6061-T6 aluminum alloy parts, through theoretical and experimental research and numerical simulation.**

In order to achieve the main objective of the doctoral activities, the following specific objectives are established.

(1) ***Development of a new tool, with an eccentric head and variable radius***, which combines the advantages of existing tools, is easy to manufacture, and facilitates the plastic deformation process..

(2) ***Comparative analysis of incremental plastic deformation processes with a single tool*** for truncated cone-shaped parts made of AA6061-T6 aluminum alloy. The choice of truncated cone-shaped parts for the study is justified by the fact that, on the one hand, this type of surface is frequently encountered in the study of incremental plastic deformation processes with a single tool, due to the reduced implementation requirements (necessary machine tool, simplicity of trajectory realization, etc.) and, on the other hand, parts of this type allow for a complex study of the phenomena specific to the incremental plastic deformation process.

The target part, made by incremental plastic deformation at a single point as part of doctoral research, is a truncated cone, Fig. 4.1.

The main geometric characteristics of the target part are: large diameter of the truncated cone, Dp = ∅96±0,5 [mm], the height of the truncated cone, H = 25±0,5 [mm] and the angle of inclination of the truncated cone wall, α = 45±1 [°].

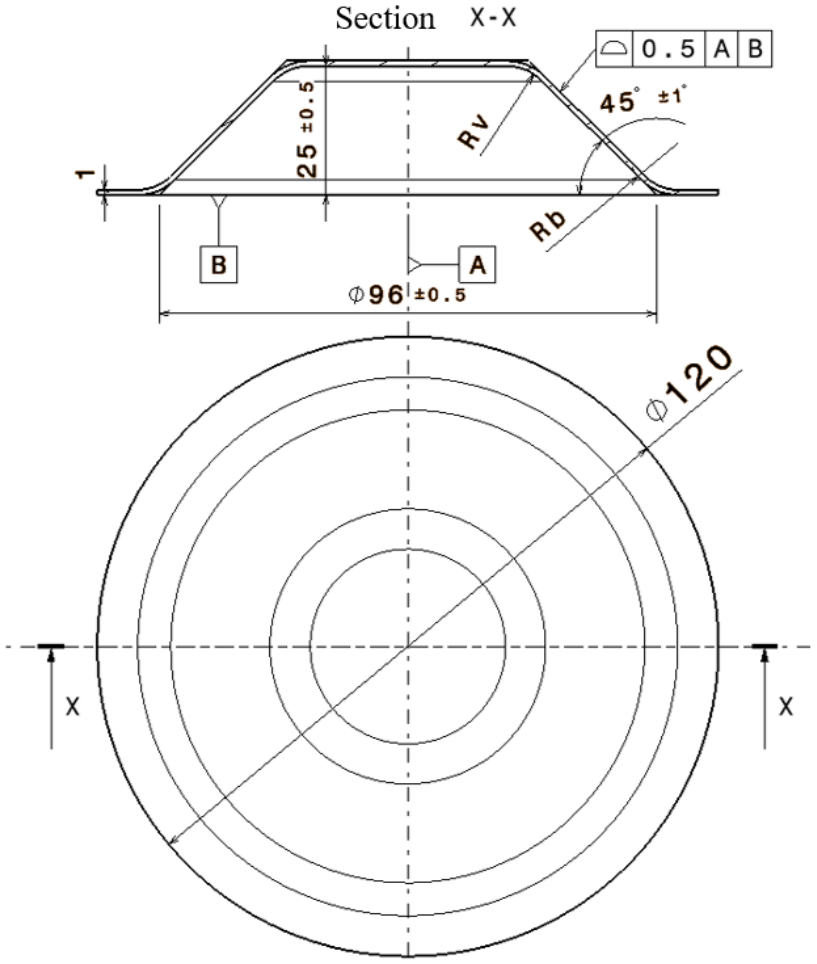


Fig.4.1. Part to be produced by incremental plastic deformation (target part)

4.3. Research and development methodology

he stages of research and development and related activities are presented in Fig. 4.3. and below.

(I) The development of a new incremental plastic deformation tool is associated with the achievement of the first specific objective. The specific activities of this stage consist of:

- conducting a critical literature review to highlight the main disadvantages and advantages of the tools used in single-point incremental plastic deformation processes;

- designing a new, innovative tool that eliminates as many of the disadvantages of the analyzed tools as possible, retains as many of their advantages as possible, and is easy to manufacture;

- actually manufacturing the new tool from the same material as the existing tools.

(II) Theoretical and experimental research on incremental plastic deformation processes using different tools aims to comparatively analyze these processes and the quality of the machined parts. Several specific activities will be carried out during this stage, which are grouped as follows.

- *Characterization of the metal sheet*, which aims to determine its chemical composition, phases, structure, and physical-mechanical properties.

- *Design and manufacture of devices for orienting and fixing the metal sheet* for machining the target part by incremental plastic deformation with a single tool on a numerically controlled vertical milling

center. These devices must ensure the possibility of measuring the process forces and temperatures during deformation, respectively, the rigidity necessary for machining the part.

- *Conducting experiments with different tools* consists of producing the target part with each of the three specified tools, using the same technological parameter values. The experiments will be conducted as follows:

- on an "elastic technological system" that includes a force measurement system and a temperature measurement system, which allows for in-depth analysis of the deformation process;

- on a "rigid technological system," when only the temperature measurement system is used, which allows for the analysis of the quality indicators of the machined parts.

- *The development of a methodology for measuring part geometry by 3D scanning* aims to use 3D scanning technology on parts processed by incremental plastic deformation and to process the data for the most accurate measurement of part geometry.

- *The analysis of incremental plastic deformation processes* aims to comprehensively analyze incremental plastic deformation processes performed with different tools. It considers the evolution of deformation forces and process temperatures, the geometry of the machined part, the roughness and microhardness of the part, and the correlations between them, identifying the "critical moments" in the process and the "critical areas" on the machined part. This analysis will be supplemented by an analysis based on the simulation of plastic deformation processes carried out in the third stage of the research.

(III) Process modeling and simulation aims to develop a numerical model that can simulate the incremental plastic deformation process at a single point with convenient accuracy and duration, and to use it for advanced analysis of the deformation process. The activities carried out are grouped as follows.

- *Characterizing the thermo-mechanical behavior of the material* aims to establish a behavior law that can be used in numerical modeling and to determine the values of its coefficients for the material used. To determine the coefficient values in the thermo-mechanical behavior law, monotonic tensile tests are performed at different speeds and temperatures, which is an important prerequisite for creating a numerical model that allows for obtaining the appropriate accuracy through simulation.

- *Development and validation of the finite element numerical model.* Several types of numerical models will be analyzed, using different strategies, which will be validated based on the experimental data obtained in the previous stage (forces, temperatures). Among these, the one that provides the best compromise between obtaining the most accurate results and the shortest calculation time will be selected.

- *The realization of numerical simulations* consists in simulating the two processes performed with different hemispherical tools and obtaining information about the incremental plastic deformation process with a single tool: the evolution and correlation over time of forces, temperatures, deformation of the semi-finished product, and the geometry of the part.

- *The analysis of incremental plastic deformation processes* consists of exploiting the results of numerical simulation and correlating them with the experimental data obtained in the previous stage.

(IV) The comparative analysis of incremental plastic deformation processes is the stage at which a comparative analysis of incremental plastic deformation processes with the three tools is carried out, with the aim of highlighting the advantages and disadvantages of using each type of tool. The completion of this stage leads to the achievement of specific objective 2.

Chapter 5. Elements of the experimental research system of the incremental plastic deformation process

The elements of the experimental research system for the incremental plastic deformation process, which also include published elements by the author [B04], are presented as follows.

5.1. Characteristics of the AA6061-T6 alloy

The actual chemical composition was determined by X-ray fluorescence spectrometry on a sample measuring 20 × 20 × 1 mm, using SPECTRO Midex M equipment.

The actual metallographic characteristics of the AA6061-T6 alloy were determined on three samples cut from the sheet-type semi-finished product. These were cut with a water jet in specific directions of the semi-finished product: in the rolling direction - at 0˚, perpendicular to the rolling direction at -90˚ and inclined - at 45˚. The metallographic samples were first analyzed using optical microscopy at 100x magnification, without chemical etching, to highlight the rolling direction of the AA6061-T6 sheet.

5.2. Elements of the incremental plastic deformation technology system and in-process measurement systems

5.2.1. Shape and dimensions of metal sheet to be processed

- *Cutting the initial sheet*

The AA6061-T6 aluminum alloy is delivered in sheet form, with different thicknesses depending on requirements. It undergoes precipitation hardening treatment in order to increase the maximum yield strength and achieve superior mechanical properties (increased tensile strength, good corrosion resistance, greater hardness, etc.) compared to untreated AA6061 alloy [O03].

- *Dimensions of the metal sheet*

Circular metal sheet products were used to conduct experimental research on incremental plastic deformation at a single point. Their outer diameter was set at ∅ = 170 mm, and two holes with a diameter of ∅ = 10 mm were made on it, to serve as orientation on the orientation and fixing device, and six through holes with a diameter of ∅ =11 mm, which serve to allow the passage of the tightening screws when fixing the metal sheet product.

- *Cutting and manufacturing of metal sheets*

In order to obtain a high repeatability of the experimental results, it was considered that the direction determined by the two orientation holes of the semi-finished product (holes with a diameter of ∅ = 10 mm) should be parallel to the rolling direction of the material, marked on the adhesive plastic film of the sheet. The outer contour of the metal sheet product and the holes in it were cut using a laser.

5.2.2. Machine tool and device for orienting and fixing the metal sheet

- *Machine tool used*

The EcoMill70 - DMG MORI [D05] numerically controlled milling center was used to perform the single-point incremental plastic deformation experiments. The use of a numerically controlled machine tool is one of the basic requirements for applying the incremental plastic deformation process to create complex surfaces.

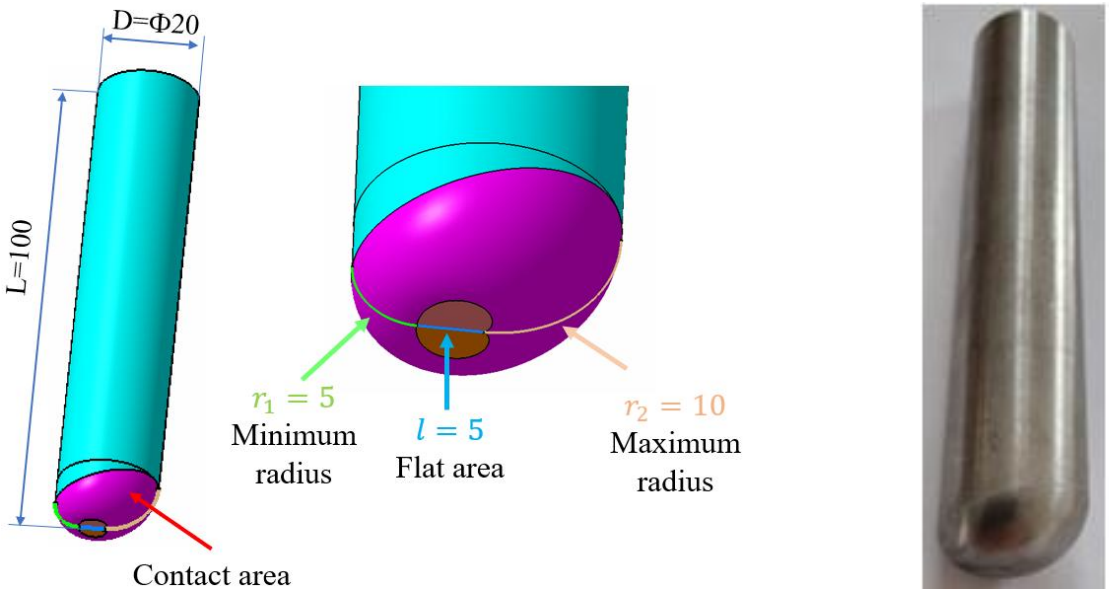
- *Design of the metal sheet orientation-fixing device*

The semi-finished product orientation and fixing device, designed according to the concept presented above and positioned on the EcoMill70 machining center table, is shown in Fig. 5.10. This is the final version we used in our experiments, in which the elevation bushing is equipped with a window large enough to allow the temperature in the process to be measured using a thermal imaging camera.



- Fig. 5.10. Device for orienting and fixing the metal sheet used in conducting experiments

5.2.3. Innovative tool with variable radius for incremental plastic deformation



a) Modelul 3D al sculei ETVR b) Scula ETVR

Fig.5.11 Innovative tool ”eccentric tool with variable radius” - ETVR [B04]

The main contribution of the research carried out in the doctoral studies is the development of a new incremental plastic deformation tool. The innovative tool, called "eccentric tool with variable radius" (ETVR), was designed and manufactured during the doctoral studies [B04], with the aim of

improving the incremental plastic deformation process at a single point. This tool is a flat-headed punch, whose radius of connection between the flat front surface and the outer cylindrical surface is variable, with a minimum value of R=5mm at one end and a maximum value of R=10mm at the opposite end, at 180° around the axis, Fig.5.11. The innovative ETVR tool was made of the same material as those with a hemispherical head, namely tool steel 1.2312 (40CrMnMoS 8-6).

The ETVR tool combines the characteristics of three different tools, namely: a flat punch, which increases the deformability of the material by raising the temperature in the tool-semi-finished product contact area due to intense friction in the flat area [K06], a punch with a large radius hemispherical head, R=10 mm, which has a favorable influence on surface quality, leading to lower roughness and higher productivity [B12], and a punch with a small radius hemispherical head, R=5 mm, which increases the formability of the material due to the smaller contact area..

In order to analyze the evolution of the contact between the ETVR tool and the semi-finished product, different angular positions of the ETVR tool were considered in relation to its own axis when machining the target part (cone trunk with wall angle α=45°), schematically represented in Fig. 5.12. It was considered that the rotation of the tool "n" is greater than its feed rate "va", a situation commonly encountered in practice.

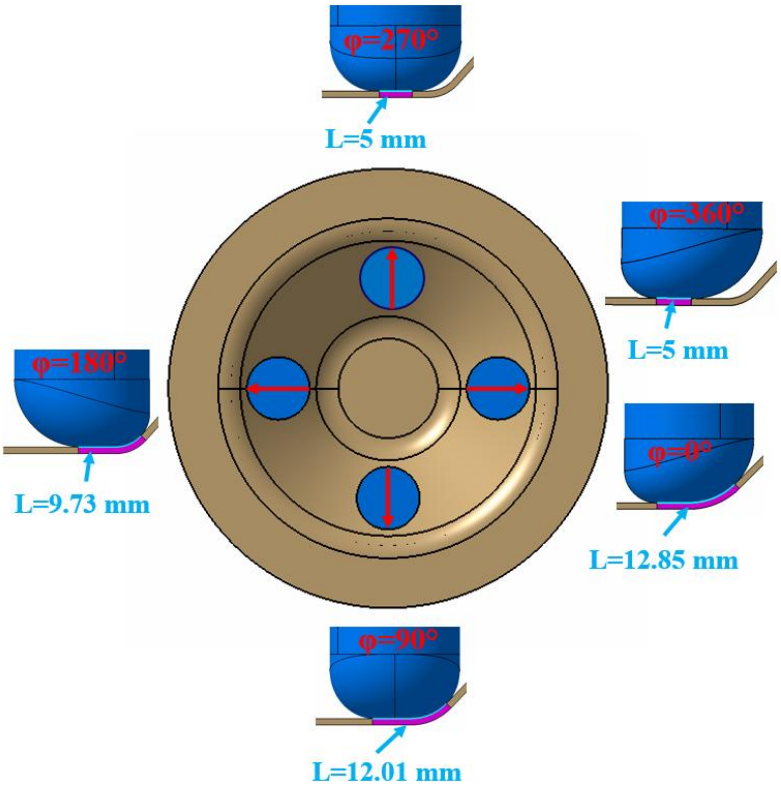


Fig.5.12. The size of the contact line between the ETVR tool and the semi-finished product for different angular positions of the latter with the target part considered

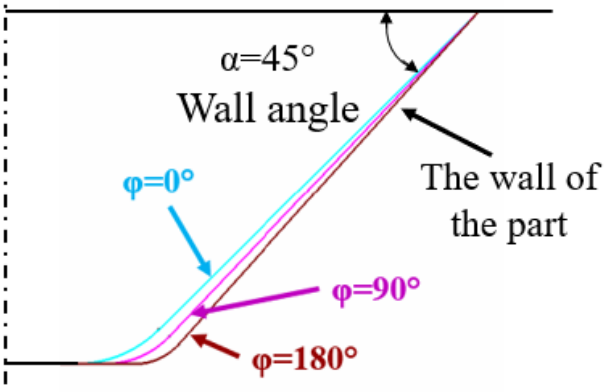


Fig.5.13. Position of the target part generator for different angular positions of the tool ETVR

Due to this variation in contact between the ETVR tool and the semi-finished product, the cone generator of the part has different angles, depending on the angular position φ of the punch, Fig. 5.13: the angle of inclination is maximum when the semi-finished product is in contact with the part of the tool with R=5 mm (φ = 180°) and is minimum when the semi-finished product is in contact with the part of the tool with R=10 mm (φ = 0°). Thus, intermittent incremental plastic deformation can contribute to achieving the deformation process with less effort and to increasing the quality of the parts obtained.

5.2.4. Tools with hemispherical heads for incremental plastic deformation

To compare the results of machining with the innovative tool, two monoblock tools with hemispherical heads were used as reference tools in the experimental research. The two tools have different active area radii and are made of the same tool steel as the innovative tool.

The first tool is a two-stage cylindrical revolution piece with an active area radius of 5 mm and an outer diameter of the orientation and fixing part of 20 mm. Its active area radius corresponds to the smallest radius of the innovative tool. The second tool has an active area radius of 10 mm and an outer diameter of the orientation and fixing part of 20 mm. Its active area radius corresponds to the largest radius of the innovative tool.

5.2.5 Real-time measurement systems for process results

For the experimental investigation of incremental plastic deformation processes at a single point, two process parameters were measured: the deformation force and the process temperature. The experimental systems used for this purpose are presented below.

- *Incremental plastic deformation force measurement system*

The forces in the incremental plastic deformation process at a single point were measured on three orthogonal axes (X, Y, and Z) using a dynamometer with elastic sensors and strain gauges, model K3D160 [M06], manufactured by ME-MEßSYSTEME.

- *Thermographic camera*

Thermography was used to measure temperatures during incremental plastic deformation, using an OPTRIS PI400i thermographic camera [O02].

5.3. Methods and means used to measure certain characteristics of machined parts

- *Roughness of machined surfaces*

The roughness of machined surfaces was measured for all machined parts using a contact method, using the MITUTOYO SJ210 [M10] portable roughness tester, which has a diamond-tipped probe.

- *Microhardness of machined surfaces*

The microhardness of the surface layer of the machined surfaces was determined using the INNOVATEST Falcon500 [I01] hardness tester.

- *Geometric accuracy of the machined parts*

The geometric accuracy of the machined parts was evaluated using two parameters: deviation from the given profile shape and part wall thickness (see chapter 7). An indirect, non-contact method using mobile scanners was used to determine these parameters. Two scanners were used, Artec Space Spider – during the research internship at ENSTA Bretagne, and GoSCAN3D – during the research carried out at the University Center in Piteşti.

5.4. Planning the experiments

Two experimental systems were used to perform incremental plastic deformation processing at a single point: one called the "elastic system" and the other called the "rigid system".

The purpose of the *elastic system* is to observe and study in depth the process of incremental plastic deformation.

The purpose of the *rigid system* is to obtain parts under normal working conditions (in the absence of vibrations caused by sources other than the process itself), which are then evaluated in terms of their quality.

The planning of the experiments aimed at the correct and efficient conduct of the experimental research. The experimental plan used for this purpose comprised 12 experiments, denoted by E1 ... E12, and is presented in Table 5.16.

Tabelul 5.16. Experimental plan

No. exp.	Type System	Tool Type	Technological parameters	Parameters measured during the process		Elements analyzed after processing					
E1	Elastic system	(SS) R=10	n=2000 [rot/min]; v_a=1000 [mm/min]; Δz =0,3 [mm].	Deformation force in the directions X,Y, Z	Process temperature	Macroscopic shape of the machined surface (scratches)	Micro-chips resulting from the process (their quantity and size)	Wall thickness of the part	Deviation from the part profile	---	---
E2											
E3		(SS) R=5									
E4											
E5		ETVR									
E6											
E7	Rigid system	ETVR		---						Surface roughness	Microhardness of the surface layer
E8											
E9		(SS) R=10									
E10											
E11		(SS) R=5									
E12											

The first six experiments were performed on the "elastic system," and the next six experiments were performed on the "rigid system." Each experiment performed with a tool (SS5, SS10, and ETVR) on each of the two machining systems was repeated in order to highlight the repeatability of the process.

The values of the incremental plastic deformation technological parameters were established based on the analysis of the works in the specialized literature [B07], [C09], [P01], [S03] and were the same in all 12 experiments performed, respectively: tool speed n=2000 [rpm], tool feed rate va=1000 [mm/min], incremental step in the Z direction, Δz =0,3 [mm].

The tool path was helical, as this has the advantage of leaving no marks on the surface of the machined parts and preventing sudden variations in the deformation forces [L05], [J07]. The helical tool path required for incremental plastic deformation was created using CATIA V5 software. It was taken into account that, for each tool used, the starting point of tool path was in the same area of the metal sheet, so that the analysis and comparison of the results would have a high degree of accuracy.

The parameters measured during the processing were: a) the deformation forces in the three directions (X, Y, and Z) and the temperatures in the process, when using the elastic experimental system (experiments E1 ... E6) and b) the temperatures in the process, when using the rigid experimental system (experiments E7 ... E12).
The elements analyzed after machining were: a) the macroscopic shape of the machined surface, the micro-chips resulting from the process, the thickness of the part walls, and the deviation from the part profile for parts machined on the experimental elastic system (experiments E1 ... E6) and b) the macroscopic shape of the machined surface, the micro-chips resulting from the process, the thickness of the workpiece walls, the deviation from the given shape of the workpiece profile, the surface roughness, and the microhardness of the surface layer, for workpieces machined on the rigid experimental system (experiments E7 ... E12).

Chapter 6. Results of theoretical-experimental research on the influence of tool shape on force and temperature in the incremental plastic deformation process

The results of theoretical and experimental research on the influence of tool shape on force and temperature in the incremental plastic deformation process, which also include published elements by the author [B02], are presented below.

6.1. Experimental stand for measuring processing force and temperature

The "elastic experimental system" was used to simultaneously measure the deformation force and temperature in the incremental plastic deformation process at a single point. This is based on the device for orienting and fixing the metal sheet (see §5.2.2), the K3D160 dynamometer, and the Optris PI400i thermographic camera (see §5.2.5).

6.2. Analysis of contact between tool and metal sheet

The process of incremental plastic deformation at a single point consists of deforming the sheet metal blank in a relatively small area, determined by the size of the contact between the tool and the blank. The size of the contact area between the tool and the metal sheet changes during the process, depending on the geometry of the active area of the tool used, the angular position of the tool (when the geometry of the active area is variable), and the position of the tool on the generation tool path, and this influences the evolution of deformation forces and machining temperatures.

6.3. Results regarding processing force

Machining with a hemispherical tool with a radius of R=10 mm (SS10)

The tool with a hemispherical head with a radius of 10 mm (SS10) was used in experiments E1 and E2, which were carried out under the same experimental conditions. The evolution of the deformation forces in the three measurement directions, X, Y, and Z, during the first experiment (E1) is shown in Fig. 6.8.

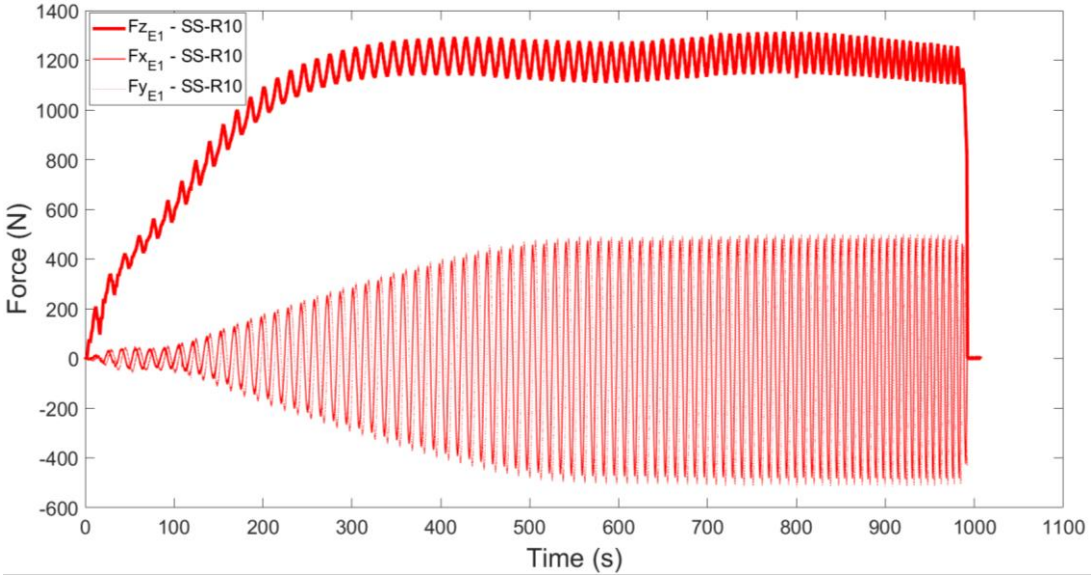


Fig.6.8. Evolution of deformation forces in the X, Y, and Z directions when machining with a hemispherical tool with a radius of 10 mm (SS10 - E1))

There is a very good overlap of the Fz forces in the two experiments, which confirms the repeatability of the experiments and the ability of the force measurement system to correctly measure the forces that occur during the incremental plastic deformation process at a single point. The forces in the X and Y directions evolve symmetrically, as expected, due to the configuration of the experimental system, reaching a maximum value of approximately 500 N. The force in the Z direction, which is of major interest in SPIF processes, evolves differently, reaching a maximum value of approximately 1315 N.

Machining with a hemispherical tool with radius R=5 mm (SS5)

Experiments E3 and E4 were performed using a hemispherical tool with a radius of R=5 mm (SS5) on the elastic system. The evolution of the deformation forces in the three measurement directions, X, Y, and Z, in the third experiment (E3) is shown in Fig.6.14.

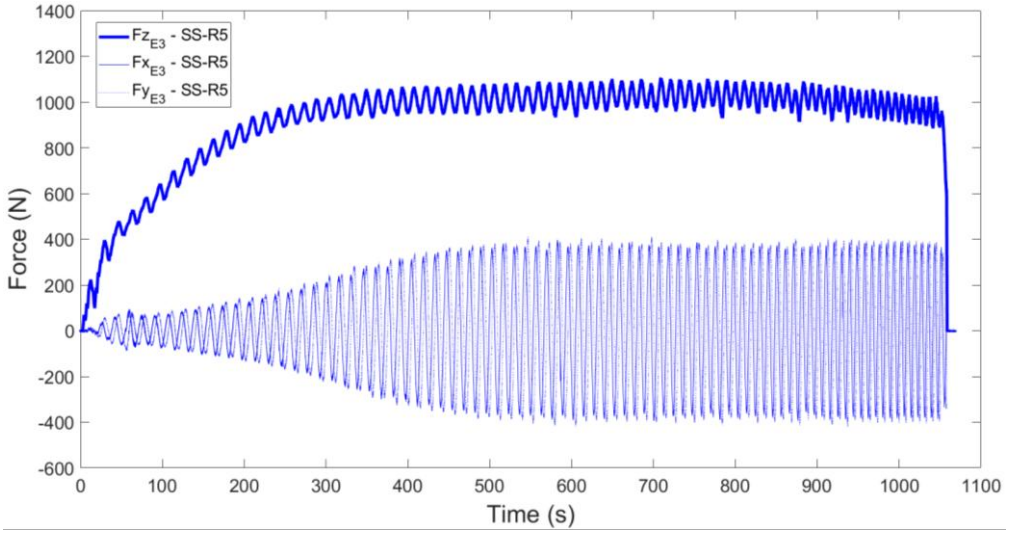


Fig.6.14. Evolution of deformation forces in the X, Y, and Z directions when machining with a hemispherical tool with a radius of 5mm (SS5 - E3)

The evolution of deformation forces when machining with a hemispherical tool with a radius of R=5 mm is similar to that when machining with a hemispherical tool with a radius of R=10 mm, but their maximum values are lower: approximately 400 N for the forces in the X and Y directions, respectively, and approximately 1105 N for the force in the Z direction. At the same time, an almost identical evolution of the deformation forces Fz is observed, which proves – in this case as well – the repeatability of the experiments in terms of deformation forces.

Processing with innovative tools (ETVR)

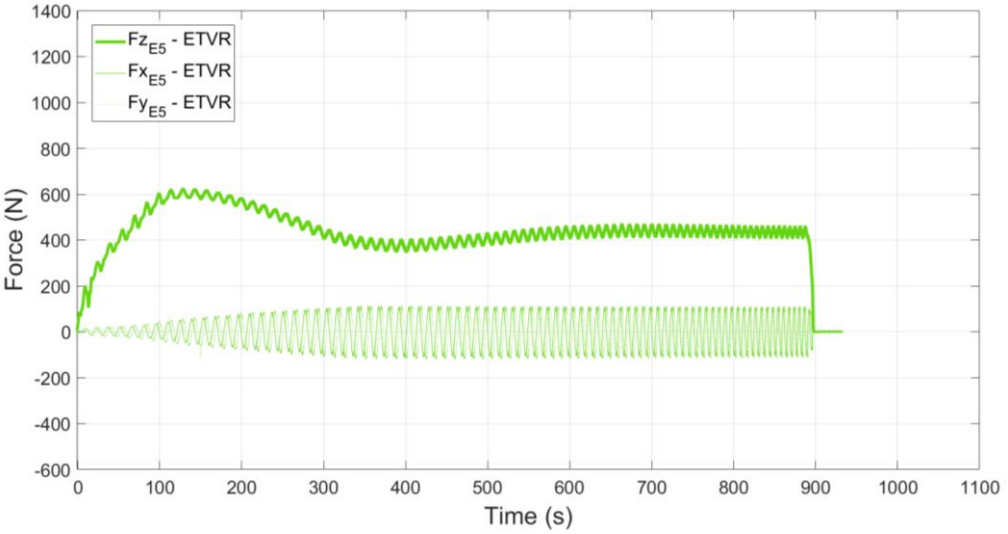


Fig.6.17. The evolution of deformation forces in the X, Y, and Z directions when machining with a variable radius eccentric tool (ETVR - E5)

Machining with the innovative ETVR tool was performed in experiments E5 and E6. The evolution of deformation forces in the three directions during experiment E5 is shown in Fig. 6.17.

However, the evolution of deformation forces when machining with the ETVR tool differs from the evolution of forces when machining with hemispherical head tools, especially in the Z direction. The deformation force Fz has a faster initial increase, reaching a maximum of Fz = 625N, then decreases and, towards the end of the process, stabilizes at a value of 470N. The forces in the X and Y directions increase almost constantly in the first part of the incremental deformation process, after which they stabilize at a value of 115N.

6.4. Results regarding processing temperatures

Calibration of the thermal imaging camera

Thermal imaging cameras measure the infrared radiation emitted by the objects being analyzed. They are calibrated at the factory using known temperature sources (calibrated black bodies), thus ensuring accurate conversion of the electrical signal into temperature and correction of internal thermal drift. In practice, thermal imaging cameras can be manually adjusted in relation to the emissivity of the observed surface, using preconfigured profiles depending on the material. However, the emissivity of surfaces varies depending on the specific observation conditions. For this reason, a method for calibrating the thermographic camera, specific to the experimental conditions of the process under study, is proposed and described below.

Machining with a hemispherical tool with a radius of R=10 mm (SS10)

he temperature evolution in experiment E1, performed when machining with a hemispherical tool with a radius of 10 mm (SS10) on the elastic experimental system, is shown in Fig. 6.22. The similar evolution of temperatures in the two experiments demonstrates the repeatability of the experiments on the experimental research system in terms of the measured temperatures.

The temperature measured during the machining process starts from the ambient temperature, around 21°C. s a result of friction between the tool and the semi-finished product, the temperature rises continuously, more intensely at the beginning of the process and more slowly afterwards, due to the variation in the tool-semi-finished product contact surface. The maximum temperature, reached at the end of the deformation process, is between 145 and 148,1°C.

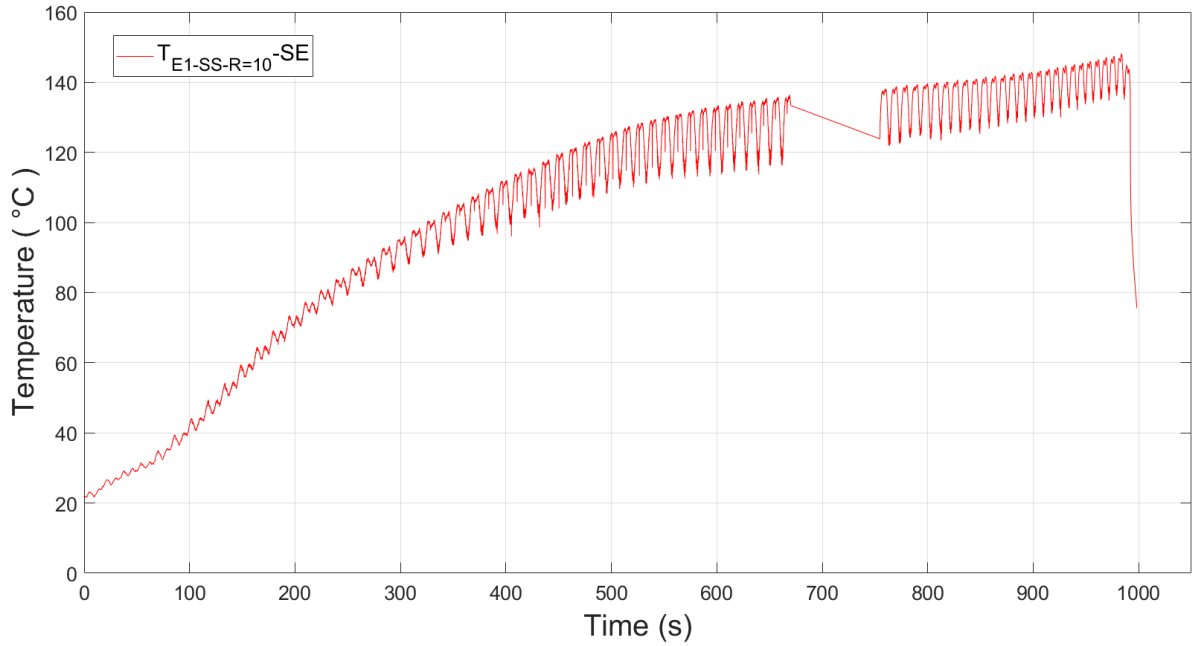


Fig.6.22. Temperature evolution during the process, when machining with a hemispherical tool SS10 - E1

Machining with a hemispherical tool with a radius of R=5 mm (SS5)

The temperature evolution in experiment E3, consisting of machining with a hemispherical tool with a radius of 5 mm (SS5) on the elastic experimental system, is shown in Fig.6.26.

The temperature measured during the machining process starts at around 27°C, higher than in experiments E1 and E2 due to the heating of the machine tool's working chamber. The temperature evolution in the machining process is similar to that in the machining with the SS10 tool, with maximum values at the end of machining ranging between 146.9 and 148.3 °C.

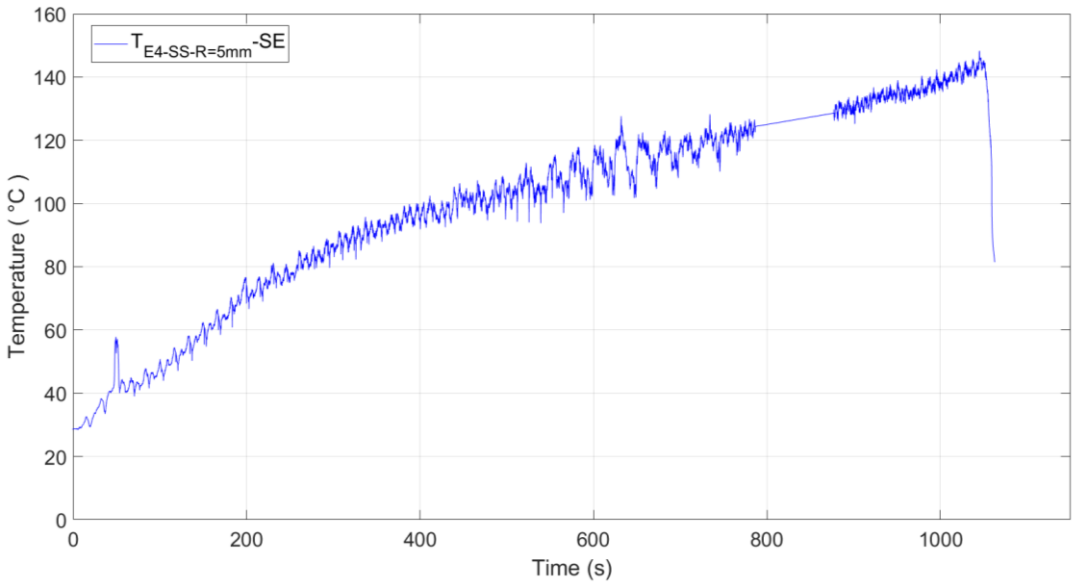


Fig.6.26. Temperature evolution during processing with a hemispherical tool with a hemispherical head SS5 - E13

Machining with innovative tool (ETVR)

The temperature evolution during machining with the innovative ETVR tool on the experimental elastic system is shown in Fig. 6.29 for experiment E5.

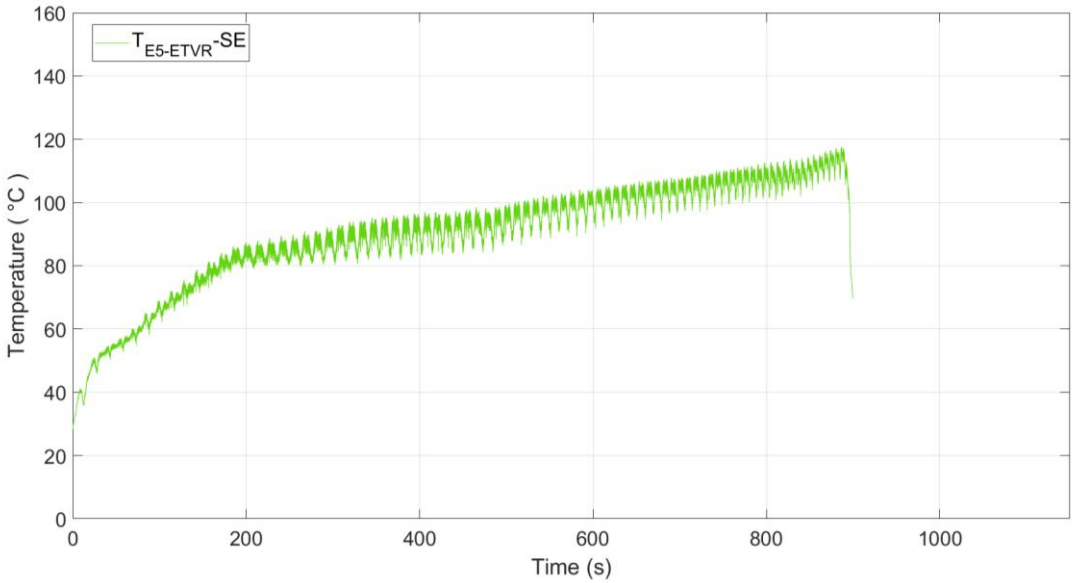


Fig.6.29. Temperature evolution during the process when machining with the innovative tool ETVR - E5

The temperature measured during the machining process starts at approximately 28°C, which is higher than in experiments E1 - E4, due to the continued heating of the machine tool's working chamber. The maximum temperature is reached at the end of processing and ranges between 115 and 117.4 °C, which is lower than when processing with hemispherical tools.

Chapter 7. Development of a methodology for measuring the geometry of the machined part through 3D scanning

The methodology presented in this chapter was developed during the doctoral research internship carried out between 17.06 – 05.07.2024 at the Ecole Nationale Supérieure de Techniques Avancées Bretagne. The research presented in this chapter also includes published elements by the author [B01] and is presented as follows.

7.1. Scanning technique

To scan a part in 3D, follow these steps.

1. Cleaning the parts.

2. Applying a powder to the surfaces of the part.

3. Orienting and fixing the part.

4. Marking the reference points in the part orientation and fixing system.

5. Effective scanning of the part.

6. Primary processing of data in the scanning equipment's specific software.

7.2. Methodology for determining the geometric accuracy parameters of the part

7.2.1. Description of the methodology

The analysis of the geometric accuracy of the machined parts was performed based on two parameters: the thickness of the part walls and the deviation from the given shape of the part profile. The two parameters were determined using the methodology presented below, based on the processing in Matlab software of the primary data obtained by scanning.

1. Representation of the scanning results.

2. Positioning of the point cloud.

3. Separation of the outer and inner surfaces of the part.

4. Correction of the position between surfaces.

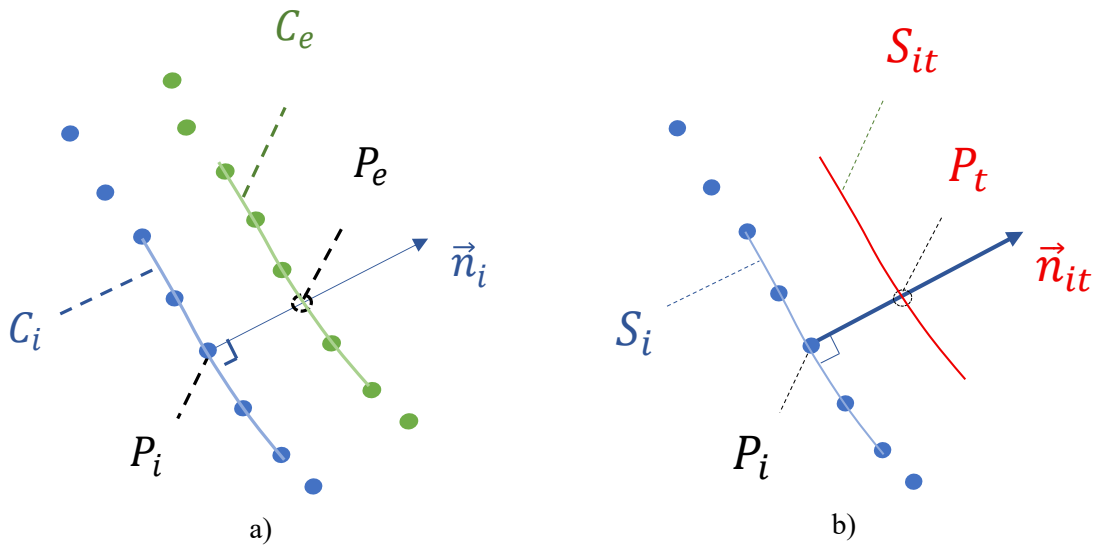
5. Construction of the theoretical shape of the part.

6. Determination of the parameters that characterize the geometric accuracy of the machined part.

In order to correctly determine the two geometric accuracy parameters of the machined part, it is necessary that the two surfaces of the part, the lower surface C_i/S_i and the upper surface C_e e correctly defined and positioned in the numerically acquired point cloud. This is achieved by analyzing the orientations of the normals to the point clouds that define the two surfaces, which are precalculated in the .stl file taken as input data.

Since the density of points on a surface is limited by the scanner's acquisition system (the minimum distance between two points cannot be less than 0.1 mm), the classic point-to-point distance measurement (closest point) is not adequate [A12]. Therefore, surface interpolation is necessary to reduce any measurement artifacts on these discrete surfaces. This is achieved in Matlab software by identifying a second-order polynomial surface $C_{i,e}$, using the least squares method. This surface is constructed successively around each point $P_{i,e}$, using all points that are at a distance less than or equal to the size to be investigated, denoted z_i. In this case, z_i = 0,3 mm was chosen because this value ensures, on the one hand, a minimum number of points for identifying the 6 parameters of the surface

and, on the other hand, ensures a correct approximation of areas with significant local variation in curvature. his creates a series of quadratic interpolation surfaces C_i and C_e, which pass through the closest measured points for each of the two surfaces of the machined part.



a) b)

The inner surface S_i is represented in **blue**; the outer surface C_e s represented in **green**; the theoretical inner surface S_{it} is marked in **red**

Fig.7.9. Method for calculating the geometric accuracy parameters of the machined part: a)determining the wall thickness, g; b) determining the deviation from the given profile shape, a b)

Once the two smoothed surfaces, C_i and C_e, have been generated, the two geometric accuracy parameters defined above can be calculated according to the diagrams in Fig. 7.9. If P_i is a point belonging to surface C_i, P_e is a point belonging to surface C_e, şi P_t is a point belonging to surface S_{it}, then the two parameters are calculated as follows:

- g = the distance between point P_i and surface C_e, noted as $d(P_i,C_e)$;
- a = the distance between point P_i and surface S_{it}, noted as $d(P_i,S_{it})$.

It should be noted that applying the methodology presented above in Matlab software is highly complex, as it is based on manipulating a large volume of data, building specific programs (Matlab scripts), and running them.

7.2.2. Validation of the method for calculating the wall thickness of the part

Within the methodology for determining the geometric accuracy parameters of the machined part, the calculation error may originate from the method used to calculate the wall thickness of the part. To verify the accuracy of the proposed method, the measured part could be cut by angularly offset planes passing through the axis of revolution of the part, then conventional measurement methods could be used to measure the thicknesses in these areas and compare them with the calculated values. However, this verification method has two drawbacks: 1) the machining method could reduce the thickness of the part in the vicinity of the cut; 2) the information obtained would be partial (point measurement) and incomplete for the entire part. Therefore, the validation of the method for calculating the wall thickness of the part was performed by calculating the wall thickness for a numerically generated reference part with ideal 3D geometry (constant thickness of 1 mm).

Chapter 8. Results of theoretical-experimental research on the influence of tool shape on the quality of parts processed by incremental plastic deformation

The results of theoretical and experimental research on the influence of tool shape on the quality of parts processed by incremental plastic deformation, which also include published elements by the author [B03], are presented below.

8.1. Experimental stand for machining parts and preparing samples for measurement

The experiments to analyze the influence of tool shape on the quality of parts machined by incremental plastic deformation, E7–E12, were performed on the "rigid experimental system" (see §5.4). Compared to the "elastic experimental system" described in §6.1, the rigid experimental system does not include the dynamometer for measuring forces and, consequently, the dynamometer support plate. To measure the three parameters (thickness, roughness, and microhardness), three specific areas of the workpiece generator were established: B (Base), M (Middle), and T (Tip), Fig. 8.3.

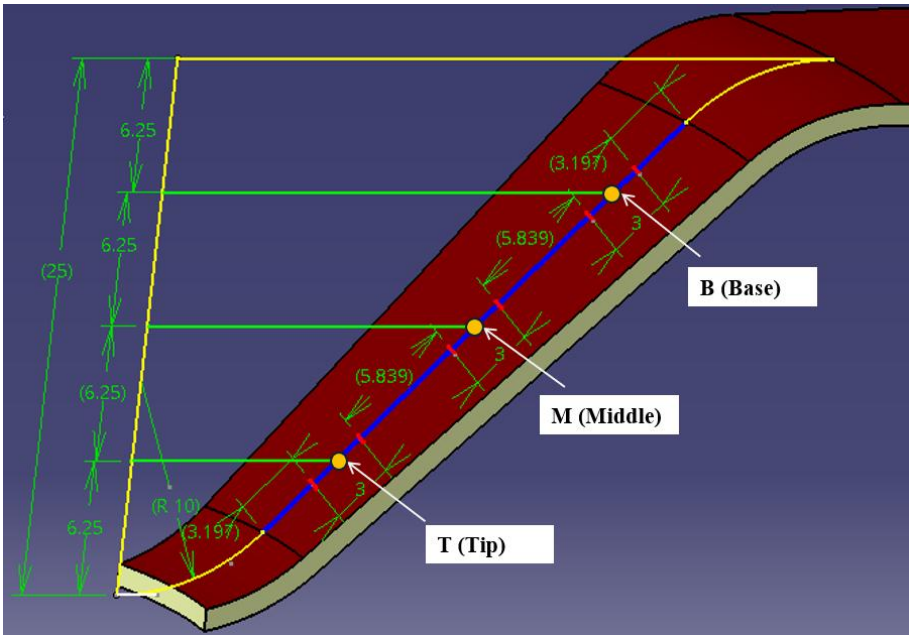


Fig.8.3. Establishing areas for measuring thickness, roughness, and microhardness parameters

8.2. Microchips from machining. Visual appearance of machined surfaces

Incremental plastic deformation machining at a single point results in microchips that appear due to intense local friction between the active area of the tool and the semi-finished product. Their size depends on the specific processing conditions and is influenced by the shape of the active area of the tool, the material of the metal sheet, the geometric shape of the part, the feed rate Va, the tool speed n, the lubricant, etc. Therefore, after each experiment, the microchips resulting from the processing were visually analyzed. Then, they were collected and analyzed under an optical microscope.

Micro-chips and visual appearance of surfaces when machining with the SS10 tool

It can be seen that there is a layer of very fine microchips on the surface of the workpiece, which are detached from the machined semi-finished product as a result of friction between the tool and the

semi-finished product. The dimensions of the microchips range from 7 to 18 µm, with the predominant dimensions being approximately 12 µm.

Microchips and visual appearance of surfaces when machining with the SS5 tool

A significant volume of microchips can be seen on the machined surface of the part, many of which are relatively large. Optical analysis of the microchips, performed at 50x magnification, reveals that they range in size from 21 to 83 µm. The predominant chip sizes are approximately 45 µm.

Microchips and the visual appearance of surfaces when machining with the ETVR tool

The chips produced during machining with the innovative ETVR tool are very small in quantity. They are very thin, and their analysis under an optical microscope at 50x magnification reveals dimensions between 2 and 51 µm, with predominant dimensions of approximately 8 µm.

8.3. Geometric accuracy of machined parts

The geometry of machined parts was evaluated based on the parameters of part wall thickness, g, and deviation from the given shape of the part profile, a. These were determined according to the methodology developed and presented in Chapter 7. Data acquisition by scanning was performed in the CRC&D-Auto laboratory at the Piteşti University Center, using GO!scan 3D equipment, and data processing was performed using Matlab software.

Geometric accuracy of parts machined with the SS10 tool

- *Wall thickness of the part machined with the SS10 tool*

The wall thickness of the workpiece machined with the SS10 tool was determined for the workpiece machined in experiment E9. The variation in the wall thickness of the workpiece superimposed on the theoretical profile of the target workpiece is shown in Fig. 8.20. The highest values of the wall thickness of the part are found on the surface of the flange and on the small base of the truncated cone, where the material was not deformed, retaining its initial dimension (equal to the thickness of the initial metal sheet of approximately 1 mm).

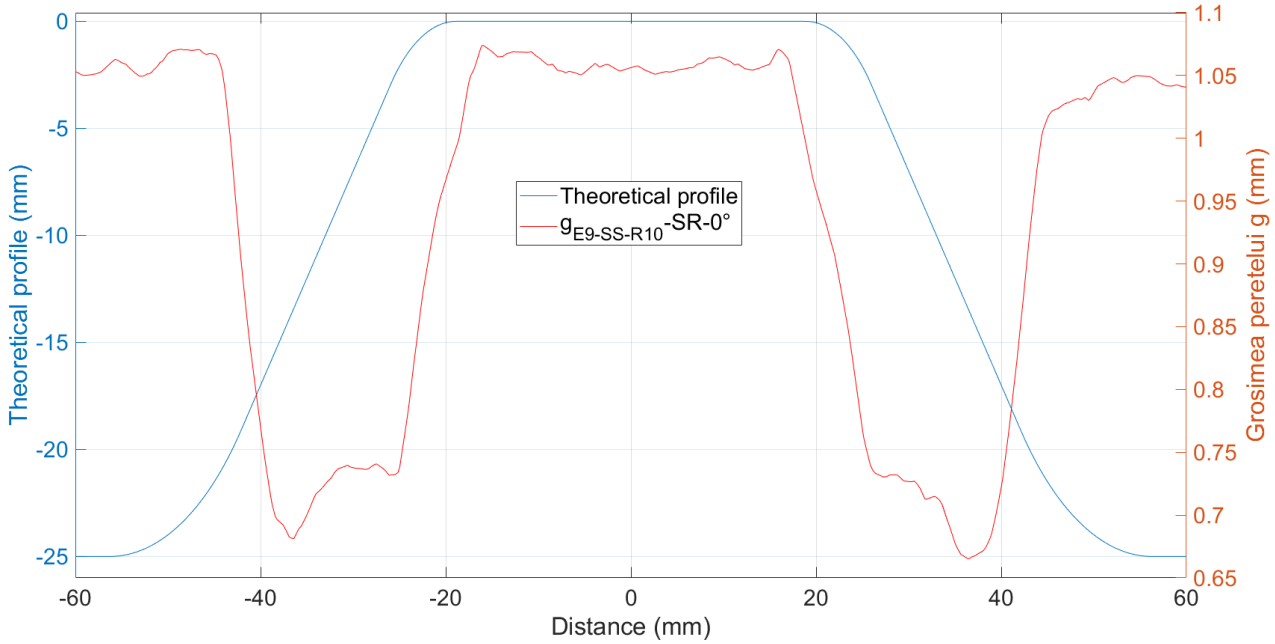


Fig.8.20. Theoretical profile and wall thickness of the workpiece machined with the tool SS10 – E9

- *Deviation from the given shape of the part profile machined with the SS10 tool*

Fig. 8.25 shows the theoretical profile of the part and the deviation from the given shape of the inner surface profile on the same graph.

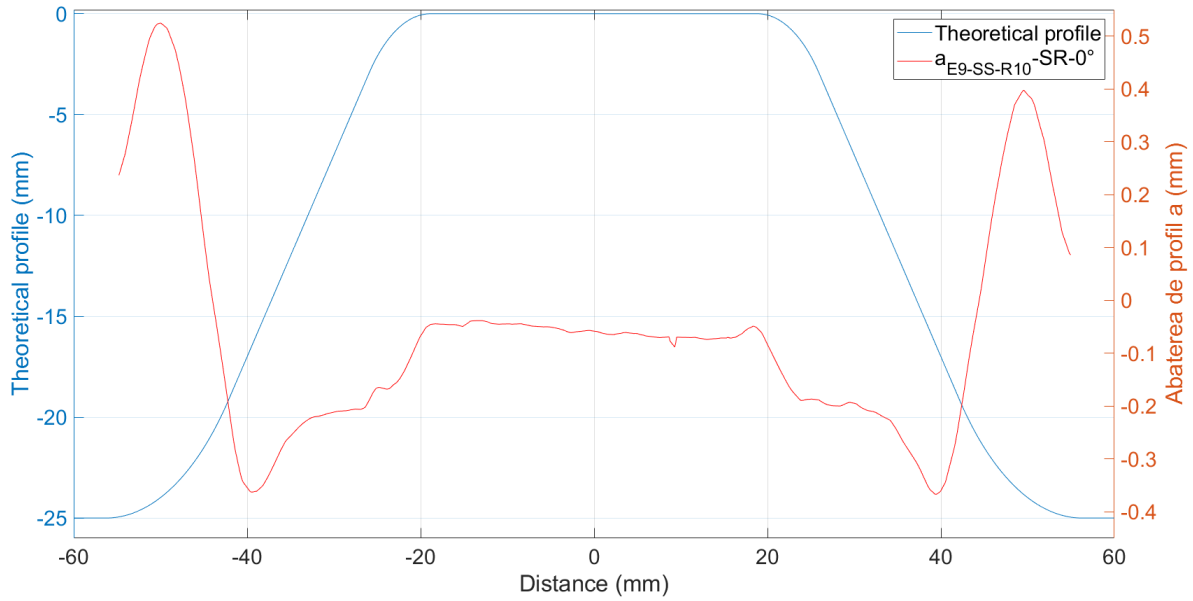


Fig.8.25. Theoretical profile and deviation from the given shape of the profile machined with the tool SS10 – E9

At the top of the truncated cone , where the material has not been deformed, there is a minimal deviation from the given profile shape, but a defect known as the "cushion effect" can be observed. The largest deviations from the given profile shape, with values exceeding 0.2 mm, are recorded in the upper area of the truncated cone.

Geometric accuracy of parts machined with the SS5 tool

- *Wall thickness of parts machined with the SS5 tool*

The highest values of part thickness are found on the flange surface and on the small base of the truncated cone, where the material has not been deformed, retaining its original dimension (equal to the thickness of the original metal sheet of approximately 1 mm). The area with the lowest wall thickness of the part, g=0.68, where the material shows excessive thinning, is the area at the base of the truncated cone. The thinning of the part wall is maximum in this area due to the fact that the metal sheet is embedded, which causes this area to be the first to be deformed and continuously elongated as the tool advances towards the center of the truncated cone.

- *Deviation from the given shape of the profile of the part machined with the SS5 tool*

At the tip of the cone, where the material has not been deformed, there is a minimal deviation from the given shape of the profile, but greater than when machining with the SS10 tool. There is also a defect known as the " pillow effect," which is much more pronounced. The largest deviations from the given profile shape, with values of approximately 0.4 mm, are recorded in the upper area of the truncated cone. The deviation from the given shape of the part profile increases rapidly in absolute value, starting from zero near the retaining ring area (base of the cone trunk), reaching a maximum absolute value of approximately 0.26 mm in the ∅40, diameter area, then decreases to 0.02 in the area of the cone trunk tip. At the middle of the truncated cone height, it has a value of 0.27 mm.

Geometric accuracy of parts machined with the ETVR tool

- *Wall thickness of parts machined with the ETVR tool*

The highest values of part thickness are found on the flange surface and on the small base of the truncated cone, where the material has not been deformed, retaining its initial dimension (equal to the thickness of the initial metal sheet of approximately 1 mm). The area with the smallest wall thickness of the part, g=0.68, where the material shows excessive thinning, is the area at the base of the truncated cone. The thinning of the part wall is maximum in this area due to the fact that the metal sheet is embedded, which causes this area to be the first to be deformed and continuously elongated as the tool advances towards the center of the truncated cone. Therefore, with the continuous thinning

of this area, its strength decreases, increasing the risk of breakage. Towards the tip of the truncated cone, the wall thickness of the part gradually increases to g=1mm, that of the undeformed material.

- *Deviation from the given shape of the profile of the workpiece machined with the ETVR tool*

The largest deviations from the given shape of the profile, with values of approximately 0.5 mm, are recorded in the upper area of the truncated cone. The deviation from the given shape of the workpiece profile increases rapidly in absolute value (the deviations from the given shape of the profile are negative: the actual inner profile of the workpiece is positioned inside the theoretical profile of the truncated cone), starting from zero near the retaining ring area (base of the truncated cone), reaching a maximum absolute value of approximately 0.45 mm in the ∅40 diameter area, after which it decreases to a value of 0.18 mm in the truncated cone tip area.

Wall thickness of parts measured with a micrometer

The wall thickness of the machined parts was determined by 3D scanning, according to the methodology developed and presented in Chapter 7. Given that samples were taken to measure roughness and microhardness, wall thickness measurements were also taken, as mentioned in §8.1, in order to compare them with those obtained by scanning.

8.4. Surface roughness of machined parts

The roughness of the semi-finished product (rolled sheet metal) and of the parts processed by incremental plastic deformation was measured in accordance with ISO 21920-2:2021 and ISO 21920-3:2021 [I04], [I05] using the MITUTOYO SJ210 roughness tester.

Surface roughness of parts processed with the SS10 tool

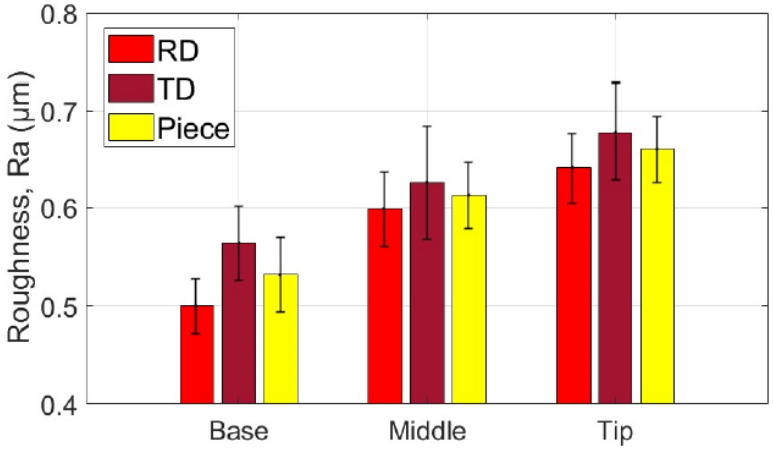


Fig.8.51. Ra roughness of the workpiece machined with the SS10 tool

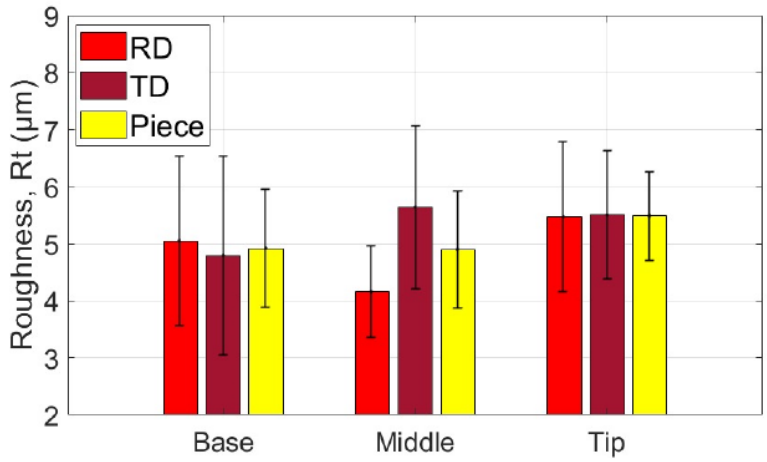


Fig.8.52. Roughness Rt of the workpiece machined with SS10 tool

The average values of the Ra and Rt parameters associated with the two specific directions of the semi-finished product and the part, respectively, are shown graphically in Fig. 8.51 and Fig. 8.52, respectively.

Surface roughness of parts machined with the SS5 tool

Fig. 8.53 shows a graph of the average values of the Ra parameters associated with the two specific directions of the semi-finished product and the part, respectively.

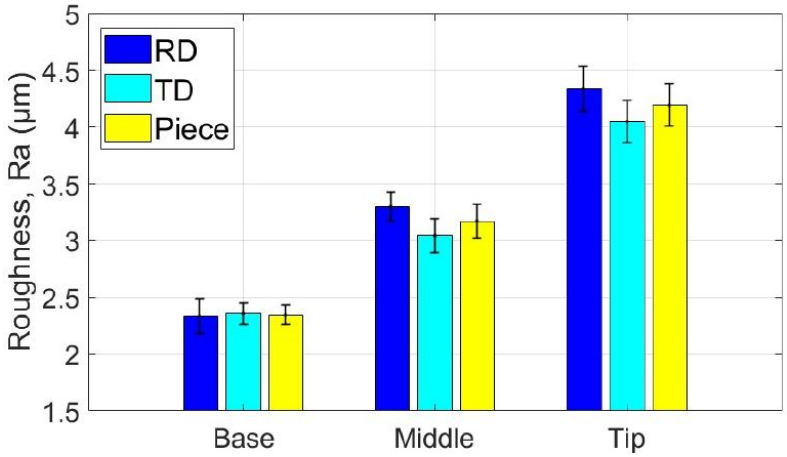


Fig.8.53. Ra roughness of the workpiece machined with the SS5 tool

Surface roughness of parts machined with the ETVR tool

Fig. 8.55 shows a graph of the average values of the Ra parameters associated with the two specific directions of the semi-finished product and the part, respectively.

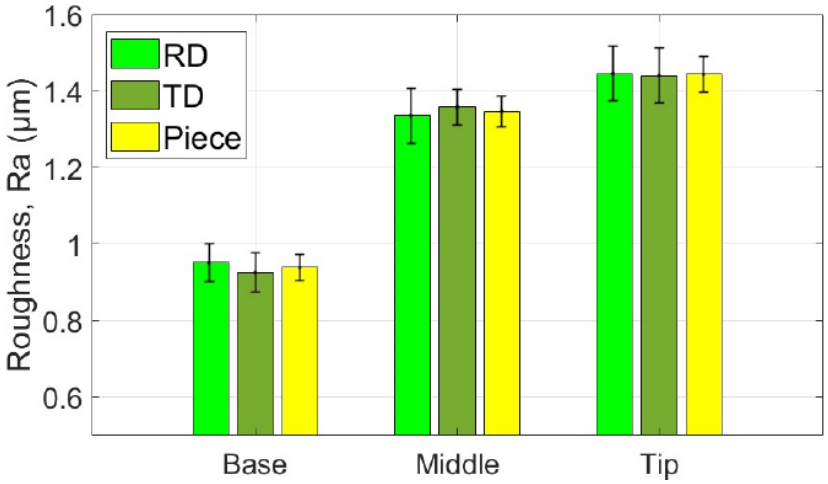


Fig.8.55. Ra roughness of the workpiece machined with the ETVR tool

8.5. Microhardness of the surface layer of machined parts

The microhardness of the surface layer of the semi-finished product (rolled sheet) and the machined surfaces was measured using the Vickers method, with a pressing load of 300 gf.

Microhardness of the surface layer of parts machined with the SS10 tool

The average HV microhardness values associated with the two specific directions of the semi-finished product and the part, respectively, are shown graphically in Fig. 8.59.

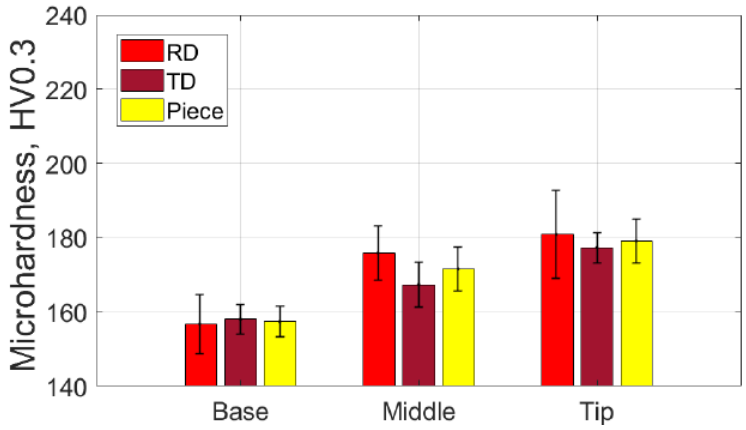


Fig.8.59. Average microhardness HV 0.3 measured on the workpiece machined with tool SS10

The average HV microhardness values associated with the two specific directions of metal sheet and the part, respectively, are shown graphically in Fig. 8.60.

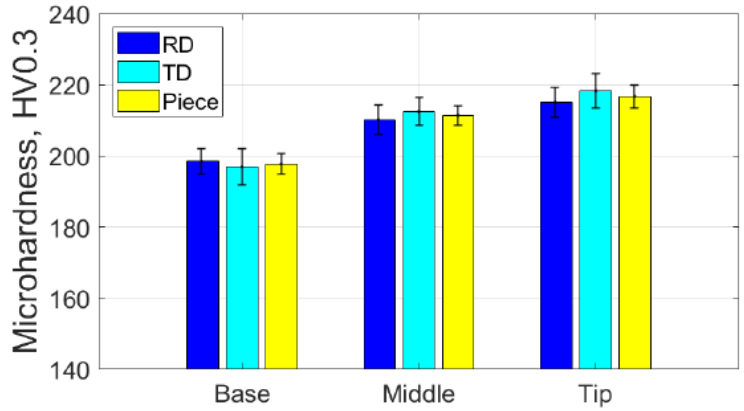


Fig.8.60. Average microhardness HV 0.3 measured on the workpiece machined with the SS5 tool

The microhardness of the surface layer of parts machined with the ETVR tool

The average HV microhardness values associated with the two specific directions of the semi-finished product and the part, respectively, are shown graphically in Fig. 8.61.

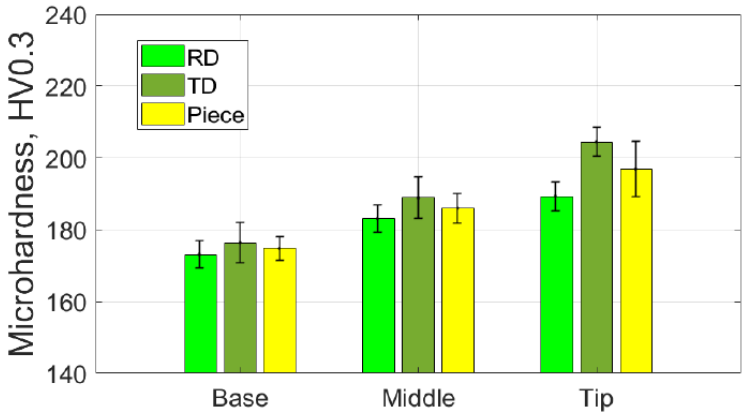


Fig.8.61. Average microhardness HV 0.3 measured on the workpiece machined with the ETVR tool

Chapter 9. Numerical modeling and simulation of the incremental plastic deformation process

The results of research on modeling and numerical simulation of the incremental plastic deformation process, which also include published elements by the author [B02], are presented below.

9.1. Building numerical models

To really get a handle on and analyze the incremental plastic deformation process, we developed numerical models using the finite element method. These were created to simulate SPIF processing with hemispherical tools of different radii: the 10 mm radius tool – SS10, and the 5 mm radius tool – SS5.

Solid modeling assumptions

Building this kind of simulation model means picking how to represent the different parts so we get a model that gives solid results but doesn't take forever to run.

Due to the assumption of a non-deformable body associated with the tool, it is necessary to define a reference point and associate it with the "kinematic coupling" constraint. Thus, the tool path imposed on the tool consists of imposing a movement on this point by defining the evolution of the coordinates as a function of time.

Friction behavior

A very important aspect in simulating the deformation process is how the contact between the tool and the part is modeled, but also between the part and the mold, which is considered fixed. The temperature that arises in the part is closely related to how the contact between the different solids is modeled, especially where there is significant relative movement, characterized by significant contact pressure. In the present study, a "penalty" contact was used in the tangential direction and a "hard contact" in the normal direction, with a friction coefficient of 0.15 [A10].

Boundary conditions

The boundary conditions are of the "displacement" type. Thus, all surfaces of the mold are rigid and have all degrees of freedom locked, creating a clamping condition. Experimentally, the degrees of freedom of the semi-finished product are canceled by applying a clamping pressure between the pressure plate and the mold. Defining this boundary condition, similar to that imposed in the experiment, leads to a considerable increase in the calculation time. The tool path is defined by the displacement velocity $\overrightarrow{v_a}$, considered constant and equal to 16.6 mm/s. This trajectory is imposed by defining the three coordinates associated with the reference point RP 1.

Thermal behavior

The temperature generated during the deformation process comes mainly from two distinct sources: friction between the tool and the semi-finished product, and deformation in the plastic range of the semi-finished product. Thus, a heat exchange between the surface of the molded sample was imposed by a free convection coefficient h_c =20 W/(m^2.K) [E02]. The conversion fraction of mechanical work into heat was considered to be 0.95.

Model discretization and computation time minimization

Due to the dynamic nature of the model, the computation time is influenced by the size of the finite element. The influence of the finite element size occurs through the stable time increment Δt. The larger this parameter is, the shorter the computation time. The discretization shown in Fig. 9.3 was chosen in order to obtain a relatively uniform distribution of elements, as well as the convergence of

various output quantities (stresses, strains, etc.) with a reasonable calculation time (40 hours) for a simulated process time of 1058s.

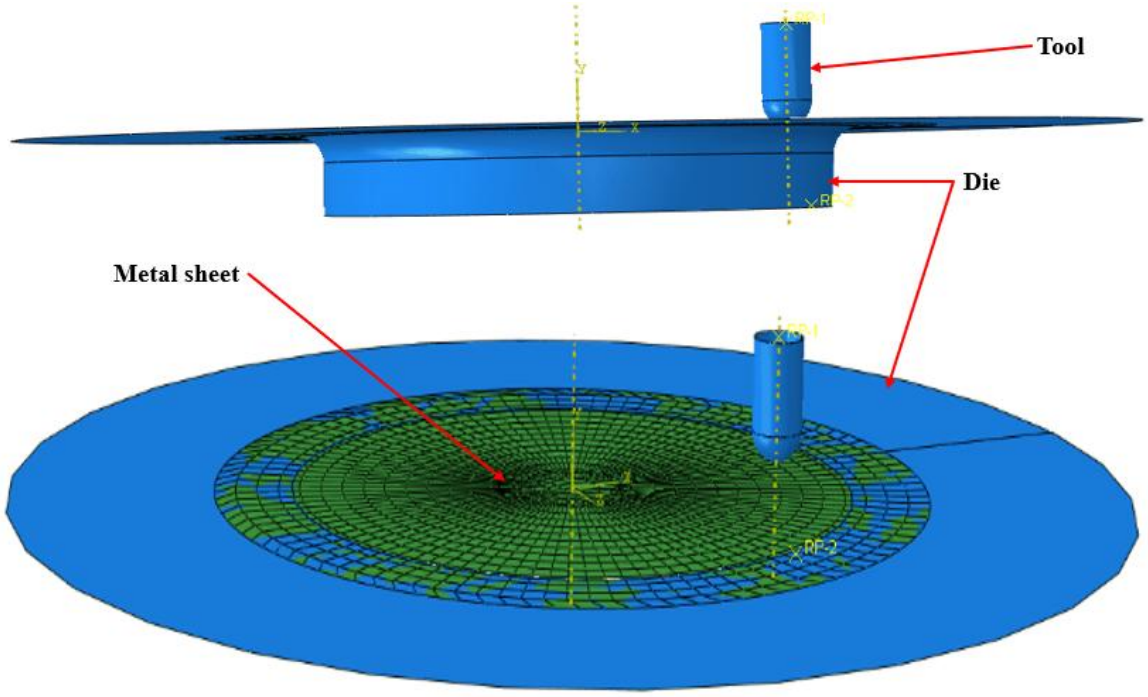


Fig.9.3. Numerical model developed for tools with hemispherical heads (SS10 and SS5)

The numerical model developed for tools with a hemispherical head (The main components of the numerical model are: the tool, the die, and the metal sheet. The tool (punch type) was created by defining the surface profile, which was rotated 360˚ around its axis of symmetry, thus obtaining its surface. Depending on the tool used, the radius of the active area was defined as 10 mm (SS10) or 5 mm (SS5). The surface was defined as an analytical surface. The die was also defined as an analytical surface and was the same for simulations with both tools. A segment was created that defines the flat surface that comes into contact with the metal sheet, the vertical wall, and the 5 mm connection radius, which corresponds to the actual dimensions of the specific plate in the metal sheet orientation and fixing device. The circular metal sheet was defined as a "shell" surface with a thickness of 1 mm (as is the actual metal sheet), and the discretization is as shown in Fig. 9.3. For the discretization of the metal sheet, 1735 quadratic elements and 24 triangular elements were used. SS10 and SS5).

hermomechanical behavior

A very important aspect in numerical modeling is the description of the thermomechanical behavior of the metal sheet. Following a bibliographic study, it was concluded that the behavior model appropriate for this process is the one proposed by Johnson-Cook.

9.2. Characterization of the thermo-mechanical behavior of AA6061-T6 alloy

Identification of parameters in the Johnson-Cook thermo-mechanical behavior model consists of performing several mechanical tests, in which the temperature and stress rate are varied. It was decided to perform tensile tests at three different temperatures: 22°C, 200°C, and 400°C, and at three different displacement speeds: 0.35 mm/min, 0.7 mm/min, and 35 mm/min. For this purpose, the methodology presented in [I03] was used.

9.3. Simulation and validation of numerical models

After developing the two numerical models, the SPIF processes performed with the two hemispherical head tools were simulated. By comparing the deformation forces, the process temperature, and the wall thickness of the part obtained from the simulation with those determined

experimentally, the numerical models were validated. Along with this validation, an analysis of the incremental plastic deformation process was also performed, as presented below.

Analysis of the results for machining with the SS10 tool

The evolution of **the deformation forces determined** by simulation and obtained experimentally are shown in Fig. 9.14. Their analysis highlights the following aspects.

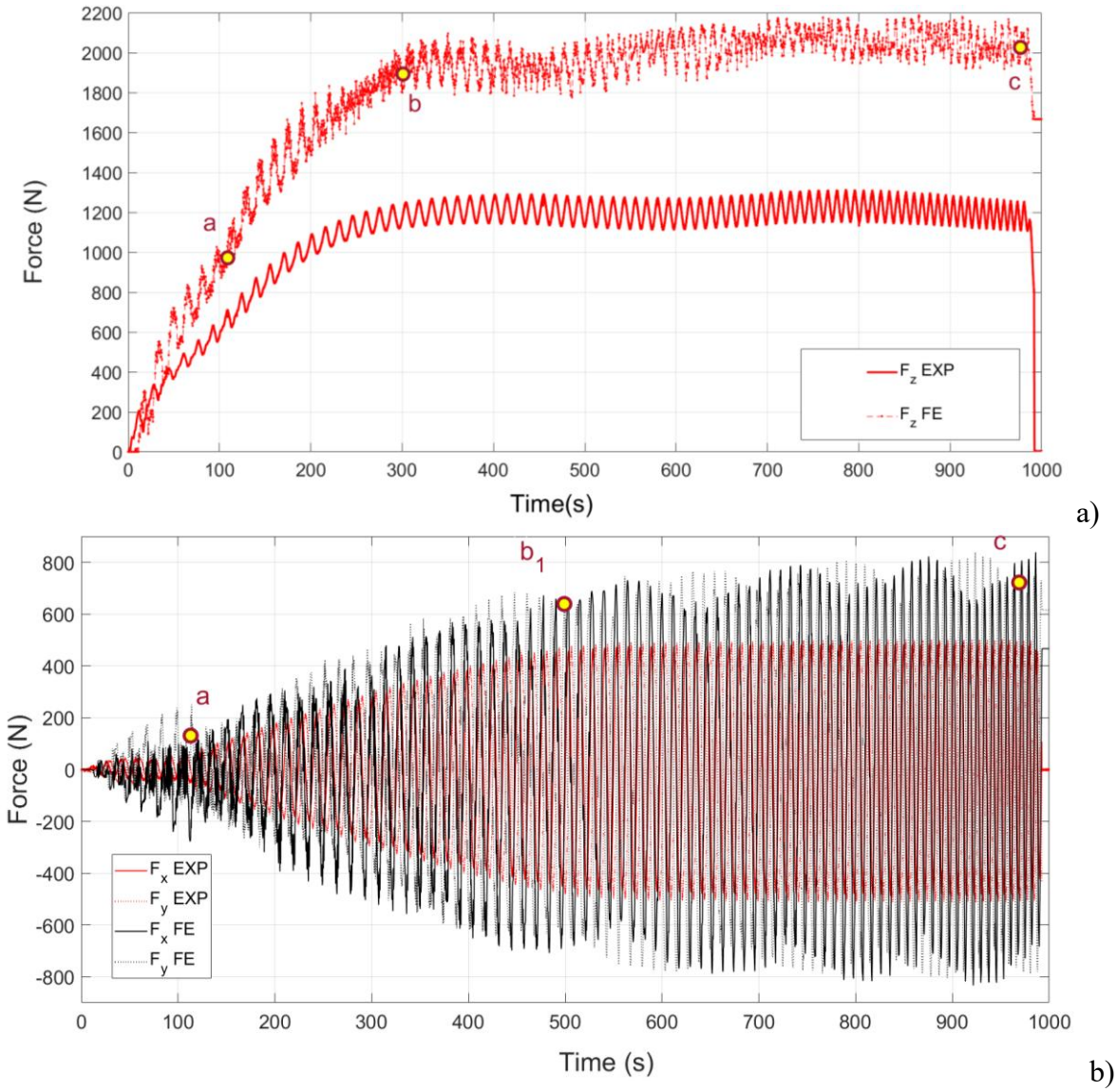


Fig.9.14. Deformation force evolution (SS10): a) along the Z axis; b) along the X and Y axes

The evolution of the temperature in the process determined by simulation and obtained experimentally is shown in Fig. 9.15. The temperature determined experimentally by thermography was determined as the average value of a 10 mm^2 area around the maximum point identified in the thermographic images. The temperature obtained by simulation was extracted as the maximum value from the field of nodal temperature values.

The evolution of the wall thicknesses of the part resulting from the simulation, respectively, after scanning the part machined with the SS10 tool, are shown in Fig. 9.16. These thicknesses are represented on two perpendicular directions of the target part. It can be seen that their evolution is similar, so that in the flange area and in the center of the cone trunk, where the semi-finished product was not deformed, the thickness value is approximately 1 mm, which corresponds to the thickness of the initial undeformed semi-finished product. In the area of the inclined walls, the thickness of the part walls is smaller (due to their thinning), and the values obtained by simulation are close to those determined by the scanning technique.

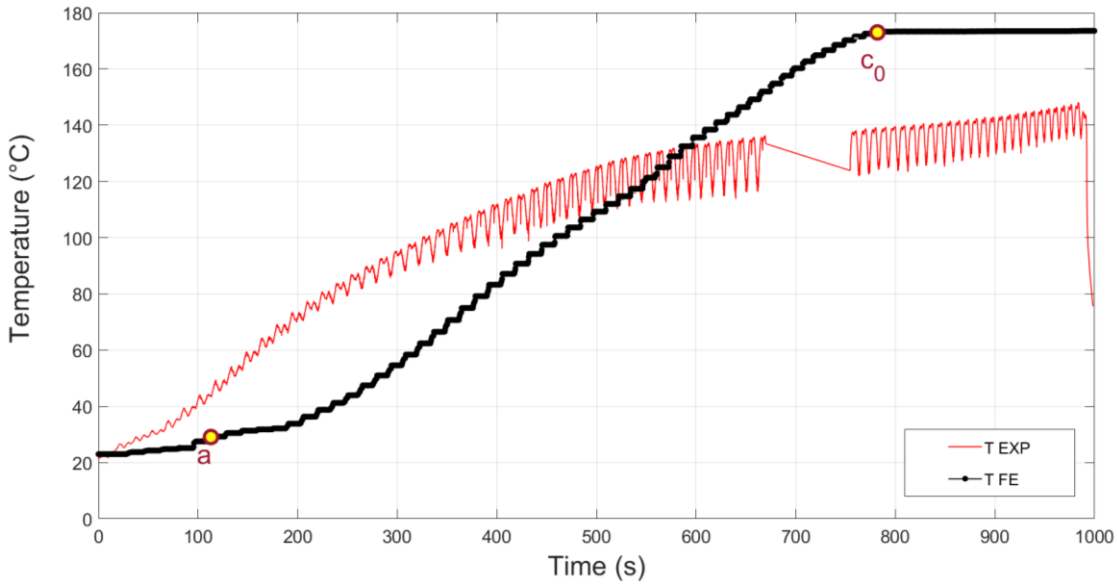


Fig.9.15. Temperature evolution during the process

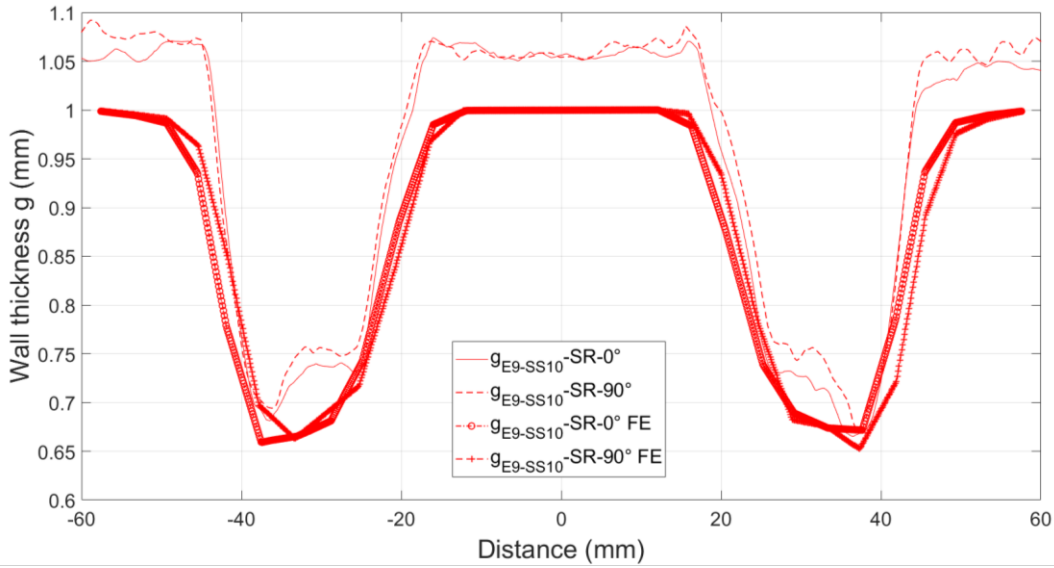


Fig.9.16. Comparison of the evolution of the thickness of the walls of the part, obtained by simulation and scanning – SS10

Analysis of the results when machining with the SS5 tool

The processes that take place are similar to those in machining with the SS10 tool, but greater variations in the forces obtained from the simulation can be observed. This significant difference from the results obtained in the simulation of machining with the SS10 tool is due to the fact that the SS5 tool has a much smaller contact surface with the metal sheet, and the discretization elements used for the metal sheet were relatively large in comparison (the same discretization elements were used as for machining with the SS10 tool).

The two temperatures, from the simulation and the experiment, were determined in the same way as for machining with the SS10 tool. The temperature evolution obtained by simulation is relatively similar to that determined experimentally, but the maximum value obtained from the simulation is very close to that obtained experimentally.

As with machining with the SS10 tool, a similar evolution of these thicknesses can be observed: in the flange area and in the center of the truncated cone, where the metal sheet was not deformed, the thickness value is approximately 1 mm (a value corresponding to the thickness of the initial undeformed metal sheet); in the area of the inclined walls, the thickness of the part walls is smaller (due to their thinning), and the values obtained by simulation are close to those determined by the scanning technique.

Chapter 10. *Comparative analysis of the researched incremental plastic deformation processes*

In order to highlight the advantages and disadvantages of using the three tools for the incremental plastic deformation of the target part, a comparative analysis was performed in relation to the results of the studied process. This also includes published elements by the author [B03].

Processing force

The evolution of the processing forces in the Z direction, Fz, during incremental plastic deformation with the three tools used, namely: tool with a hemispherical head with radius R=10mm – SS10, tool with a hemispherical head with radius R=5mm – SS5, and eccentric tool with variable radius – ETVR, is shown in Fig. 10.1.

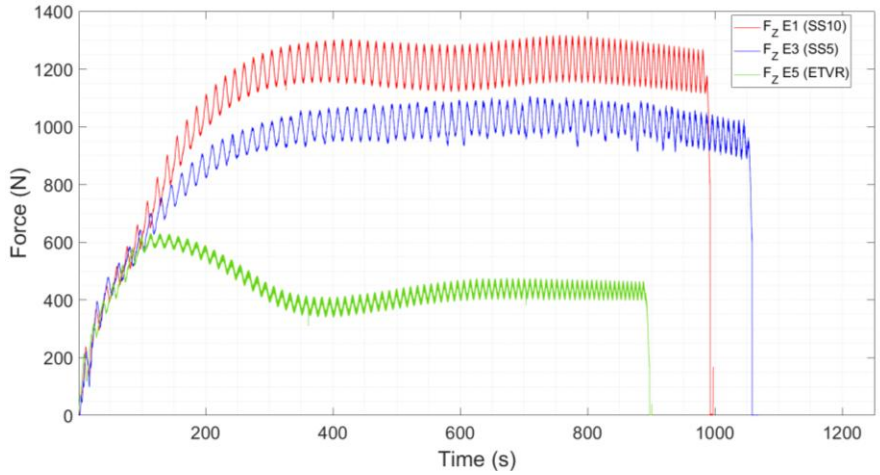


Fig.10.1. Evolution of machining forces in the Z direction when machining with - SS10 (E1) and hemispherical head tools and - SS5 (E3) variable radius eccentric tool - ETVR (E5)

The evolution of the machining forces Fz when using hemispherical tools is similar, consisting of a continuous increase at the beginning of the process, followed by stabilization at the maximum value. This evolution was correlated with the evolution of the theoretical surface area, respectively, the theoretical contact line between the tool and the semi-finished product (see §6.3). When machining with a hemispherical tool with a larger radius, the machining forces Fz are higher than when machining with a hemispherical tool with a smaller radius: Fz = 1315 N at E1-SS10, while at E3-SS5 Fz = 1105 N.

The evolution of the machining force Fz when using the ETVR variable radius eccentric tool differs from that of machining with hemispherical tools: at the beginning of machining, there is a similar increase in the force Fz – up to a maximum value, which is followed by a decrease in this force and stabilization in the second part of the process. The maximum value of the force Fz, approximately 625 N (at E5), is much lower than the maximum values of Fz when machining with hemispherical tools. The value of the force Fz in the stable part of the process is 460 N.

Processing temperature

The evolution of temperatures in the process during incremental plastic deformation with the three tools used is shown in Fig. 10.5. The evolution of the process temperature when using the SS10 (E1) and SS5 (E3) hemispherical head tools is quite similar, consisting of a continuous increase, followed by a tendency to stabilize towards the end of the deformation process. The maximum temperatures in the process are obtained with the hemispherical head tools: 145.1°C when machining with SS10 (E1), 148.3°C when machining with SS5 (E3), and 117.5°C when machining with ETVR (E5).

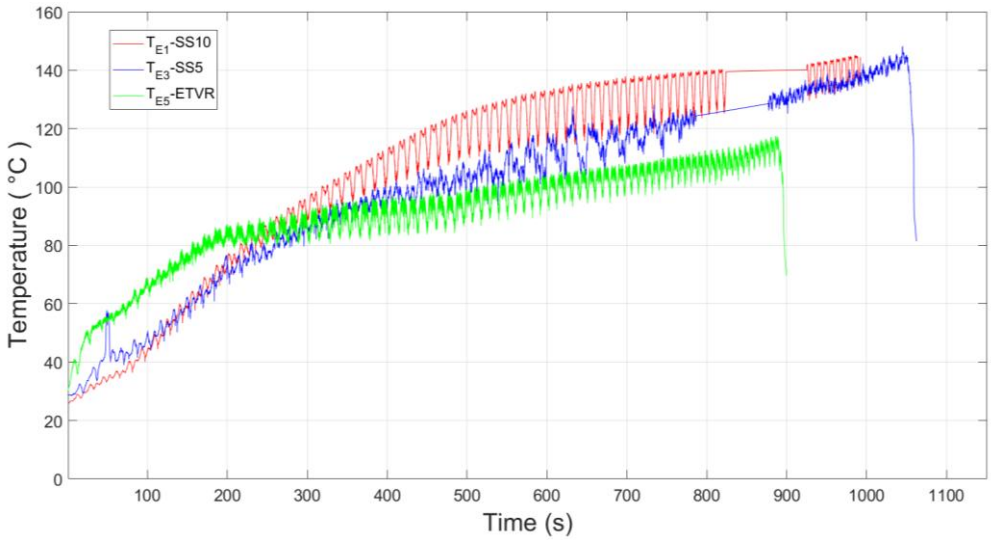


Fig.10.5. Temperature evolution during processing with SS10 (E1), SS5 (E3), and ETVR (E5) tools

Microchips and visual appearance of machined surfaces

- When machining with the SS5 (E3) tool, the largest amount of chips is produced at the end of the machining process. The chips are the largest in size, with variable dimensions (between 21 and 83 µm) and average dimensions of approximately 45 µm.

- When machining with the SS10 (E1) tool, the amount of chips present on the workpiece at the end of the process is lower than when machining with the SS5 tool, and their size is much smaller: between 7 and 18 µm, with average dimensions of approximately 12 µm.

- When machining with the ETVR tool (E5), the predominant chips are small, with sizes ranging from 2 to 51 µm and average sizes of 8 µm.

Geometry of machined parts

The variation in wall thickness of parts machined with the three rigid system tools (E7, E9, and E11) is shown in Fig. 10.6. The shape of these variations is similar, with the exception that machining with the SS5 tool leads to a relatively constant thinning on the inclined area of the cone trunk compared to the other two tools, which result in a thickness closer to 40 mm from the axis of the part.

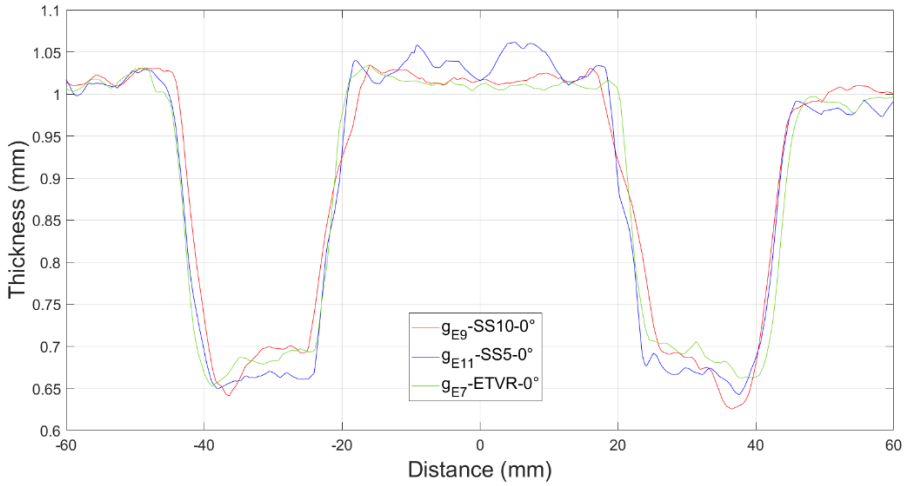


Fig.10.6. Variation in thickness of parts machined with SS10 (E7), SS5 (E9), and ETVR (E11) tools on a rigid system

The variation in deviation from the given shape of the profile of the workpieces machined with the three tools on the rigid system is shown in Fig. 10.8. The evolution and magnitude of these deviations are relatively similar, but there are also some differences between the machined parts, as highlighted below: the pillow effect is more pronounced when machining with the SS5 tool and is almost non-

existent when machining with the SS10 tool; the smallest profile deviation is obtained when machining with the SS5 tool, and the largest with the innovative ETVR tool, and the largest profile deviations are obtained at a distance of 40 mm from the axis of symmetry of the part.

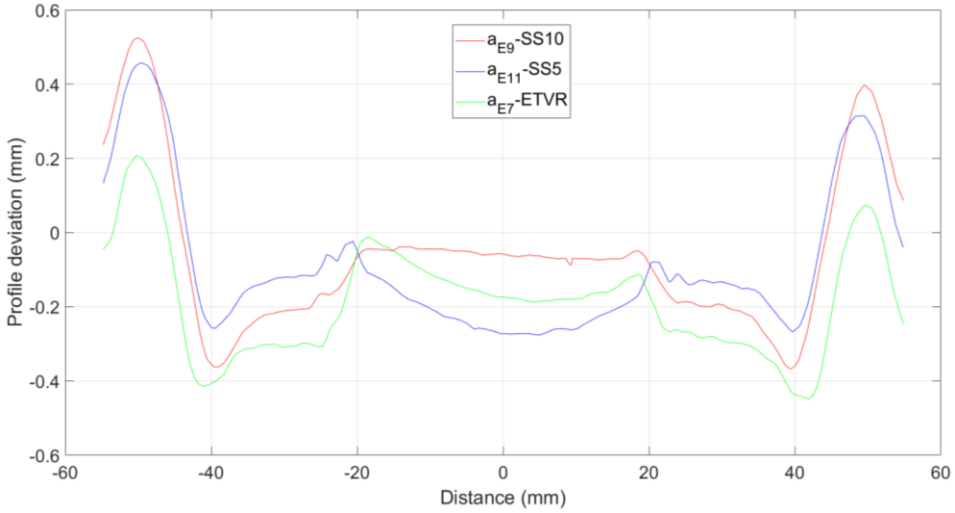


Fig.10.8. Variation in profile deviation of parts machined on a rigid system with tools – a) SS10 (E7), – b) SS5 (E9), and – c) ETVR (E11)

Roughness of machined surfaces

The experimental results showed a progressive increase in Ra roughness on the truncated cone generator (from base to tip) for all parts machined with the three tools, as shown in Fig. 10.10.

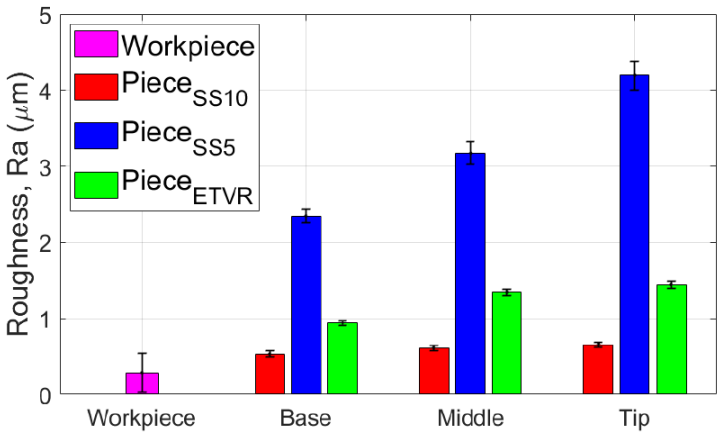


Fig.10.10. Average values of the roughness parameter Ra of the parts machined with the three tools

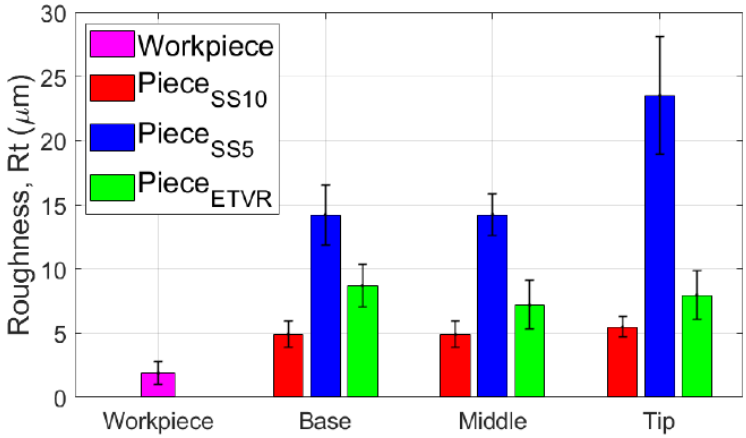


Fig.10.11. Average values of the roughness parameter Rt of the parts machined with the three tools

With regard to the Rt roughness parameter, the results differ significantly between the parts machined with the three tools, as shown in Fig. 10. 11: the SS5 tool resulted in the highest values of the roughness parameter Rt (over 25 µm in the tip area), reflecting deep scratches and channels caused by abrasive contact between the tool and the metal sheet and the accumulation of micro-chips; the

SS10 tool generated moderate values of the Rt parameter (~5–5.5 µm), with an oscillating evolution between areas: at the tip, a slight increase in Rt is observed due to the accumulation of micro-chips; the innovative ETVR tool led to intermediate results for the Rt parameter (average Rt between 7 and 9 µm), with a downward trend from the base to the middle and a slight recovery at the tip.

Microhardness of the surface layer of machined surfaces

The results obtained show that work hardening is stronger at the tip of the cone, due to the increase in the degree of local deformation towards the end of machining, Fig. 10.12.

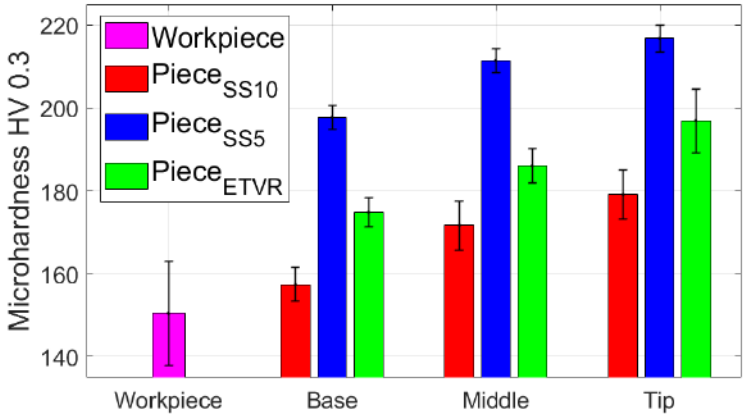


Fig.10.12. Average HV0.3 microhardness values of parts machined with the three tools

he highest microhardness values, and therefore also the highest work hardening values, were recorded when using the SS5 tool, with average values ranging from 197.7 HV at the base of the cone to 216.7 HV at its tip, with a variation of 19 HV along the cone's generator. The lowest microhardness values, and therefore also the lowest work hardening values, were recorded when using the SS10 tool, with average values ranging from 157.4 HV at the base of the cone to 179.1 HV at its tip, and with a variation of 21.7 HV along the generator of the truncated cone.

Machining with the ETVR tool resulted in average microhardness values intermediate to those obtained when machining with the SS10 and SS5 tools, respectively, with average microhardness values between 174.8 and 196.9 HV.

Influence of material anisotropy on roughness and microhardness

The average values of the Ra roughness parameter of SPIF machined parts show a general trend of increasing Ra roughness in the TD direction compared to the RD direction, but with some local exceptions, especially in the tip area of parts machined with the SS5 tool.

For the roughness parameter Rt of surfaces machined by SPIF, the differences between the average values measured in the two directions are even more evident. Since the Rt parameter is sensitive to extreme values (scratches, roughness), it had higher and more variable values on RD, due to the overlap of the tool marks with the rolled texture, and recorded more uniform values on TD, where the tool slid parallel to the spiral tool path.

In the case of HV microhardness, the values were generally higher on RD than on TD. This reflects a compaction of the grains aligned with the tool direction, the favorable orientation of plastic deformation for local work hardening, and the reduction of intergranular microcracks.

Correlated roughness-microhardness analysis

The analysis of these correlations leads to some conclusions relevant to the research undertaken: SPIF machining with the SS10 tool results in fine and uniform surfaces, but produces moderate work hardening of the material; SPIF machining with the SS5 tool results in rough surfaces, with possible extreme defects, but with intense material work hardening; SPIF machining with the ETVR tool results in surfaces that represent a compromise between surface quality and material work hardening.

Chapter 11. Final conclusions and main contributions to the development and numerical modeling of the incremental plastic deformation process

(1) From the critical analysis of the current state of research and development and industrial applications regarding incremental plastic deformation, important conclusions were drawn, presented in Chapter 3.

(2) Considering the data and conclusions from the analysis of the current state of incremental plastic deformation processes and systems, the research and development directions presented in §4.1 were considered to be promising.

(3) In relation to the current stage and directions of research and development regarding incremental plastic deformation processes and systems, the main objective of the research and development activity within the doctoral program (see also §4.2) has been determined as follows: *the development of the process and system for single-point incremental plastic deformation of AA6061-T6 aluminum alloy parts through theoretical and experimental research and numerical simulation.*

(4) The relevant conclusions regarding the doctoral research and development activity for achieving its main objective, in relation to the methodological reference points (see §4.3), are as follows.

• The modular device for orienting and fixing the metal sheet during incremental plastic deformation processing at a single point, developed as part of doctoral research (see §5.2.2), has a rigid and flexible construction that allowed the processing of parts under appropriate conditions, as well as simultaneous or separate measurement during processing of the processing force and temperature in the process (see §6.1).

• The innovative tool, called "Eccentric Tool with Variable Radius – ETVR," designed and developed during doctoral studies (see §5.2.2), has a variable contact surface with the metal sheet during the incremental plastic deformation process, depending on the minimum and maximum values of the variable radius of the active area, the angular position of the tool, and the position of the tool on the generation tool path (see §6.1).

• When machining with the larger radius hemispherical tool SS10, higher machining forces Fz result than when machining with the smaller radius hemispherical tool SS5: Fz = 1315 N and Fz = 1105 N, respectively. The maximum value of the force Fz when machining with the innovative tool – ETVR is the lowest, approximately 625 N, and in the stable part of the process it is 460 N (see chapter 10).

• The deformation forces in the horizontal plane (X and Y axis directions) are symmetrical and are determined by the lateral redistribution (in the horizontal plane) of the material during deformation and friction between the tool and the material. Their maximum value is lower than the maximum value of the deformation forces in the Z-axis direction (see §6.3).

• The evolution of deformation forces in the horizontal plane is characterized by an initial increase, associated with the elastic deformation zone, followed by a relatively constant evolution, associated with plastic flow. The stabilization of this evolution is correlated with the stabilization of the theoretical contact area/theoretical contact line length between the tool and the metal sheet (see §6.3).

• When machining with the larger radius hemispherical tool – SS10, the machining forces Fx and Fy are higher than when machining with the smaller radius hemispherical tool – SS5: Fx = Fy = 487 N, respectively, Fx = Fy = 397 N. The maximum value of the force Fx when machining with the innovative tool – ETVR is the lowest, approximately 111 N (see chapter 10).

• The temperature measured during the plastic deformation process increases continuously as a result of friction between the tool and the metal sheet, more intensely at the beginning of the process and more slowly afterwards, being correlated with the variation of the tool-metal sheet contact surface. The maximum temperatures reached at the end of the processes are: 145.1°C when machining with the SS10 tool, 148.3°C when machining with the SS5 tool, and 117.5°C when machining with the innovative tool. The maximum temperature when using the ETVR tool is the lowest, due to the intermittent contact between the tool and the metal sheet (see §6.4 and chapter 10).

• The validation of the methodology for determining the geometric accuracy parameters of the part was first performed by calculating the wall thickness for a numerically generated reference part with ideal 3D geometry. Statistical analysis of the results obtained revealed a deviation of less than 0.01 mm between the calculated values and the ideal values (see §7.2.2). The developed methodology was also validated by measuring the wall thickness of the machined parts with a micrometer. The minimum absolute differences between the two measurement methods are less than 0.01 mm at the base of the cone, and the maximum difference is approximately 0.02 mm (see §8.3).

• When machining parts by incremental plastic deformation with the three tools, very fine microchips are formed, which are detached from the machined metal sheet as a result of friction between the tool and the metal sheet (see §8.2). The dimensions of the microchips range from 7 to 18 μm when machining with the SS10 tool, from 21 to 83 μm when machining with the SS5 tool, and from 2 to 51 μm when machining with the innovative ETVR tool, and their average values are: 12 μm, 45 μm, and 8 μm, respectively (see §8.2 and Chapter 10).

• The minimum wall thickness values of the parts machined with the three tools are very similar: g = 0.67 when machining with the SS10 tool, g = 0.68 when machining with the SS5 tool, and g = 0.68 when machining with the ETVR tool (see §8.3). The workpieces machined with the SS5 and ETVR tools have a more uniform wall thickness across the entire conical area (see Chapter 10).

• The deviation from the given shape of the profile of the parts machined with the three tools has similar variations: the minimum values are in the area of the retaining ring (base of the cone trunk) and the tip of the cone trunk, where the deformation of the material is also minimal, and the maximum values are in the conical area of the part, at a diameter of ∅40. The largest deviations from the given shape of the workpiece profile result from machining with the innovative tool – ETVR, of 0.45 mm, followed by those from machining with the SS10 tool, 0.37 mm, and those from machining with the SS5 tool, 0.26 mm (see §8.3 and chapter 10).

• The Ra roughness increases progressively along the truncated cone generator, from the base to the tip, on all parts machined with the three tools. The intensity of this increase depends on the tool geometry: Ra = 0.532 – 0.66 μm when machining with SS10, Ra = 0.939 – 1.444 μm when machining with ETVR, and Ra = 2.346 – 4.194 μm when machining with SS5 (see §8.4 and Chapter 10).

• The roughness Rt of the parts highlights the deep scratches and roughness on the machined surfaces, which are correlated with the sizes of the micro-chips generated by the tools. Thus, the highest Rt values resulted from machining with the SS5 tool - Rt over 25 μm in the tip area, followed by

machining with the ETVR tool - average Rt between 7 and 9 μm, and the lowest values resulted from machining with the SS10 tool - Rt ~5–5.5 μm (see §8.4 and Chapter 10).

• The highest microhardness values, and therefore the highest work hardening values, were obtained when using the SS5 tool – HV = 197.7 HV - 216.7, and the lowest microhardness values were obtained when using the SS10 tool – HV = 157.4 HV - 179.1 HV. Machining with the ETVR tool led to average microhardness values intermediate to those obtained when machining with the SS10 and SS5 tools, respectively, to average microhardness values between 174.8 and 196.9 HV (see §8.5 and Chapter 10).

• The forces obtained through simulation are very similar in shape to those determined experimentally, but the maximum values obtained through simulation are higher than those determined experimentally. The causes of these differences are determined by the use of the mass scaling strategy to reduce simulation time, the description of thermo-mechanical behavior with the Johnson-Cook law did not allow accurate modeling for all temperatures, the use of a constant value for the friction coefficient, and material anisotropy (see §9.3).

• The temperature evolutions obtained through simulation are relatively similar to those determined experimentally, but the maximum values obtained through simulation are higher than those determined experimentally. The causes of these differences are determined by the adiabatic approach used in this model, which does not allow for the integration of the thermal conduction phenomenon; the use of oil lubrication in experiments, which leads to a different temperature distribution than in the case without lubrication used in the simulation; the use of a constant friction coefficient and a fixed fraction of conversion of mechanical work into heat (see §9.3).

• The wall thickness developments of the parts obtained through simulation have similar shapes to those determined experimentally. In the area of the inclined walls of the part, the values obtained through simulation are close to those determined through the scanning technique. The values in the undeformed areas, determined by scanning, are higher than those in the simulation, which is due to the fact that anti-reflective powder was applied to the surface of the part, and its thickness influences the thickness of the final part (see §9.3).

• The measurement of roughness parameters Ra and Rt, respectively microhardness HV in the rolling direction RD, respectively in the transverse direction of the metal sheet and the machined parts, highlighted the existence of their anisotropy. Therefore, it is considered that the orientation of the metal sheet in relation to the shape of the part to be produced is not a minor detail, but an important experimental parameter that must be analyzed, controlled, and integrated into the machining strategies (see Chapter 10).

• here was a noticeable trend of increasing average roughness Ra with increasing microhardness HV, which is fairly linear. The more pronounced roughness of the machined surface (high Ra) reflects a more severe deformation of the material in the surface layer of the part, associated with grain deformation and increased microhardness (see Chapter 10).

• The roughness parameter Rt tends to increase with increasing HV microhardness, but the linearity of this dependence is no longer valid for parts machined with the SS5 tool. This is explained by the fact that deep scratches appear when machining with the SS5 tool, which do not necessarily lead to work hardening, therefore the increase in HV is not proportional to the increase in Rt (see chapter 10).

(5) By fulfilling the main objective of doctoral research and development activities, the doctoral thesis makes a number of contributions, the most relevant of which are highlighted below.

• Conducting a critical study on the current state of research and development and industrial applications related to incremental plastic deformation processes and systems.

• Development of a modular device for orienting and fixing metal sheet for single-point incremental plastic deformation processing, which allows the processing of parts of different sizes, as well as simultaneous or separate measurement of the processing force and temperature during processing..

• Development of an innovative tool called "Eccentric Tool with Variable Radius – ETVR", which creates a variable contact surface with the metal sheet during the incremental plastic deformation process and combines the advantages of small and large hemispherical head tools, as well as flat head tools.

• Development of an experimental methodology for determining the geometric accuracy of machined parts, using three-dimensional scanning and data processing in Matlab.

• stablishing, through theoretical and experimental research, the influence of the geometry of the active area of three tools, two tools with hemispherical heads of different radii and the innovative ETVR tool, on the process parameters of machining force and machining temperature and on the quality of the machined parts, assessed by the deviation from the given shape of the part profile, the thickness of the part walls, the visual appearance and the roughness parameters Ra and Rt of the surfaces, the microhardness HV of the surface layer of the part.

• Development of a valid numerical model using the ABAQUS Explicit program to simulate the incremental plastic deformation process with hemispherical head tools. The simulations performed allowed for an in-depth analysis of the incremental plastic deformation processes performed with the two hemispherical head tools.

• Performing comparative analyses of incremental plastic deformation processes with the three tools, based on the process parameters and quality indicators of the evaluated parts.

* * *

Through its subject matter, approach, and results, the doctoral thesis develops knowledge of incremental plastic deformation processes and systems.

The scientific importance of this doctoral thesis lies in its contributions to theoretical and experimental research on incremental plastic deformation processes and systems at a single point.

The practical importance of this doctoral thesis lies in the fact that the research and development methodology, models, and working methods specific to incremental plastic deformation processes and systems, as well as the results of the research carried out, represent a system support system useful to students in technological specializations, teachers and researchers, specialists and industrial organizations, as appropriate.

Future research directions related to the doctoral thesis topic may include: considering other materials with different ductilities for testing the innovative tool; comparative study of the deformability of AA6061-T6 alloy or other materials with the innovative tool and tools with a hemispherical head; extending the comparative study by varying the technological parameters of the process to identify possible synergies between them and the geometry of the active part of the tool; continuing the development of numerical models, including for the innovative tool.

List of published works resulting from scientific research within the doctoral program

I. WORKS PUBLISHED IN ISI INDEXED JOURNALS

1) *Innovative Tool for Improving Surface Quality in SPIF: A Comparison Between Hemispherical and Variable-Radius (ETVR) Tools*, **Emanuel Bădulescu,** Eduard Laurenţiu Nițu, Daniela Monica Iordache, Claudiu Bădulescu.

Jurnal: Materials – MDPI, 18, 4275, 2025. https://doi.org/10.3390/ma18184275; *WOS*: în curs de indexare.

Paper published in a journal indexed in ISI Web of Science, Impact Factor 3,2 - JCR - Q2 (Metallurgy and Metallurgical Engineering) / CiteScore - Q1 (Condensed Matter Physics)

2) *Research on the Numerical Modeling of the Incremental Plastic Deformation Process Using a Hemispherical Tool*, **Emanuel Bădulescu**, Daniela Monica Iordache, Eduard Laurenţiu Nițu, Claudiu Bădulescu.

Jurnal: Paper accepted for publication in ACTA TECHNICA NAPOCENSIS, Applied Mathematics, Mechanics, and Engineering, vol. 68, Issue Special I, 2025; WOS: in the process of being indexed. (Paper presented at International Conference on Integrated Engineering - CIE/C2I 2025, 5-6 may 2025, Timișoara).

3) *Robust Noncontact Scanner Measurement Strategy to Detect the Shape and the Thickness of Single Point Incremental Forming Parts*, **Emanuel Bădulescu,** Yannick Argouarc'h, Eduard Laurenţiu Nițu, Daniela Monica Iordache, Claudiu Bădulescu.

Jurnal: International Journal of Advanced Manufacturing Technology, work under evaluation.

II. WORKS PUBLISHED IN BDI INDEXED JOURNALS

1) *Tools for the incremental deformation of sheet metal using a single point: presentation of an innovative new tool*, **Emanuel Bădulescu,** Eduard Laurenţiu Nițu, Daniela Monica Iordache.

Jurnal: Materials Research Proceedings 46, 291-299, 2024. https://doi.org/10.21741/9781644903377-38 (Paper presented at International Conference on Innovative Manufacturing Engineering and Energy - IManE&E2024, 23-25 oct 202a, Athens)

III. PARTICIPATION IN INTERNATIONAL CONFERENCES

1) International Conference on Innovative Manufacturing Engineering and Energy - IManE&E2024, 23-25.10.2024, Athens (online participation)*:*

Tools for the incremental deformation of sheet metal using a single point: presentation of an innovative new tool, **Emanuel Bădulescu,** Eduard Laurenţiu Nițu, Daniela Monica Iordache.

2) International Conference on Integrated Engineering - CIE/C2I 2025, 5-6 may 2025, Timișoara (online participation):

Research on the Numerical Modeling of the Incremental Plastic Deformation Process Using a Hemispherical Tool, **Emanuel Bădulescu**, Daniela Monica Iordache, Eduard Laurenţiu Nițu, Claudiu Bădulescu.

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[B02] **Bădulescu E.,** Iordache D. M., Nițu E. L., Bădulescu C., *Research on the Numerical Modeling of the Incremental Plastic Deformation Process Using a Hemispherical Tool*, lucrare susţinută la International Conference on Integrated Engineering - CIE/C2I 2025 , Timisoara, Romania, May 5-6, 2025, acceptată spre publicare în ACTA TECHNICA NAPOCENSIS, Vol. 68, Issue Special I, Series: APPLIED MATHEMATICS, MECHANICS, AND ENGINEERING

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