WWW.RSTJOURNAL.COM
SUPPLEMENT 1/2019
ISSN-E: 2344-0007 / ISSN-L: 2344-0007

Engineering

THE REVIEW OF THE ACHIEVEMENTS IN THE FIELD OF INCREMENTAL FORMING

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ABSTRACT:
INCREMENTAL FORMING PROVIDES SIGNIFICANTLY HIGHER FLEXIBILITY OF FORMING IN COMPARISON TO CONVENTIONAL FORMING PROCESSES. SINGLE POINT INCREMENTAL FORMING (SPIF) REPRESENTS THE MOST SIMPLE FORM OF INCREMENTAL FORMING, WHERE FORMING OF THE SHEET METAL IS ENABLED USING A WIDE VARIETY OF TOOLS. THE MAIN DISADVANTAGE OF INCREMENTAL FORMING IS LOWER ACCURACY OF FORMING COMPARED TO OTHER CONVENTIONAL PROCESSES. THE AIM OF MANY STUDIES IN THE PAST REGARDING INCREMENTAL FORMING WAS TO INCREASE THE ACCURACY, REDUCE FORMING FORCES AND IMPROVE THE FORMABILITY OF THE SHEET METAL. THIS ARTICLE COVERS SUMMARIES OF STUDIES REGARDING INNOVATIVE APPROACHES TO IMPROVE ALL OF THE ABOVE-MENTIONED ASPECTS OF INCREMENTAL FORMING. IT ALSO ATTEMPTS TO PRESENT THE MAIN PARAMETERS OF INCREMENTAL FORMING AND THEIR INFLUENCE ON THE CHARACTERISTICS OF THE FORMED PRODUCT. IT IS ALSO DISCUSSED, WHY THE FORMABILITY IN INCREMENTAL FORMING IS SIGNIFICANTLY HIGHER THAN THAT OF CONVENTIONAL FORMING PROCESSES, SUCH AS STAMPING. A NUMBER OF OTHER INCREMENTAL FORMING APPROACHES AND THEIR MAIN CHARACTERISTICS ARE PRESENTED, AS ARE AREAS OF INCREMENTAL FORMING IN TODAY'S INDUSTRY AND AREAS OF POSSIBLE IMPROVEMENT IN THE FUTURE.

KEY WORDS: SINGLE POINT INCREMENTAL FORMING, FORMABILITY, GEOMETRIC ACCURACY, TECHNOLOGY ASSESSMENT

INTRODUCTION

The requirements for more flexible production of sheet metal parts dictated the development of new unconventional forming processes. One such process is also single point incremental forming (SPIF). The latter enables forming of the initial sheet metal step by step into

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desired shape[3]. The tools, of various shapes, are usually installed on the CNC machine, which is shown in (Figure 1). The mentioned process is slow compared to other conventional sheet metal forming processes, which produce a part of a similar shape (e.g. deep drawing). But on the other hand it allows higher flexibility in forming, because the equipment used may stay unchanged for various formed shapes.

Machines that can be used in incremental forming are usually CNC milling machines, robots or specially designed devices. The main advantage of robots is their flexibility and larger working area. They also have many disadvantages, such as enabling smaller maximum forces, less precise positioning of the tool and thus less precise forming process. On the other hand, CNC machine is a better choice if we reach higher forces during forming, as they have higher stiffness. CNC machine also enables an easy mounting of holding frame, which allows fixing of the sheet metal, on its working table.

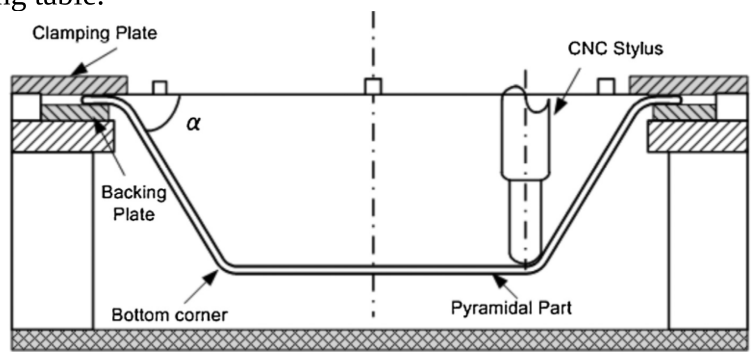

Figure 1: Schematic representation of single point incremental forming (SPIF)[4]

When in contact with the tool, the sheet is being formed in the desired shape and simultaneously also thinning. Excessive thinning of the sheet metal leads to its rupture, which indicates the forming limit. The failure of the sheet metal occurs at a maximum wall angle, which is affected by the material selection, the initial sheet thickness and numerous other forming parameters, among which the diameter of the tool and the forming step can be highlighted. In comparison to other processes, the main limitation of incremental forming is the shape of the formed part, more specifically its wall angle. However, the tearing of sheet metal can also be influenced by other design features, such as quick transitions in wall orientation, forming of narrow channels or small radii in the corner[5]. In addition to certain design constraints of products formed with incremental forming, we can also point out an additional limitation of incremental forming that is the long production time of one piece, which is longer than that of conventional processes[6,7].

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[3] Behera, Amar Kumar et al.; *Single point incremental forming: An assessment of the progress and* technology *trends from 2005 to 2015*, School of Mechanical Engineering, University of Leeds, 2017;
[4] Behera, Amar Kumar et al.; *Single point incremental forming: An assessment of the progress and*
[5] Afonso, Daniel et al.; *Integration of design rules and process modelling within SPIF technology-a review on the industrial dissemination of single point incremental forming*, Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, 2017;
[6] Jeswiet, Jack; *Single point and asymmetric incremental forming*, Department of Mechanical and Materials Engineering, Queen's University, 2015;
[7] Petek, Aleš et al.; *Economical and ecological aspects of single point incremental forming versus deep drawing technology*. Aedermansdorf: Trans Tech Publications, 2007, vol. 344, p. 931-938;

ISSN-E: 2344-0007 / ISSN-L: 2344-0007

TECHNOLOGY OVERVIEW

Single point incremental forming (SPIF) does not need a die, which means a more cost efficient solution of forming and a more flexible approach to forming of many different types of products without changing the required equipment. In the case of SPIF, the sheet of the material must be clamped and properly supported, as this prevents its movement, thereby reducing the inaccuracy of the forming process[8]. One of the main problems of this forming process is its inaccuracy. The latter is influenced by parameters such as sheet thickness, the slope of the wall, the depth of the forming step and also the size of the tool. By reducing the depth of the step, in any case, we have a positive effect on the accuracy. The latter can be improved by using smaller tools in the case of larger wall angles and using larger tools in the case of smaller wall angles[9]. To improve the accuracy, the thickness of the sheet metal and the forming force must be appropriately controlled during the forming process[10]. The type of sheet metal, with its mechanical properties, directly influences the value of the forming force[11]. We should not neglect the influence of the thickness of the used sheet metal or the size of the tool. The increase in both the thickness of the sheet metal or the size of the tool increases the value of the forming force[12]. The latter also depends on a number of other process parameters, among others on the wall angle. The maximum value of the wall angle, before the fracture occurs, is in the literature often equated with the formability of a particular material. With a reduction of tool diameter and depth of the increment step the formability of the process can be increased. The latter is also affected by sheet thickness and the material type. In addition to increasing the formability, we also want to improve the surface roughness, which is again under great influence of the tool diameter, step depth and also the type of the material being formed[13]. By increasing the step depth the surface hardness can also be increased. Additional, increase of feed rate of the used tool also has a significant effect on the increase of the surface hardness of the final product[14].

The forming of sheet metal in incremental forming is limited by a fracture that occurs at a specific wall angle. In the literature the maximum wall angle that can still be reached before fracture is often equated to formability. The formability in incremental forming is influenced by numerous process parameters, including the selected sheet material. In order to determine the formability of the particular material or to determine the effects of specific parameters on formability itself, incremental forming of specially designed test pieces is conducted. Such tests

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[8] Bansal, Ankush et al.*; Prediction of forming forces in single point incremental forming,* Department of Mechanical and Aerospace Engineering, Indian Institute of Technology Hyderabad, India, 2017;

[9] Hussain, Ghulam et al.*; Improving profile accuracy in SPIF process through statistical optimization of forming parameters,* College of Mechanical & Electrical Engineering, Nanjing University of Aeronautics and Astronautics, China, 2010;

[10] Bansal, Ankush et al.*; Prediction of forming forces in single point incremental forming,* Department of Mechanical and Aerospace Engineering, Indian Institute of Technology Hyderabad, India, 2017;

[11] Aerens, Richard et al.; *Advances in force modelling for SPIF.*, Catholic University of Leuven, Belgium, 2009;

[12] H. Mostafanezhad et al.; *Optimization of Two-point incremental forming process of AA1050 through response surface methodology,* Measurement, Accepted manuscript, 2018;

[13] Mulay, Amrut et al.; *Experimental investigations into the effects of SPIF forming conditions on surface roughness and formability by design of experiments,* Mechanical Engineering Department, National Institute of Technology, India, 2016;

[14] Mulay, Amrut et al.; *Performance evaluation of high-speed incremental sheet forming technology for AA5754 H22 aluminum and DC04 steel sheets,* Mechanical Engineering Department, National Institute of Technology, India, 2017;

include incremental forming of conical or pyramidal parts with specified wall angle values, that are shown in (Figure 2-a) and (Figure 2-b). The wall angle is gradually increased for each further test piece with a fixed wall angle until the formed sheet is torn. In order to shorten the testing procedure a test piece with changing wall angle can be used, the geometry of which is shown in (Figure 2-c). In the latter geometry, we simply measure the formed part depth where the fracture occurs and determine the wall angle at this depth, which is shown in (Figure 2-c)[15].

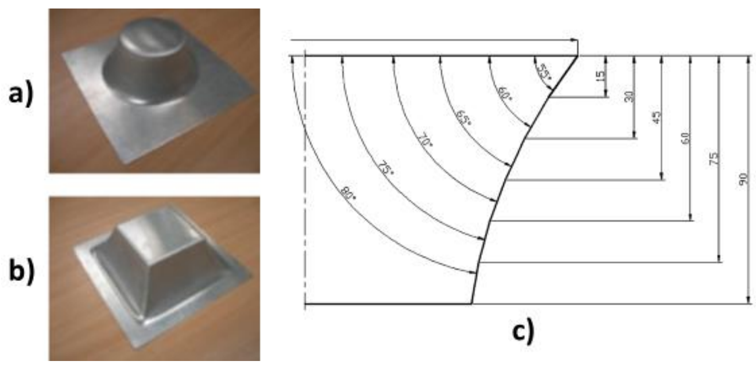

Figure 2: a) Truncated conical shape, b) truncated pyramidal shape and c) geometry of a cross section with variable wall angle used on shapes a) or b)[16]

In the case of SPIF process, the fracture occurs in two possible ways. According to the literature[16,17], localization can occur prior to the break or a tear occurs without prior localization. For tools with a diameter larger than 15 mm localization occurs and consequently there is a drop of the formability level[16]. The difference in failure mechanism is the main reason for the larger formability of SPIF compared to conventional forming processes like stamping. With SPIF forming the delamination of laminated materials is reduced[18] due to localized deformation under relatively small tool. The latter was shown in the study by Al-Ghamdi and Hussain[19], where a comparison was made between SPIF forming and stamping of the steel-Cu composite, the components of which were merged with rolling.

Formability can also be increased by local heating of the sheet metal[18]. The easiest way to achieve this is by rotating the tool. In the study by Buffa et al.[20] the temperature of the sheet metal was increased by increasing the tool rotational speed, which also increased the formability or the maximum wall angle of all formed parts. **Error! Reference source not found.** shows a diagram o

[15] Silva, Maria B. et al; *Failure mechanisms in single-point incremental forming of metals,* Mechanical Engineering Department, Instituto Superior Tecnico, TULisbon,, 2010;

[16] Silva, Maria B. et al; *Failure mechanisms in single-point incremental forming of metals,* Mechanical Engineering Department, Instituto Superior Tecnico, TULisbon,, 2010;

[17] Petek, Aleš; *The definition of stable technological window by incremental sheet metal forming: dissertation.* Ljubljana: [A. Petek], 2008, p. 139;

[18] Petek, Aleš et al.; *Particularities of an incremental forming application in multi-layer construction elements.* Strojniški vestnik, 2009, vol. 55, no. 7/8, p. 423-426;

[19] Al-Ghamdi, Khalid and Hussain, Ghulam; *On the comparison of formability of roll-bonded steel-Cu composite sheet metal in incremental forming and stamping processes,* Department of Industrial Engineering, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia, 2016;

[20] Buffa, Gianluca et al.; *On the improvement of material formability in SPIF operation through tool stirring action*, Department of Chemical, Management, Computer Science and Mechanical Engineering, University of Palermo, 2012;

f rotational speed of the tool in correlation with the maximum draw angle at the fracture for a conical test piece formed from aluminium 6082-T6.

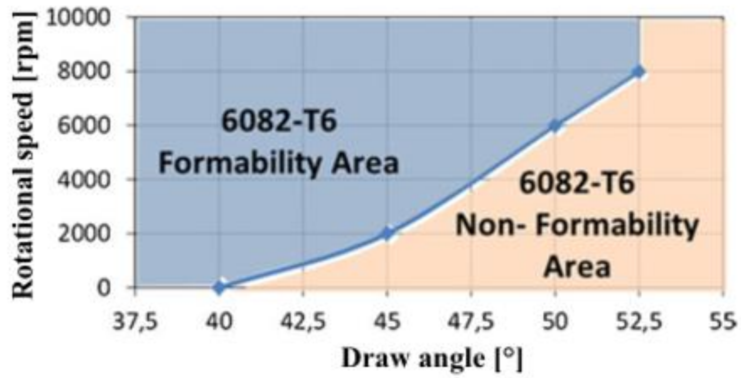

Figure 3: Formability limit curve for AA6082-T6[20]

As the main reason for increasing the formability or the maximum angle with increase in the rotational speed of the tool, dynamic recrystallization was exposed. This results in the decrease in grain size following by the consequential drop in micro hardness, which is one of the weaknesses in this approach of improving the formability. By rotating the tool during SPIF forming, in addition to formability, we can also influence roughness, as demonstrated in the study by Liu et al.[21]. From the results of the mentioned study it is clear that with increasing tool rotational speed roughness always improves compared to the state of the surface of the part formed without tool rotation. The SPIF forming always worsens the surface roughness compared to the initial sheet metal.

Preheating of the sheet metal prior to the process has similar effect as the rotation of the tool analysed by Shrivastava et al.[22], where aluminium alloy AA1050 was preheated to different temperatures. Increasing the temperature of the preheating process improves the geometric accuracy of the manufactured workpiece and reduces the wall thickness. Generally, by the material heating a reduction of the forming force is achieved. The latter is valid regardless of whether local warming or preliminary global warming of the entire sheet is carried out[22].

[21] Liu, Zhaobing; *Friction stir incremental forming of AA7075-O sheets: investigation on process feasibility, School of Mechanical and Electronic Engineering*, Wuhan University of Technology, China, 2017;
[22] Shrivastava, Parnika; *Improvement in formability and geometrical accuracy of incrementally formed AA1050 sheets by microstructure and texture reformation through preheating, and their FEA and experimental validation*, Department of Mechanical Engineering, PDPM Indian Institute of Information Technology, India, 2018;

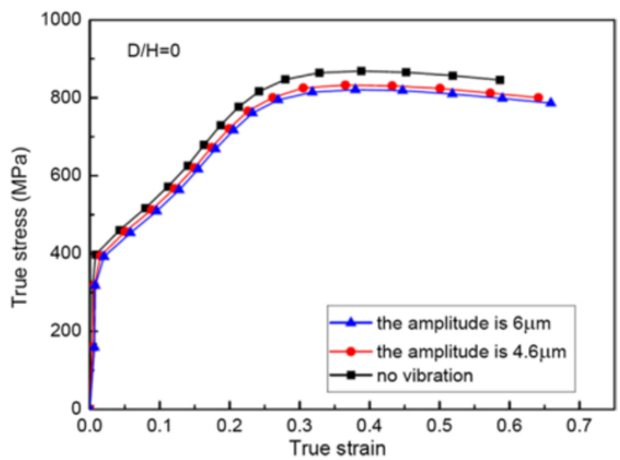

Figure 4: True stress-strain curves obtained with standard compression tests of pure titanium samples[23]

Material formability can also be improved by supplementing ultrasound vibrations during the forming process. Liu et al.[23] made a study on the effect of ultrasound vibration on the friction and deformation resistance during standard compression test of pure titanium samples. As shown in (**Error! Reference source not found.**), the increase in the amplitude of the vibration causes the d ecrease in flow stress and also yield stress, but minimally affects elastic deformations. The increase in the vibration amplitude also influences the reduction of the average grain size, but on the other hand has a minimal effect on the temperature rise inside the material.

Ultrasound vibrations can also be used in the field of SPIF forming to increase the formability. In the study by Li et al.[24] the SPIF forming with ultrasound tool vibrations was achieved with a specially designed module providing the ultrasound vibrations. The module was mounted between the CNC machine and the tool. Numerical analyses with Abaqus software package delivered diagrams (Figure 3) showing the influence of the vibration amplitude and vibration frequency on the axial force during forming. From the diagram (Figure 3-a) it is evident that the axial force decrease until the frequency of 40 kHz and starts to rise again. The reason for the increase of the axial force is rapid tool hitting against the material and consequential material vibration. Similarly, the influence of the vibration amplitude is evident on (Figure 3-b). The latter diagram is obtained with a simulation of the SPIF forming process with a fixed frequency of vibration of 20 kHz. Despite the tool vibrations the influence of the tool size on the formability remains as well. The study of Li et al.[25] shows the influence of the tool size and the tool vibration frequency on the perpendicular force according to the part forming in the SPIF process with the

[23] Liu, Tao et al.; *Effects of ultrasonic vibration on the compression of pure titanium*, Key Laboratory for Liquid-Solid Structural Evolution & Processing of Materials (Ministry of Education), Shandong University, China, 2018;
[24] Li, Pengyang; *Evaluation of forming forces in ultrasonic incremental sheet metal forming, Evaluation of forming forces in ultrasonic incremental sheet metal forming*, China, 2017;
[25] Li, Yanle et al.; *Effects of ultrasonic vibration on deformation mechanism of incremental point-forming process*, School of Mechanical Engineering, Shandong University, China, 2017;

ISSN-E: 2344-0007 / ISSN-L: 2344-0007

additional ultrasound vibrating of the tool. It can be seen, that with a larger tool the vertical forces are larger, when there is no added vibration. When the vibration amplitudes are large enough, we achieve larger vertical forces with a smaller tool compared to a larger one. The value of the amplitude, where the reversal occurs, depends on the material being formed.

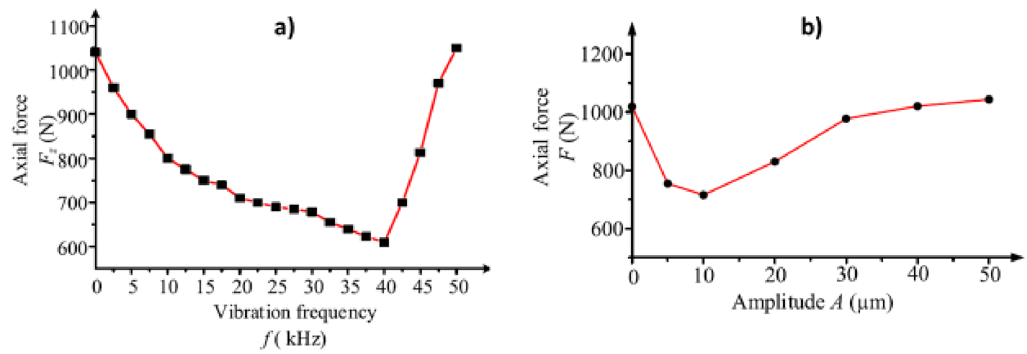

Figure 3: a) Values of the mean axial force at different vibration frequencies and b) values of mean axial force at different vibration amplitudes[26]

In the study by Lu et al.[27] the vibration due to the rotation of the tool was investigated on the magnesium sheet. SPIF forming was performed using three basic tools. Figure 4-a shows a classical hemispheric tool with a diameter of 5 mm, that does not cause vibration while rotating and is used for comparison with newly developed tools. The new tool, shown on (figure 4-b), has a diameter of 4.5 mm and an offset from the rotational axis by 0.5 mm. While rotating, the latter tool provides cyclic hitting on the surface of the material and thus ensuring vibration. Inside the study they also developed a tool with an elliptical head, shown in (Figure 4-c). With such type of tool, that hits the sheet twice per rotation, the frequency of the vibration can be increased. With this the value of the horizontal force was reduced during forming and, above all, the temperature.

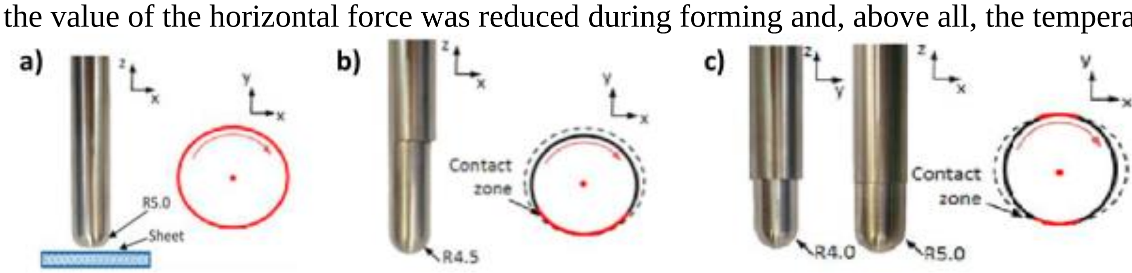

Figure 4: *Three types of forming tools used: a) conventional hemispheric tool, b) single-offset tool and c) dual-offset tool*[27]

In order to improve design accuracy of the product obtained with SPIF forming, we can resort to multi-stage SPIF forming. Thus, with a larger number of tool passages, we gradually change the shape and thus achieve the desired angle of the walls with better accuracy. Furthermore,

[26] Li, Pengyang; *Evaluation of forming forces in ultrasonic incremental sheet metal forming, Evaluation of forming forces in ultrasonic incremental sheet metal forming*, China, 2017;
[27] Lu, Bin et al.; Microstructure refinement by tool rotation induced vibration in incremental sheet forming, Department of Mechanical Engineering, The University of Sheffield, United Kingdom, 2017;

at the same time more even distribution of sheet metal thickness is achieved. In addition to the larger number of tool passages of SPIF, a specific stage can also be replaced with other forming processes. Thus, in the study by Shamsari et al.[28] the authors present a hybrid two-stage SPIF forming process, where the first stage of the forming is represented by hydraulic bulging of the sheet metal and the second stage by classical SPIF forming process. As shown in (Figure 5), with the first stage of forming the required height of the dome is achieved by applying the required pressure. The dome is then turned before the start of stage two of the forming process, properly re-clamped and formed into specific shape.

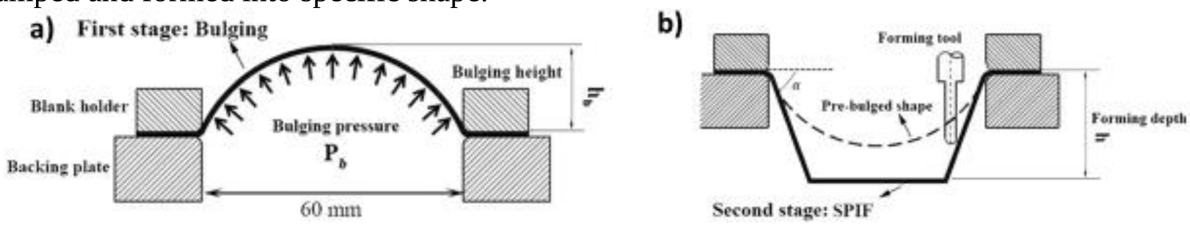

Figure 5: *Two forming stages in the hybrid two-stage incremental forming process: a) hydraulic bulging and b) subsequent SPIF forming*[28]

With the hybrid two-stage forming, a greater depth of forming and better sheet thickness distribution in the wall area of the product are achieved compared to one-stage or even conventional two-stage SPIF forming[28]. The main weakness of the hybrid two-stage SPIF forming is the convex bottom surface after bulging, which limits the use of the presented process combination. In general, the multi-stage SPIF forming enables an improvement in formability in terms of attainable wall angles and also forming depths, but with this approach we may strongly influence the time and consequently the price of forming.

In addition to workpiece warming, the precision of formed SPIF products can also be improved by appropriate subsequent cooling. In a study by Ambrogio et al.[29] the SPIF forming process with induction heating and addition of cryogenic cooling with liquid nitrogen of formed pieces was carried out on titanium alloy Ti-6Al-4V. Cryogenic cooling reduces the elastic springback of the unclamped sheet and with this better accuracy of the forming process is achieved. Figure 6 shows a comparison of the geometric accuracy for the test piece formed with and without added cryogenic cooling and their deviation from the ideal profile.

[28] Shamsari, Mohsen et al.; *Formability improvement in single point incremental forming of truncated cone using a two-stage hybrid deformation strategy*, Mechanical Engineering Department, Babol Noshirvani University of Technology, Iran, 2017;
[29] Ambrogio, Giuseppina et al.; Induction heating and cryogenic cooling in single point incremental forming of Ti-6Al-4V: process setup and evolution of microstructure and mechanical properties, Department of Mechanical, Management and Manufacturing Eng, University of Calabria, Italy, 2016;

SPIF enables forming of both metals and polymeric materials. Marques et al.[30] presented forming of four polymeric materials, namely PET, PC, PA and PVC. Using standard bulging tests and tensile tests, general mechanical properties were determined and it was realized that PET has

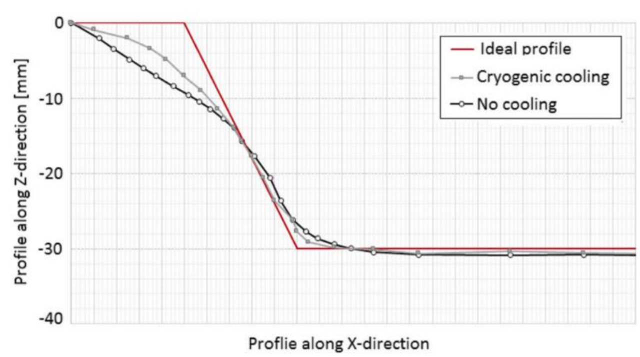

Figure 6: *Comparison of ideal profile and profiles of test pieces with and without cryogenic cooling*[31]

the best formability of all in the study tested materials. The latter was also confirmed by the classical SPIF forming tests, where the fracture of the cone made out of PET occurred at the wall angle of nearly 90°. Forming of polymeric materials is limited by the formation of cracks on the periphery of the product or by wrinkling on its bottom radius being similar to metallic materials. The SPIF forming of polymeric materials may change their density, which is not the case in forming of metals. The latter characteristic is a major problem with PVC products, where the density drops as the wall angle of the product increases. When processing polymers, the wall of the product can also become completely white. This is connected with the aggregation of cracks inside the polymer. Maximum attinable wall angle for polymer products is similar to that of metal products[30] . The difference between the standard SPIF tests for polymeric materials and those for metals is evident influence of the initial wall angle when the polymer samples with variable wall angles are analysed[30]. Nevertheless, the use of polymers opens new possibilities for SPIF forming in the field of prototype development.

CONCLUSION

Conventional SPIF forming can be improved with different approaches enabling an increase in the formability or improvement of forming accuracy. The formability can be improved in a simple way by heating the sheet. Such an approach is particularly suitable for materials with low ductility, such as magnesium and titanium[32]. By heating, additional slip planes are activated

[30] Marques, Tania A. et al.; *On the potential of single point incremental forming of sheet polymer parts*, IDMEC, Instituto Superior Tecnico, Technical University of Lisbon, Portugal, 2011;
[31] Ambrogio, Giuseppina et al.; Induction heating and cryogenic cooling in single point incremental forming of Ti-6Al-4V: process setup and evolution of microstructure and mechanical properties, Department of Mechanical, Management and Manufacturing Eng, University of Calabria, Italy, 2016;
[32] Duflou, Joost R. et al.; *Single point incremental forming: state-of-the-art and prospects*, Department of Mechanical Engineering, KU Leuven, Belgium, 2017;

within the microstructure of the material, which in turn means an increase in the formability. Forming at elevated temperatures also reduces the springback and forming forces. Due to all above mentioned reasons, in literature we encounter various ways of heating the sheet metal, which is being heated on the local area beneath the small tool or globally, where the whole sheet of metal is heated at once. Local heating can be divided into laser heating, electric heating and also heating by rotating the tool[33,34]. In addition to rotation, vibration of the tool is one promising approach that decreases the value of the forming force[35]. The correct choice of vibration frequency and amplitude is important. Cyclic hitting of the tool against the sheet metal can be achieved with a frequency generator and other necessary additional equipment, or only with the appropriate shape of the tool and its rotation[36].

The main advantage of SPIF is its flexibility in forming of different products and the ability to perform the forming itself on a conventional CNC milling machine or on a robot. The main disadvantage of incremental forming compared to conventional forming processes is the long lead time of a specific product. Thus, the incremental forming, including SPIF, is mainly aimed at the small batch production. The SPIF investment justification limit is usually between 100 and 1000 products[37]. Because the shape of a convex product formed with SPIF derogates from the desired shape below 1 mm, the mentioned forming process can be used in many fields such as biomedicine, architecture, thermoforming mould production and, above all, prototyping, where the above mentioned flexibility of incremental forming plays a vital role[37]. In addition to improving the accuracy of incremental forming, the lead times for products can be shortened, while retaining or even further increasing the formability level with many different innovative approaches.

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[33] Liu, Zhaobing; *Friction stir incremental forming of AA7075-O sheets: investigation on process feasibility, School of Mechanical and Electronic Engineering*, Wuhan University of Technology, China, 2017;

[34] Shrivastava, Parnika; *Improvement in formability and geometrical accuracy of incrementally formed AA1050 sheets by microstructure and texture reformation through preheating, and their FEA and experimental validation*, Department of Mechanical Engineering, PDPM Indian Institute of Information Technology, India, 2018;

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