Incremental sheet forming parameters and applications: a review

Parâmetros e aplicações de formação de folha incremental: uma revisão

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ABSTRACT
The present work introduces a literature review on the Incremental Sheet Forming process application and main parameters. This process is used to manufacture small batches of parts and formed sheets prototypes, as a semi-spherical-tipped tool yields form to a sheet using a pre-defined trajectory and various step-downs (Δz). In this work we describe the Incremental Sheet Forming process variations, application examples, the types of machines used and the diagram characteristics that describe the formed material's strain limits. The article also presents a detailed study on the influence of the main strength parameters required to execute the process, material formability, surface finishing and final product accuracy.

Keywords incremental sheet forming (ISF), prototyping, review.

RESUMO
O presente trabalho apresenta uma revisão bibliográfica sobre o processo de aplicação e os principais parâmetros do processo de Formação de Chapas Incrementais. Este processo é utilizado para fabricar pequenos lotes de peças e protótipos de folhas formadas, como uma ferramenta semi-esférica de ponta cede forma a uma folha utilizando uma trajetória pré-definida e várias etapas (Δz). Neste trabalho descrevemos as variações do processo de Conformação Incremental de Chapas, exemplos de aplicação, os tipos de máquinas utilizadas e as características dos diagramas que descrevem os limites de deformação do material conformado. O artigo também apresenta um estudo detalhado sobre a influência dos principais parâmetros de resistência necessários para executar o processo, a formabilidade do material, o acabamento superficial e a precisão do produto final.

Palavras-chave: formação de chapas incrementais (ISF), prototipagem, revisão.

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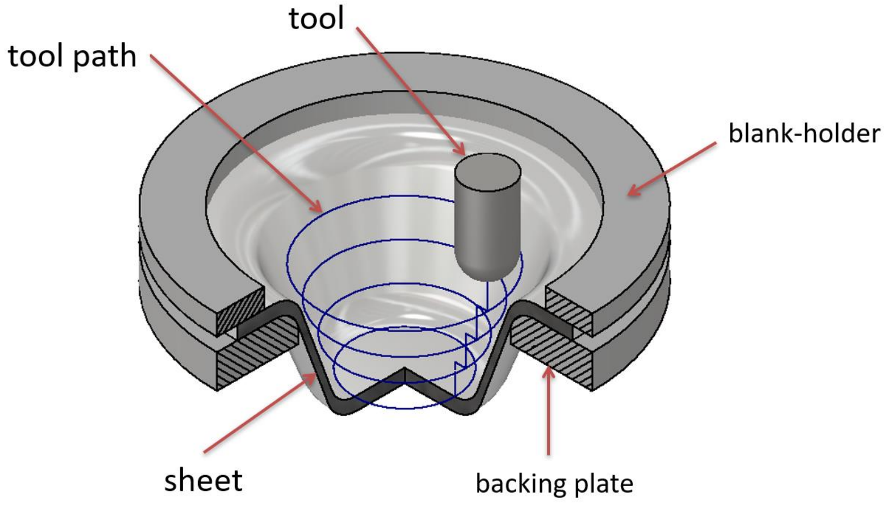
1 INTRODUCTION

Incremental Sheet Forming (ISF) is generally applied to fast prototyping and small batches of parts manufacturing. It can be used in different materials' sheet forming, providing high formability and making it possible to manufacture complex shapes [1,2]. This process is extremely flexible, as it does not require specific tools [3] and can be performed on a CNC machine [4].

To carry out the process, the sheet to be formed must be fixed between a backing plate and a blank-holder. Then a tool with a semi-spherical tip performs the sheet forming according to its trajectory, as shown in Figure 1. This process can be performed with or without tool rotation.

Fig. 1. Incremental Sheet Forming process

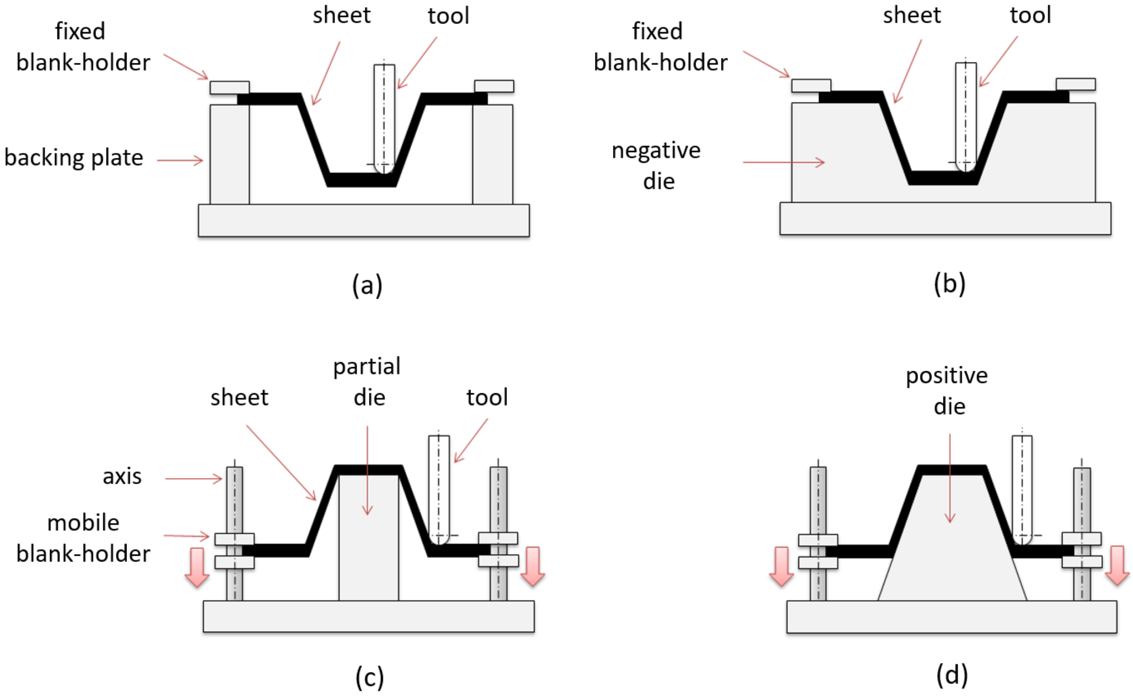


Two patents published in 1967 can be considered the precursors to the current Incremental Sheet Forming process, one published by Leszak [5] and the other by Berghahn and Murray [6]. Years later, in Mason's works of 1978, the process was carried out on a lathe [7], and later, in the works of Iseki *et al.* in 1989, on a milling machine, which allowed non-symmetrical parts manufacturing [8].

2 PROCESS VARIATION

The Incremental Sheet Forming process presents some variations. The main ones are shown in Figure 2.

Fig. 2 Incremental Sheet Forming process main variations: (a) SPIF, (b) TPIF with negative die, (c) TPIF with partial die and (d) TPIF with positive die.



The process' most common form is SPIF (Single Point Incremental Forming), in which the sheet is fixed between a backing plate and a blank-holder while a semi-spherical tool performs the sheet forming by increasing its trajectory, without the need to use a die, as shown in Figure 2 (a).

The TPIF (Two Point Incremental Forming) process is carried out with a negative, partial or positive die below the sheet to be formed. TPIF is used to improve geometric tolerances in complex parts manufacturing, without substantial extra cost, as the dies can be manufactured with low-cost materials (such as low carbon steels, polymeric materials and wood) [2,9].

In the TPIF with negative die, the sheet is placed between a fixed blank-holder and a die, while the tool executes its trajectory forming the sheet against the die, as shown in Figure 2 (b).

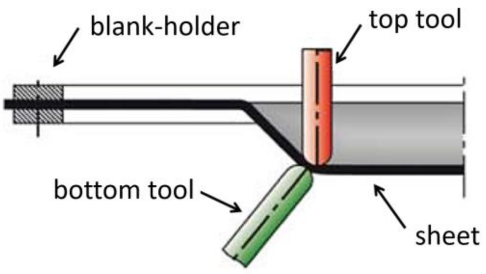
In the TPIF with partial die, indicated in Figure 2 (c), as well as in the TPIF with positive die, indicated in Figure 2 (d), it is necessary to use a system consisting of guides and mobile blank-holder, which allows the sheet to move downward as the tool executes its trajectory against it.

As in the TPIF with partial die, the die does not present the shape of the part to be formed exactly, in comparison with the TPIF with die, this grants less geometric accuracy to the part.

When comparing TPIF with positive die and TPIF with negative die, it appears that despite requiring more complex tools (with mobile parts), the TPIF with positive die requires less strength to perform the formability, which generates less residual stress in the sheet and consequently greater geometric accuracy due to the lower elastic return [10].

Another variation in the Incremental Sheet Forming process is Double Sided Incremental Forming (DSIF), which, much like SPIF, is performed without die. However, in this variation, the two tools used are synchronized, one at the upper part and the other in the lower part of the sheet, as indicated in Fig. *2* [11]. The DSIF process allows further deformation and greater geometric accuracy than the SPIF process, besides being more flexible and presenting lesser costs than the TPIF process (which require die manufacturing) [12].

Fig. 2. DSIF [11]



Although the Incremental Sheet Forming process allows parts manufacturing with large deformations (greater than in conventional stamping) [13], parts manufacturing with wall angles close to 90° are difficult to obtain in just one tool pass [14]. To overcome this difficulty, the Multi-pass Single Point Incremental Forming process (MSPIF) was developed, which allows uniform thickness distribution with greater wall angles [14,15]. In the MSPIF process, profiles are formed at intermediate angles, as shown in Fig. *3*.

Fig. 3. MSPIF [14]

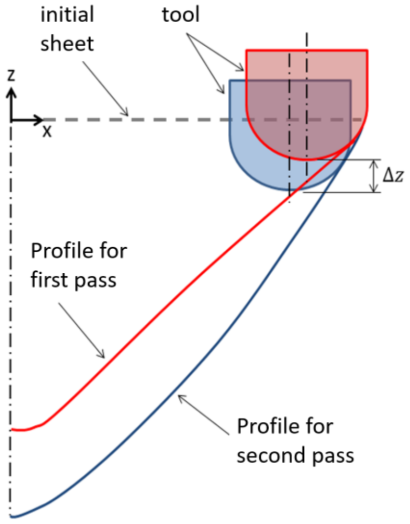
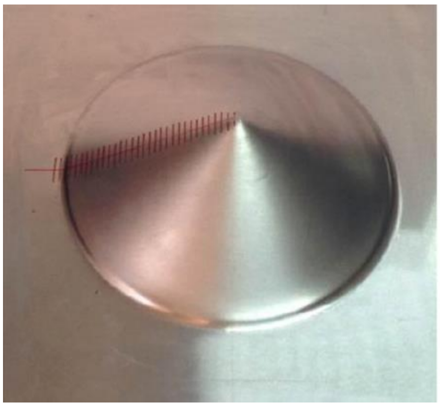
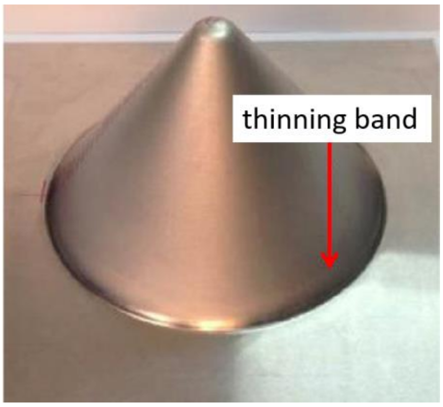


Fig. *4*(a) shows a MSPIF process application, in which the first tool pass was made at an angle of 30° in AA5052 aluminum alloy with an 1 mm initial thickness. In Fig. *4*(b) the part is presented after the second tool pass with a 60° wall angle, and in this figure it is also indicated that at the cone base there is a sudden reduction in sheet thickness.

Fig. 4. MSPIF process application: (a) Cone after 1º tool pass and (b) cone after 2° tool pass [14]



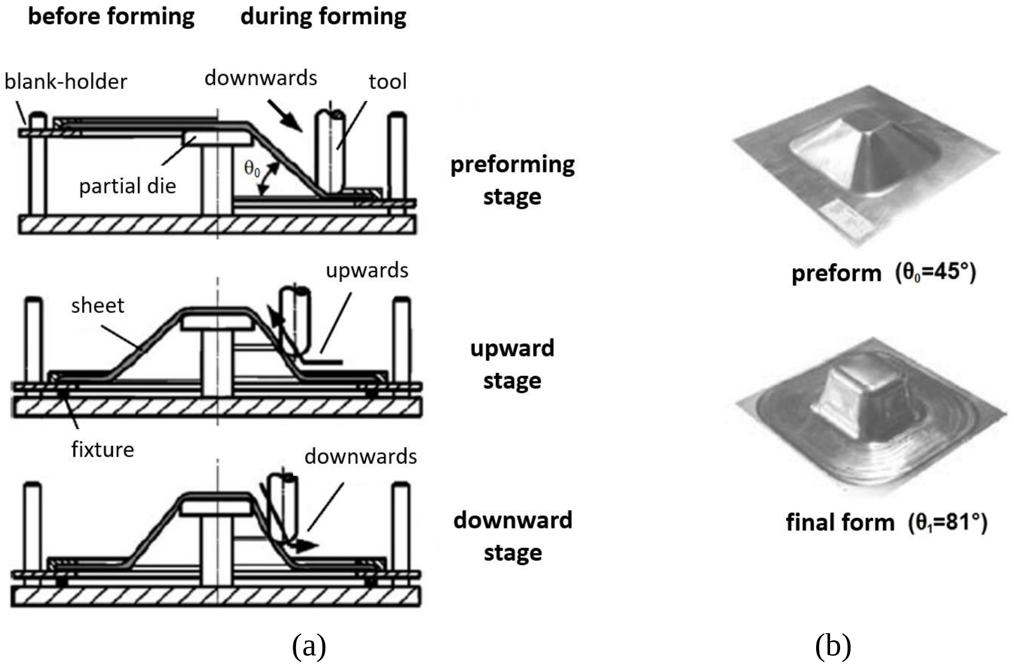
(a)



(b)

There is still the possibility of combining the Incremental Sheet Forming processes previously presented, according to the part to be manufactured peculiarities. **Erro! Fonte de referência não encontrada.**(a) shows the multi-pass TPIF with partial die application. In this process, three strain passes were performed, alternating downward and upward tool movements. **Erro! Fonte de referência não encontrada.**(b) shows the formed part's result after the first pass (pre-form) with initial wall angle $\theta' = 45°$, and below it there is the final formed shape after the third pass with wall angle $\theta = 81°$ [16].

Fig. 5. Multiple-passes TPIF with partial die: (a) Process stages (b) Pre-form and final form [16]

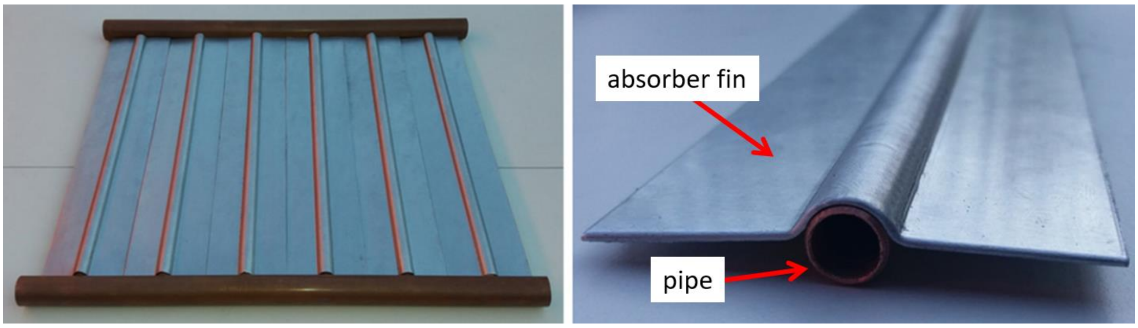


3 APPLICATIONS

Several applications have been studied due to the fact that the Incremental Sheet Forming process does not require specific tools, allowing fast prototyping or small batches of parts manufacturing [1], and as it also allows for forming with greater strains than those obtained in conventional stamping [13].

In the studies of Schreiber and Schaeffer [17], a series of experiments was conducted in order to define the Incremental Sheet Forming parameters for solar collector fins manufacturing. These fins were manufactured with 1 mm thick AA1100-H14 pure aluminum and the process was made using TPIF with a negative partial die. Fig. 6(a) shows the fin assemble manufactured through Incremental Sheet Forming mounted on cooper tube coils, while Fig. 6(b) shows the aluminum fin formed over the copper tube assembly in detail.

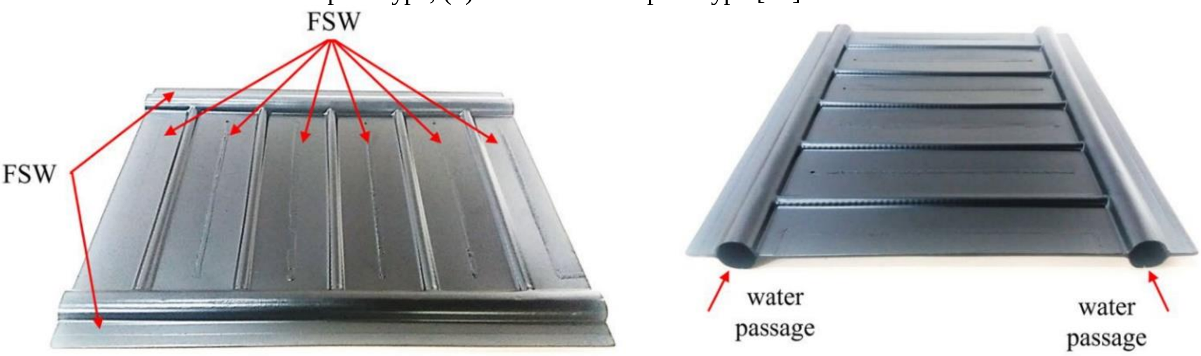
Fig. 6. Solar Collector Fin Prototype manufactured by Incremental Sheet Forming: (a) Fin sets mounted on the copper tube coil and (b) Fin mounted on copper tube in detail [17]



(a) (b)

Schreiber *et al.* [18] developed a new model of absorber plate for flat plate solar collectors through the processes of Incremental Sheet Forming and Friction Stir Welding (FSW). In this work, the absorber plate was formed and welded symmetrically with two 1 mm thick aluminum sheets, in order to allow water ducts to be formed between them. Figure 8(a) shows the FSW locations on prototype, while Figure 8(b) water ducts for prototype.

Fig. 8. Prototyping of absorber plate for solar collector by ISF and FSW processes: (a) FSW locations on prototype, (b) water ducts for prototype [18]



(a) (b)

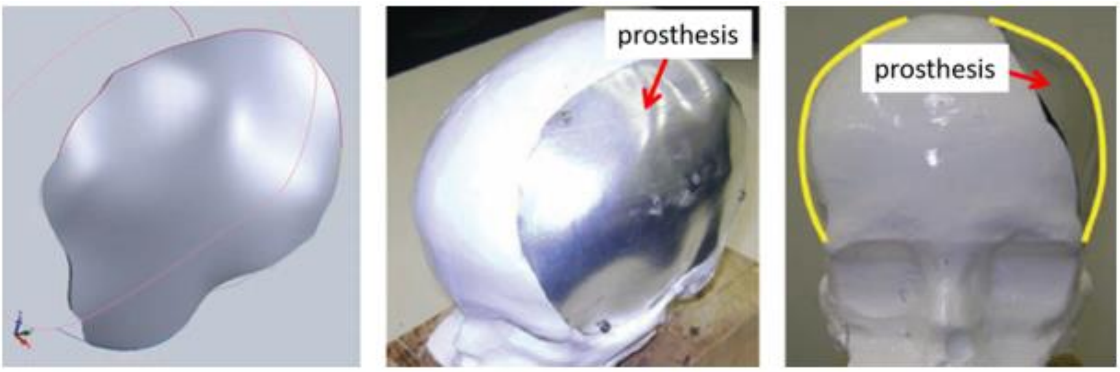
Jeswiet *et al.* [19] manufactured the solar oven cavity with 1.3 mm thick AA8006-O aluminum alloy using the SPIF process. In this study, it was concluded that this product's Incremental Sheet Forming has lower costs than conventional stamping manufacturing, or fiberglass manufacturing of the same product. In addition, the part's elastic return after forming remained within the tolerance required for the application. Fig. (a) shows a solar oven representation in side view, with a glass cover and the to-be-formed cavity, while Fig. (b) and Fig. (c) show the oven's cavity internal and side views after forming, respectively.

Fig. 9. Solar Oven Prototype with cavity manufactured using Incremental Sheet Forming: (a) Assembly's lateral view, (b) Formed cavity internal part and (c) Cavity's external part [19]

(a) (b) (c)

Castelan *et al.* [20] carried out the CAD design and 0.5 mm thick pure titanium grade 2 skull prosthesis manufacturing using the negative die TPIF process. In this study, it was concluded that the Incremental Sheet Forming process can be used to manufacture custom implants, even though some dimensional variations have occurred in the final part. This dimensional variation after cutting the product can be reduced by changing the cutting method and heat treatment. Furthermore, a biomodel's 3D printing was also carried out in which the prosthesis was installed. This biomodel's manufacture was intended to assist in preoperative planning and improve communication between doctor and patient. Fig.(a) shows the prosthesis CAD drawing, while Fig.(b) and Fig.(c) show the prosthesis assembly on the skull biomodel isometric and frontal sectional views, respectively.

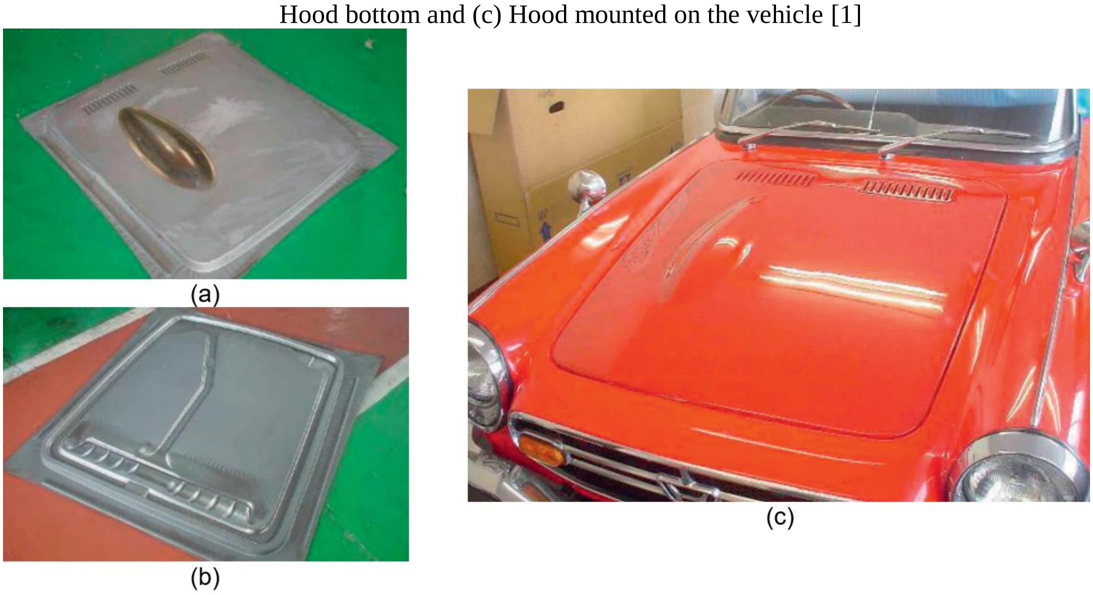
Fig.10. Titanium skull prosthesis prototype manufactured using Incremental Sheet Forming: (a) CAD Project, (b) Prototype assembly isometric sectional view and (c) the assembly's frontal sectional view [20]



(a) (b) (c)

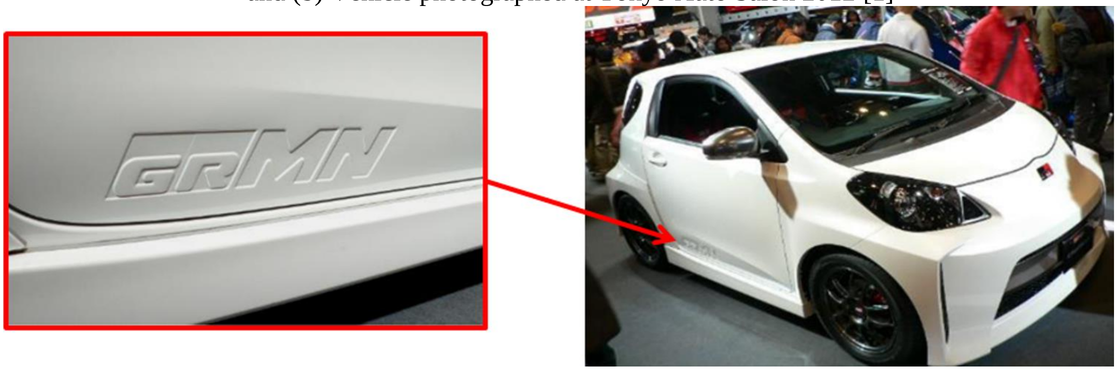
In a partnership between Honda Motor Co. Ltd. and Amino Corp., work was carried out to develop replacement automotive parts to be manufactured using the Incremental Sheet Forming process [1]. In this work, they digitalized the Honda S800 hood's external and internal parts, then submitted the 0.7 mm thick JIS SPCE steel sheets to a stretching operation, which was then passed through Incremental Sheet Forming. Fig. 7(a) and Fig. 7(b) show the outside and inside of the hood after forming, while Fig. 7(c) shows the hood mounted on the vehicle.

Fig. 7. Honda S800 hood manufactured with Incremental Sheet Forming: (a) Patterned hood top, (b) Hood bottom and (c) Hood mounted on the vehicle [1]



Another Incremental Sheet Forming process application example was the TOYOTA IQ-GRMN special edition logo embossing on the door [1]. Usually this type of customization is added using adhesives or chrome plastic parts, but in TOYOTA IQ-GRMN the door previously manufactured by conventional stamping received the embossed details through Incremental Sheet Forming's tool displacement. **Erro! Fonte de referência não encontrada.**(a) shows the detail formed on the vehicle door and **Erro! Fonte de referência não encontrada.**(b) shows the TOYOTA IQ-GRMN at Tokyo Auto Salon 2012.

Fig. 8. Incremental Sheet Forming on the door of the TOYOTA iQ-GRMN: (a) Logo formed on the door and (b) Vehicle photographed at Tokyo Auto Salon 2012 [1]

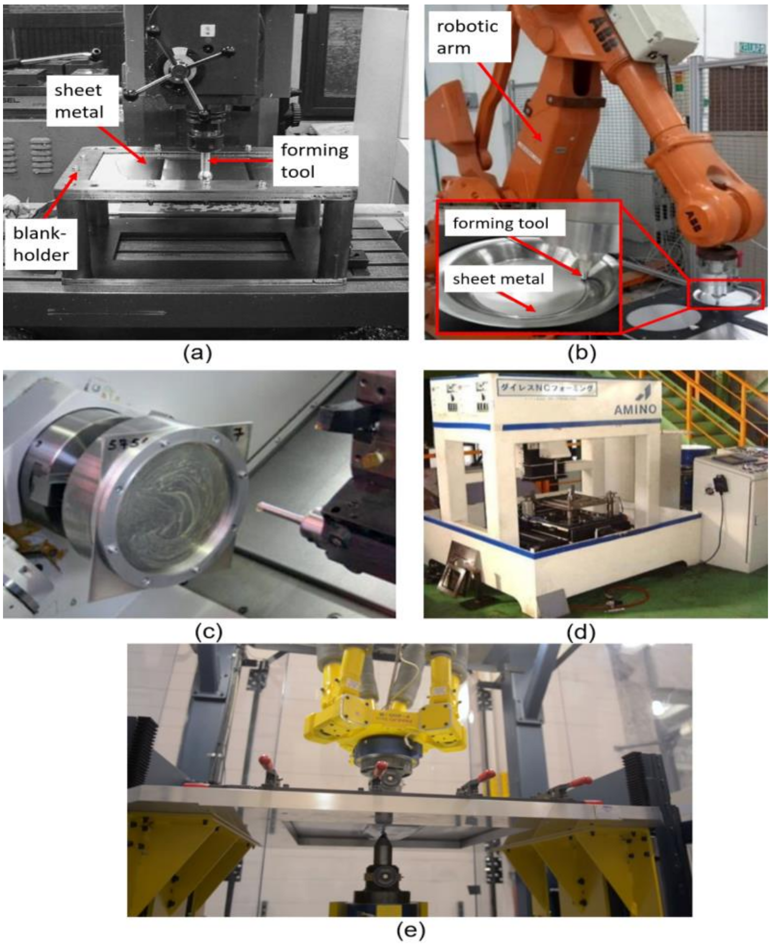


(a) (b)

4 MACHINES

The Incremental Sheet Forming process can be performed on different types of machines, such as milling machines [4], CNC lathes [4], robotic arms [11], [21], or in machines specific to the process [1], [22]. Fig.9 presents a machine overview that can be applied to the Incremental Sheet Forming process.

Fig.9. Incremental Sheet Forming Machines: (a) CNC milling machine [4], (b) Robotic arm [21], (c) CNC lathe [4], (d) Incremental Sheet Forming Amino Machine [1], (e) Incremental Sheet Forming F3T [22].



Several Incremental Sheet Forming studies have been carried out with CNC machines [4], [23], [24]. The advantage of using a milling machine is that it allows asymmetric parts manufacturing, while in the lathe, its application is restricted to axial symmetric parts [25]. Fig.9(a) shows the CNC milling machine use in the Incremental Sheet Forming process, while Fig.9(c) shows a CNC lathe in use.

Industrial robotic arms can also be used in the incremental sheet forming processes and because they allow tool movements in six axes, they allow complex parts forming [21]. However, it has as a disadvantage the low rigidity of the robot when compared to a milling machine [25]. A Fig.9(b) shows an Incremental Sheet Forming process with a robotic arm application example.

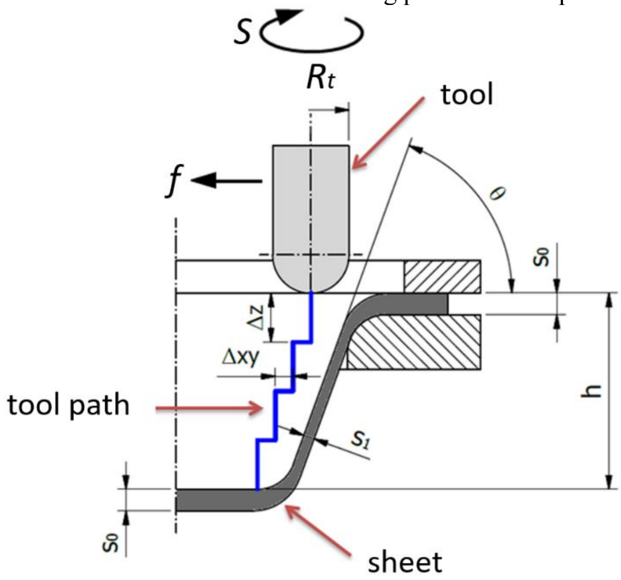
Machines specific to the Incremental Sheet Forming process, because they were built exclusively for this purpose, usually have features that facilitate the process application. Fig.9(d) shows a machine developed by Amino Corp. specific to Incremental Sheet Forming, which has a mobile sheet device for carrying out the TPIF process with a positive die [1,26].

Another equipment dedicated to Incremental Sheet Forming example is the F3T (Ford Freeform Fabrication Technology), developed by the Ford Motor Company, which is shown in Fig.9(e). The F3T has an upper head moving the forming tool on the metal sheet and a lower head with another tool acting as a support for carrying out the DSIF process [22].

5 PROCESS PARAMETERS

Many Incremental Sheet Forming process parameters, such as feed rate speed (*f*), rotation speed (*S*), step-down (Δz) and tool radius (R_t), as well as the type of lubrication used and process temperature, influence in the required strength for each process' creation, material formability, surface finishing and final product's accuracy. Fig. *10* presents SPIF Incremental Sheet Forming process' main parameters.

Fig. 10. SPIF Incremental Sheet Forming process' main parameters



As Fig. *10* indicates, the path performed by the tool determines the formed sheet's final shape, with the initial sheet thickness (s_0) being reduced to the final thickness (s_1), according to the wall angle used (θ), which is determined by the lateral increment value

(Δxy). The maximum formed depth (h), as well as the maximum wall angle are referential parameters for comparison between the different material's formability [17,27].

It is possible to establish the relationship between the wall angle (θ) and the formed sheet's final thickness (s_1), which is called cosine law and is shown in Equation 1 [28].

$$s_1 = s_0 \cdot cos\,\theta \tag{1}$$

Where:

s_1 = Final sheet thickness (mm);
s_0 = Initial sheet thickness (mm);
θ = Wall angle (°).

To obtain a greater wall angle, the initial sheet thickness must be increased [28] taking into account that tool diameter and step-down have little influence on the maximum wall angle [29].

There is also a relationship between true thickness strain (φ_3) and maximum wall angle (θ_{max}) obtained in radians, according to Equation 2 [30].

$$\theta_{max} = \frac{\pi}{2} - e^{\varphi_3} \tag{2}$$

Where:

θ_{max} = Maximum wall angle (rad);
φ_3 = True thickness strain (-).

5.1 STEP-DOWN (Δz)

The tool's step-down in Incremental Sheet Forming influences the process time, formability, surface finish, accuracy and strength required to carry out the process.

The higher the step-down value used, the shorter the processing time [17,31–33], however the formability will be lesser as well [31,34,35]. Since high step-down values increase the stress in the process, causing the fault to occur earlier [36].

In addition, the increase in step-down causes greater roughness in the formed part [26,34], decreases its accuracy [32,35,37] and requires greater strength to perform the forming [26,38].

In the work by Jeswiet *et al.* [26], it was concluded that the use of large values step-downs, in addition to increasing the strength required to carry out the process and increasing the roughness, can also cause the “orange peel” effect on the printed surface.

In the work of Schreiber and Schaeffer [17], it was found that when using high rotation associated with low step-down, despite obtaining greater formability, material removal from the sheet in the form of powder may occur, which may indicate inefficient lubrication.

5.2 ROTATION SPEED (*S*)

The tool’s rotation speed influences the formability, the surface finish and the strength required to carry out the process.

The tool’s rotational movement generates friction and causes heating to the part-tool interface [39]. As such, the increase in rotation speed grants greater formability to the part [17,26,36,39] and results in less strength required to carry out the forming process [40]. However, increasing the rotation speed can also increase the roughness of the part that is being formed [26].

In the research carried out by Durante *et al.* [41] on AA7075-T0’s Incremental Sheet Forming with rotation speed ranging from 0 and 800 rpm, it was found that with increase in the tool rotation there is a tendency to increase temperature, as well as decrease the strength required for forming. However, roughness variation in the studied parts proved to be insignificant.

In the work carried out by Schreiber and Schaeffer [17] on AA1200-H14’s Incremental Sheet Forming with rotation speeds varying from 50 to 800 rpm, the increase in tool rotation generates an increase in the material's formability. However, this study also indicated that when using large values for step-down (between 1 and 2 mm), the rotation has no influence on formability.

In the studies by Xu *et al.* [39] on AA5052-H32 aluminum’s Incremental Sheet Forming with rotation speeds varying from 0 to 7000 rpm for, the results show that the increase in material formability at low speeds (up to 1000 rpm) occurs due to variations in the friction conditions, whereas at higher speeds the temperature increase effect is responsible for the highest formability.

5.3 FEED RATE SPEED (*f*)

The tool's feed rate speed influences the process time, formability and surface finish of the formed part.

Feed rate speed increase allows the formed parts' manufacturing to be done in a shorter period of time [32], however, it also decreases the material's formability [35].

According to the studies by Ham and Jeswiet [36] on AA3003 aluminum's Incremental Sheet Forming, it was concluded that with the feed rate speed decrease (associated with the rotations from 100 rpm to 600 rpm), there is an increase in frictional heat generation, which as a consequence causes the material's increased formability.

For Teixeira *et al.* [42], the greatest strains in AA1200-H14 aluminum's Incremental Sheet Forming were obtained using low feed rate values. However, when associating low feed rate (200 mm/min) with high rotation value (800 rpm), the "orange peel" effect appearance on the printed surfaces was verified.

Rauch *et al.* [32] concluded that the feed rate used in the process (between 500 mm/min to 1500 mm/min) does not have a significant influence on the formed part's geometric accuracy, nor on the strength required to carry out the process.

However, in the study by Fan *et al.* [35] on TiAl2Mn1.5's Incremental Sheet Forming while hot, it was possible to eliminate distortion in the parts by increasing the process temperature and decreasing the feed rate from 800 mm/min to 400 mm/min.

5.4 TOOL RADIUS (R_t)

The selected tool radius value for the Incremental Sheet Forming process influences formability, surface finish, accuracy and strength required for forming the part.

The greater the tool radius used in Incremental Sheet Forming, the lower the formability of the sheet to be formed [26,33,35].

The use of small tool radiuses promotes greater deformations before the material breaks, as the stresses are concentrated in a small region under the tool. While large tool radiuses promote greater stress distribution over a larger area and the process is similar to conventional stamping, allowing for less strain [30].

In addition, with the increase in the tool radius, there is also an increase in roughness [26] and elastic return [35] in the formed part, as well as an increase in the strength required to perform the strain [33,38].

Studies that relate the tool radius and formed sheet thickness have been successful in finding a critical value for the $R_t \approx 2{,}2.s_0$ relation (where r_t is the tool radius and

s_0 the sheet's thickness), which is to say that, in following this relation, it is possible to obtain the greatest strains in the formed sheet, regardless of the material to be formed [27].

5.5 TEMPERATURE

By applying heat to the material during forming it is possible to reduce the strength required to form the sheet, increasing the material's formability and decreasing the parts' elastic return, as verified in the studies by Al-Obaidi *et al.* [43], in which induction heating was carried out on DC04, DP800 and 22MnB5 steels.

In Fan *et al.* [35]'s work on TiAl2Mn1.5's Incremental Sheet Forming with heating being applied through electric currents, it was verified that the increase in the process temperature, in addition to contributing to greater material formability, allowed the forming of shapes without axial symmetry free of geometric distortion.

In the study by Khazaali and Fereshteh-Saniee [37] on 0.5 mm thick Ti-6Al-4V titanium alloy sheets' Incremental Sheet Forming with an electric heating system, it was found that at higher temperatures there is less elastic return from the formed part.

The increase in temperature in the process can also be seen by increasing tool rotation, generating an increase in the material's formability [44].

5.6 LUBRICATION

As for the use of lubricants in Incremental Sheet Forming, their function is to reduce the final product's roughness, reducing the friction between tool and material, cooling the part and the tool, reducing tool wear and reducing the strength exerted by the tool [45].

In Azevedo *et al.* [46]'s work, the lower roughness achieved in DP780 steel sheets was provided by Finarol B5746 oil and AS-40 grease, while for AA1050 aluminum, SAE 30 oil and AL-M grease were used. In these studies, it was concluded that the greater the material's hardness, the lower the lubricant's viscosity must be in order to obtain a better finish. When assessing strength, they did not show significant differences for different lubricants.

In the studies of Jawale *et al.* [47] on copper sheets, the formed part's lower roughness was obtained with Castrol Magnaglide D68 mineral oil compared to Copaslip, AS40, Weicon Ni Special, Weicon montage greases.

5.7 PARAMETER INFLUENCE OVERVIEW

Table 2 shows the influence of the main parameters in the Incremental Sheet Forming process. The first column presents the parameters that, if increased, have consequences for the formed parts, and these consequences, such as process time, formability, surface finish, accuracy and required strength are listed in the other columns.

Table 1: Parameter influence in the Incremental Sheet Forming process

Parameter increase:	**Consequence in:**				
	Process time	**Formability**	**Surface finishing**	**Accuracy**	**Required force**
Step-down (Δz)	Decreased [17,31–33]	Decreased [31,34,35]	Worsens [26,34]	Decreased [32,35,37]	Increased [26,38].
Rotation speed (*N*)	-	Increased [17,26,36,39]	Worsens [26]	-	Decreased [40].
Feed rate speed (*F*)	Decreased [32]	Decreased [35]	Worsens [42][a].	-	-
Tool radius (r_t)	-	Decreased [26,30,33,35]	Worsens [26]	Decreased [35]	Increased [33,38]
Temperature	-	Increased [35,43]	-	Increased [35,37,43]	Decreased [43].

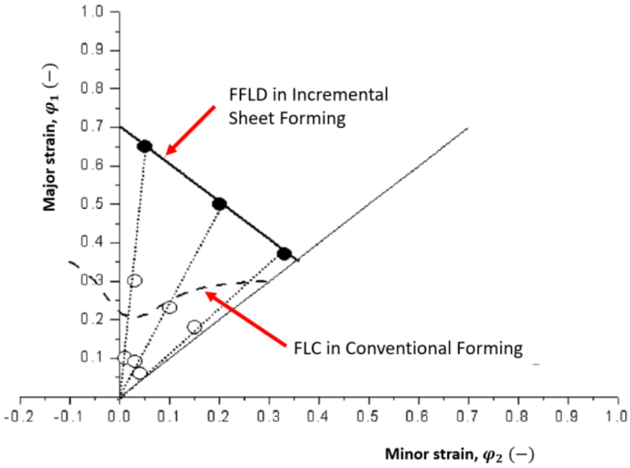
[a] Associating smaller feed rate speed with higher rotation value.

The blank boxes in Table 2 correspond to the fact that there are no relevant consequences in these situations, or that there is a lack of sufficient research to affirm the opposite.

6 STRAIN LIMITS

In the Incremental Sheet Forming process, the strain limits are different from those expressed in the Forming Limit Curve - FLC, which is generally used to define the formability limits in the Conventional Stamping process. Fracture Forming Limit Diagram - FFLD is the one that best describes the material's formability in Incremental Sheet Forming. Fig. *11* shows a comparison between the FLC and the FFLD for a given material, where it is possible to identify that the formability (characterized by the main deformations φ_1 and φ_2) is greater in Incremental Sheet Forming than in Conventional Stamping.

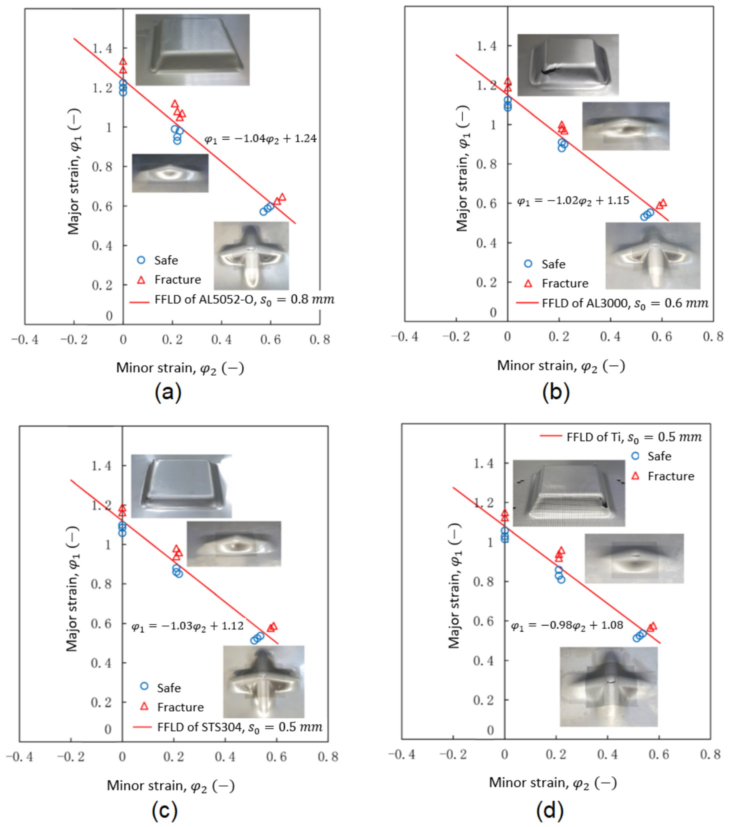
Fig. 11. Comparison between FLC and FFLD [13]



As shown in Fig. *11*, FFLD is defined as a straight line in the first quadrant of type $\varphi_1 = a\varphi_2 + b$ [48], noting that, in several studies, this coefficient value is considered equal to "-1" [30,48], resulting in a negative slope. It is also verified that in the case of plane state strain (when $\varphi_2 = 0$) the formability is extremely high [13], and that in all cases its value is higher than that obtained in the FLC.

Do *et al.* [48] defined the two aluminum (AL5052-O and AL3000), stainless steel (STS304) and pure titanium equations for FFLD with different thickness values as shown in Fig. *12*. In that study, the FFLD was defined through incrementally forming three formats: a pyramid with four sides ($\varphi_2 = 0$), a straight inclined groove ($\varphi_1 \neq \varphi_2$), and a crossed inclined groove ($\varphi_1 = \varphi_2$). In Fig. *12*, it is possible to identify that in the study, despite the difference between materials and thicknesses, the FFLD angular coefficient varied between -0.98 and -1.04.

Fig. 12. FLLD of different materials: AL5052-O, s_0=0,8 mm (a), AL3000, s_0=0,6 mm (b), STS304, s_0=0,5 mm (c), Ti, s_0=0,5 mm (d) [48]



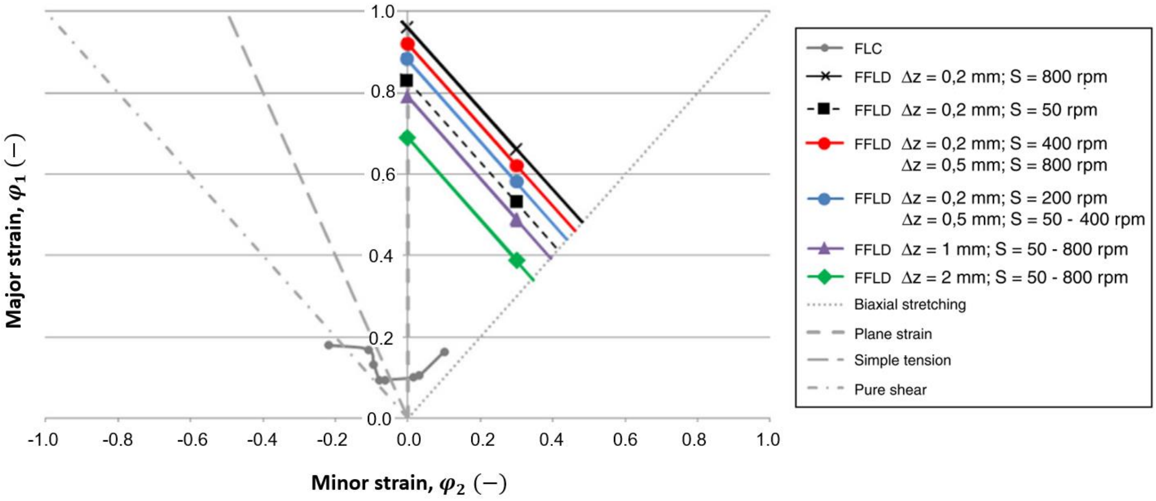
If the FFLD angular coefficient is considered $a = -1$, thickness strain φ_3 (obtained by Equation 3) will be constant, independent from the strain type that the sheet is submitted to [49]. And from the thickness strain determination it is possible to estimate the final sheet thickness, according to Equation 4.

$$\varphi_3 = -(\varphi_1 + \varphi_2) \tag{3}$$

$$s_1 = s_0 \cdot e^{\varphi_3} \tag{4}$$

However, as the material's formability varies with the process parameters used in Incremental Sheet Forming, it is possible to obtain several FFLD for the same material, according to the parameters used. In Figure 17, different FFLDs of the same material are presented, considering the angular coefficient $a = -1$. A comparison with FLC is also shown. In this study, AA1200-H14's Incremental Sheet Forming was carried out keeping the tool's feed rate constant and varying the step-down and rotation in each experiment. This work concluded that the increase in rotation associated with the decrease in the step-down allows greater strain limits to the formed part [17].

Fig.13. Different FFLD with step-down variation and tool rotation in comparison to AA1200-H14's FLC [17]



7 CONCLUSIONS

The Incremental Sheet Forming process provides high formability to the formed material and is efficient in rapid prototyping and in small batches of parts manufacturing, since it does not require specific tools and machinery. Because it is a flexible process, Incremental Sheet Forming can be performed on different machine types, such as milling machines, CNC lathes, and robotic arms or even using specific machines.

In relation to the main parameters' influence in the process, it can be concluded that:

- Process time can be reduced with step-down and feed rate speed increase;
- The formability process can be increased with rotation speed and temperature increase, or the decrease in step-down, feed rate speed and tool radius;
- The part's surface finishing can be improved with step-down, rotation speed, feed rate speed and tool diameter decrease;
- Process accuracy can be increased with temperature increase, or with step-down and tool radius decrease;
- The necessary strength to perform the process can be decreased with the increase in rotation speed and temperature, or with step-down and tool radius decrease.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

[1] Amino M, Mizoguchi M, Terauchi Y, Maki T. Current status of “Dieless” Amino’s incremental forming. Procedia Eng 2014;81:54–62. https://doi.org/10.1016/j.proeng.2014.09.128.

[2] Li Y, Chen X, Liu Z, Sun J, Li F, Li J, et al. A review on the recent development of incremental sheet-forming process. Int J Adv Manuf Technol 2017;92:2439–2462. https://doi.org/10.1007/s00170-017-0251-z.

[3] Lu H, Liu H, Wang C. Review on strategies for geometric accuracy improvement in incremental sheet forming. Int J Adv Manuf Technol 2019;102:3381–417. https://doi.org/10.1007/s00170-019-03348-3.

[4] Ambrogio G, Filice L, Gagliardi F. Improving industrial suitability of incremental sheet forming process. Int J Adv Manuf Technol 2012;58:941–7. https://doi.org/10.1007/s00170-011-3448-6.

[5] Leszak E. Apparatus and process for incremental dieless forming. US3342051A, 19 set, 1967.

[6] Berghahn WG, Murray JGF. Method of dielessly forming surfaces of revolution. US3316745, 1967.

[7] Mason B. Sheet metal forming for small batches. University of Nottingham. Nottingham, UK., 1978.

[8] Iseki H, Kato K, Sakamoto. S. Flexible and incremental sheet metal forming using a spherical roller. Proc 40th JJCTP 41 1989;41:44.

[9] Ceretti E, Giardini C, Attanasio A. Experimental and simulative results in sheet incremental forming on CNC machines. J Mater Process Technol 2004;152:176–84. https://doi.org/10.1016/j.jmatprotec.2004.03.024.

[10] Araghi BT, Manco GL, Bambach M, Hirt G. Investigation into a new hybrid forming process: Incremental sheet forming combined with stretch forming. CIRP Ann - Manuf Technol 2009;58:225–8. https://doi.org/10.1016/j.cirp.2009.03.101.

[11] Meier H, Magnus C, Smukala V. Impact of superimposed pressure on dieless incremental sheet metal forming with two moving tools. CIRP Ann - Manuf Technol 2011;60:327–30. https://doi.org/10.1016/j.cirp.2011.03.134.

[12] Peng W, Ou H, Becker A. Double-Sided Incremental Forming: A Review. J Manuf Sci Eng 2019;141:050802.1-050802.12. https://doi.org/10.1115/1.4043173.

[13] Park JJ, Kim YH. Fundamental studies on the incremental sheet metal forming technique. J Mater Process Technol 2003;140:447–53. https://doi.org/10.1016/S0924-0136(03)00768-4.

[14] Cao T, Lu B, Xu D, Zhang H. An efficient method for thickness prediction in multi-pass incremental sheet forming. Int J Adv Manuf Technol 2015:469–83. https://doi.org/10.1007/s00170-014-6489-9.

[15] Xu D, Malhotra R, Reddy NV, Chen J, Cao J. Analytical prediction of stepped feature generation in multi-pass single point incremental forming. J Manuf Process 2012;14:487–94. https://doi.org/10.1016/j.jmapro.2012.08.003.

[16] Kitazawa K, Nakajima A. Cylindrical Incremental Drawing of Sheet Metals by CNC Incremental Forming Process. 6th ITCP, 1999, p. 1495–500.

[17] Schreiber RG, Schaeffer L. Manufacture of absorber fins for solar collector using incremental sheet forming. J Mater Res Technol 2019;8 (1):1132–40. https://doi.org/10.1016/j.jmrt.2018.07.018.

[18] Schreiber RG, Teixeira AR, Pereira RSF, da Silva Osório F, Schaeffer L. Prototyping of absorber plate for solar collector by ISF and FSW processes. J Brazilian Soc Mech Sci Eng 2021;43:1–12. https://doi.org/10.1007/s40430-021-03083-5.

[19] Jeswiet J, Duflou JR, Szekeres A, Lefebvre P. Custom manufacture of a solar cooker - A case study. Adv Mater Res 2005;6–8:487–92. https://doi.org/10.4028/www.scientific.net/AMR.6-8.487.

[20] Castelan J, Schaeffer L, Daleffe A, Fritzen D, Salvaro V, Da Silva FP. Manufacture of custom-made cranial implants from DICOM® images using 3D printing, CAD/CAM technology and incremental sheet forming. Rev Bras Eng Biomed 2014;30:265–73. https://doi.org/10.1590/rbeb.2014.024.

[21] Ismail NA, Ismail MIS, Radzman MAM, Ariffin MKAM, As'arry A. Parametric optimization of robot-based single point incremental forming using Taguchi method. Int J Integr Eng 2019;11:217–24. https://doi.org/10.30880/ijie.2019.11.01.023.

[22] Ford Media. Ford's Advanced Prototyping, Personalization and Low-Volume Production Technology 2013. https://www.youtube.com/watch?time_continue=62&v=Wl5_wUVxRvw (accessed August 22, 2019).

[23] Filice L, Fratini L, Micari F. Analysis of material formability in incremental forming. CIRP Ann - Manuf Technol 2002;51:199–202. https://doi.org/10.1016/S0007-8506(07)61499-1.

[24] Baruah A, Pandivelan C, Jeevanantham AK. Optimization of AA5052 in incremental sheet forming using grey relational analysis. Measurement 2017;106:95–100. https://doi.org/10.1016/j.measurement.2017.04.029.

[25] Emmens WC, Sebastiani G, Boogaard AHVD, van den Boogaard AH. The technology of Incremental Sheet Forming-A brief review of the history. J Mater Process Technol 2010;210:981–97. https://doi.org/10.1016/j.jmatprotec.2010.02.014.

[26] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J, Allwood J. Asymmetric Single Point Incremental Forming of Sheet Metal. CIRP Ann - Manuf Technol 2005;54:88–114. https://doi.org/10.1016/S0007-8506(07)60021-3.

[27] Al-Ghamdi KA, Hussain G. Threshold tool-radius condition maximizing the formability in SPIF considering a variety of materials: Experimental and FE investigations. Int J Mach Tools Manuf 2015;88:82–94. https://doi.org/10.1016/j.ijmachtools.2014.09.005.

[28] Duflou JR, Verbert J, Belkassem B, Gu J, Sol H, Henrard C, et al. Process window enhancement for single point incremental forming through multi-step toolpaths. CIRP Ann - Manuf Technol 2008;57:253–6. https://doi.org/10.1016/j.cirp.2008.03.030.

[29] Ham M, Jeswiet J. Forming limit curves in single point incremental forming. CIRP Ann - Manuf Technol 2007;56:277–80. https://doi.org/10.1016/j.cirp.2007.05.064.
[30] Martins PAF, Bay N, Skjoedt M, Silva MB. Theory of single point incremental forming. CIRP Ann - Manuf Technol 2008;57:247–52. https://doi.org/10.1016/j.cirp.2008.03.047.

[31] Kim Y. H, Park J. J. Effect of process parameters on formability in incremental forming of sheet metal. J Mater Process Technol 2002;130–131:42–6. https://doi.org/10.1016/S0924-0136(02)00788-4.

[32] Rauch M, Hascoet JY, Hamann JC, Plenel Y. Tool path programming optimization for incremental sheet forming applications. CAD Comput Aided Des 2009;41:877–85. https://doi.org/10.1016/j.cad.2009.06.006.

[33] Centeno G, Bagudanch I, Martínez-Donaire AJ, García-Romeu ML, Vallellano C. Critical analysis of necking and fracture limit strains and forming forces in single-point incremental forming. Mater Des 2014;63:20–9. https://doi.org/10.1016/j.matdes.2014.05.066.

[34] Bhattacharya A, Maneesh K, Reddy N V., Cao J. Formability and Surface Finish Studies in Single Point Incremental Forming. J Manuf Sci Eng 2011;133:061020.1-061020.8. https://doi.org/10.1115/1.40054.58.

[35] Fan G, Gao L, Hussain G, Wu Z. Electric hot incremental forming: A novel technique. Int J Mach Tools Manuf 2008;48:1688–92. https://doi.org/10.1016/j.ijmachtools.2008.07.010.

[36] Ham M, Jeswiet J. Single point incremental forming and the forming criteria for AA3003. CIRP Ann - Manuf Technol 2006;55:241–4. https://doi.org/10.1016/S0007-8506(07)60407-7.

[37] Khazaali H, Fereshteh-Saniee F. A comprehensive experimental investigation on the influences of the process variables on warm incremental forming of Ti-6Al-4V titanium alloy using a simple technique. Int J Adv Manuf Technol 2016;87:2911–23. https://doi.org/10.1007/s00170-016-8665-6.

[38] Duflou J, Tunçkol Y, Szekeres A, Vanherck P. Experimental study on force measurements for single point incremental forming. J Mater Process Technol 2007;189:65–72. https://doi.org/10.1016/j.jmatprotec.2007.01.005.

[39] Xu D, Wu W, Malhotra R, Chen J, Lu B, Cao J. Mechanism investigation for the influence of tool rotation and laser surface texturing (LST) on formability in single point incremental forming. Int J Mach Tools Manuf 2013;73:37–46. https://doi.org/10.1016/j.ijmachtools.2013.06.007.

[40] Torsakul S, Kuptasthien N. Effects of three parameters on forming force of the single point incremental forming process. J Mech Sci Technol 2019;33:2817–23. https://doi.org/10.1007/s12206-019-0528-2.

[41] Durante M, Formisano A, Langella A, Minutolo FMC. Technology The influence of tool rotation on an incremental forming process. J Mater Process 2009;209:4621–6. https://doi.org/10.1016/j.jmatprotec.2008.11.028.

[42] Teixeira AR, Schreiber RG, Schaeffer L. Influência das velocidades de Avanço e Rotação na Estampagem Incremental de Alumínio. Rev Ferram 2018:22–6.

[43] Al-Obaidi A, Kräusel V, Landgrebe D. Hot single-point incremental forming assisted by induction heating. Int J Adv Manuf Technol 2016;82:1163–71. https://doi.org/10.1007/s00170-015-7439-x.

[44] Buffa G, Campanella D, Fratini L. On the improvement of material formability in SPIF operation through tool stirring action. Int J Adv Manuf Technol 2013;66:1343–51. https://doi.org/10.1007/s00170-012-4412-9.

[45] Daleffe A. Estudo do processo de estampagem incremental em chapa de alumínio puro. Porto Alegre: Dissertação - Universidade Federal do Rio Grande do Sul (UFRGS); 2008.

[46] Azevedo NG, Farias JS, Bastos RP, Teixeira P, Davim JP, Sousa RJA, et al. Lubrication aspects during Single Point Incremental Forming for steel and aluminum materials. Int J Precis Eng Manuf 2015;16:589–95. https://doi.org/10.1007/s12541-015-0079-0.

[47] Jawale K, Duarte JF, Reis A, Silva MB. Microstructural investigation and lubrication study for single point incremental forming of copper. Int J Solids Struct 2018;151:145–51. https://doi.org/10.1016/j.ijsolstr.2017.09.018.

[48] Do V-C, Pham Q-T, Kim Y-S. Identification of forming limit curve at fracture in incremental sheet forming. Int J Adv Manuf Technol 2017;92:4445–55. https://doi.org/10.1007/s00170-017-0441-8.

[49] Gouveia B, Rodrigues J, Martins P. Tecnologia Mecânica: Tecnologia da Deformação Plástica - Volume III. Lisboa: Escolar Editora; 2011.