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Incremental sheet forming for prototyping automotive modules

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Abstract

Actually, in many industrial applications, like automotive industry, mass decreases and fuel economy constitute very important features. Light alloys are extensively used in automotive applications and simultaneously, the constant industrial progress forces low-cost innovative machining routes to be used after the manufacturing process oriented to transform the product into a right shape with high accuracy of the geometry and good surface quality. In this paper, a general overview of the actual state-of- the-art about the Incremental Sheet Forming (ISF) is presented including some experimentally results of the current research in this field performed by the authors. The target of the research is oriented on the validation of the possibility to use a common milling machine, as ISF apparatus, and to find the most suitable process parameters to be assumed for the production of automotive sheet made by Ti alloys.

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Keywords: Incremental sheet forming; cold deformation; light alloys; automotive sheets.

1. Introduction

Automotive industry is looking for both competitive materials and production processes, in order to act on a possible mass reduction and fuel economy which in turn involve a real improvement in the use of environmentally friendly products. For such reasons, from one hand light alloys are extensively used for automotive component production and from the other hand development of low-cost innovative machining routes to be used when the products are manufactured can be considered important achievements. In the scenario described above, ISF can be

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considered as a flexible technology to deform a metal sheet into the preferred profile and in more than one cases it can be deliberated as an excellent alternative technique to other material forming procedures.

One should note, that while the conventional forming technologies are suitable for mass production, ISF is more convenient for small-scale manufacturing. Additionally, the ISF process can guarantee a quick response for geometry modifications compared to a more traditional technique. ISF method requires less complex tools [1]: it employs a Computer Numerical Control machine (CNC), nowadays available at large scale, to realize the finished part; the tool is in continuous contact with the sheet surface while the sheet edges are pressed with a blank-holder to avoid their sliding. ISF technique is based on the application of a certain grade of deformation on a sheet shaped material to achieve a specific form, ensuring good surface quality and an accurate geometry too. In the past years, ISF was mainly adopted in small-scale productions and prototypes for the automotive industries, but at the present time it founds application in aerospace and biomedical industries as well [2-4]. This flexible manufacturing technology could be considered as an alternative to the material stamping with the same observation as above; while the stamping technology is appropriate for mass production, ISF is more convenient for the small-scale ones. In addition, the ISF process is attractive also from environmental point of view [5]. The tool is in continuous contact with the sheet surface while sheet edges are pressed with a blank-holder to avoid their sliding [6-8]. According to the current literature [9-12], different metal forming processes have been developed which are directly correlated also to the enormous development in the field of the computer controlled machine knowledge, of the symmetric single point forming route growth and of the progress in tool route postprocessors in CAD software packages [12-14]. In the Single Point Incremental Forming process (SPIF), also called negative forming, the deforming tool operates on the upper surface of the sheets producing a local deformation. In the Double Side Incremental Forming (DSIF) there are two tools performing their action on both sides of the sheet, while the Two Point Incremental Forming (TPIF), called positive forming, uses a partial or a full die for deforming both the internal and external sheet surfaces. The partial die is used as a strength support, while the full die is present as negative mould of the final form [13,14]. As reported in [11-14], the most important parameters involved into the forming process are: (i) sheet material and thickness, (ii) tool material, shape and diameter, (iii) spindle rotation, (iv) feed rate, (v) tool path and step down, (vi) CNC program control, (vii) force applied, (viii) working temperature, (ix) lubricant.

Nature and thickness of sheets influence the process parameters: the force required in the forming process increases as the plate thickness rises [14], but the same depth changes is different since it is governed by the properties of the material interested in the forming. One of the characteristics which made ISF technique flexible is related to the possibility to employ it for different materials. In fact, some studies [15, 16] the authors have focused their attention on SPIF of thermoplastic materials in order to find the best parameters which determine the sheet deformation, while others investigations evaluate the formability of materials in terms of glass transition temperature. The studies are related to the use of ISF as possible processing route for light alloys at high temperatures [17], for Cu alloys [18-20], for steel [12,21], for Al alloys at room temperatures [22-24], for titanium alloys [25-28] and for Mg alloy [29], just to mention some.

Anyway, the choice of the forming parameters is strongly correlated not only to the properties of the material to be processed, but also to the force that has to be applied on the material and the possible tool shape and tool path [30] which fit the properties of the material and the selected forming route. Several studies [31-36] have investigated the formability grade for metal sheets by defining the forming limit diagram (FLD); the formability using numerical simulations based on finite elements (FE) analysis have been considered by other authors [37-39] to define the correct forming-process variables. The variation in the fracture-wall-angle of the sheet with respect to the fracture prediction obtained using FEM analysis has been reported in [40]. According to [41], the effects of temperature, forming speed and the influence of the grain size and the strain rate on the FLD in case of Al alloys belonging to the 5000 series have been reported. According to such investigations, high temperatures lead to an increase in the maximum applicable strain, especially if the tool speed decreases, while at room temperature no influence of the temperature on the strain-rate has been found. On the basis of the studies reported by the authors in [42], the grain size has an important role in the deformation rate, and in particular low grain size intensifies the probability of fracture.

The interaction between the tool and the sheet to be processed determines the force that has to be applied and on the basis of the friction, a suitable lubrication is needed, in order to reach a good sheet-surface finishing properties and to avoid any stress formation during the whole forming process. The last mentioned aspect is a consequence of the severe deformation applied: the ISF process tends to induce high residual stresses into the material which is deformed affecting the lifetime during application [18].

Different tool shapes and diameters have been reported [2, 11, 12], but the most employed shapes are the hemispherical tip, the ball tip and the flat tip [43]. As concerns the tool path different analysis have been carried out [1, 30, 44]: helical, unidirectional or bidirectional types can be used successfully.

An evaluation of the forming tendency on A5052 aluminum alloy at room temperature has been reported in [45]: good formability has been achieved using high tool-rotation (of about 12000 rpm), outcome which is in a good agreement with [46].

The sheet position (top or bottom) affects the fracture behavior and the same Al alloy can reveal different mechanical resistance as a function of such situation [45]. When vibration is used during forming, high mechanical resistant structures with a high accuracy as geometry regards have been obtained, as illustrated in [47]. The level of the sheets deformation is directly correlated to the operational temperature and the anisotropy of the alloy influences the results, as stated in [48, 49]. Moreover, the precision of the shape decreases as temperature increases.

In this contexts, the present paper reports a general overview of the actual state-of- the-art about ISF, including some experimentally results of the current research in this field performed by the authors. The research did not go to offer new forming procedures, but new approaches, underlining the effects of the process parameters on the process proficiency when used for different kind of alloys. In particular, the present research is born following an industrial need concerning (1) the verification of the possibility to use a common milling machine, actually already employed for other purpose, as ISF apparatus, and (2) to find the most suitable process parameters to be assumed for the production of automotive sheet made by Ti alloys. For this purpose, different metallic alloys have been investigated: carbon steel and lightweight alloys, characterized by a high strength to density ratio and low formability, like aluminum alloy and finally the outcomes have been used for the deformation of Ti alloys at room temperature.

2. Experimental

In the present research, low carbon steel (DX54: 0,12% C, 0,5% Si, 0,6% Mn, 0,3% Ti, 0,045% S, 0,1% P and Fe as balance), aluminum alloy (EN AW 5083: 0,4% Si, 0,4% Fe, 0,1 %Cu, 0,4÷1% Mn, 4÷4,9% Mg, 0,05÷0,25% Cr, 0,25% Zn and 0,15% Ti+ Zr and Al as balance), commercially pure titanium alloy Ti-CP (Ti grade 1: 0,08% C, 0,2% Fe, 0,03% N2, 0,18% O2, 0,015% H2 and Ti as balance) and Ti6Al4V alloy (Ti grade 5: 0,08% C, 0,4% Fe, 0,05% N2, 0,2% O2, 0,015% H2, 5,5÷6,75% Al and 3,5÷4,5% V with Ti as balance) have been investigated. The alloys have been provided in sheet forms and then have been cut into square-shape geometries: for the DX54, EN AW 5083 and Ti6Al4V alloys the dimensions are 1500 mm x 1500 mm x 1,5 mm, while for the Ti grade 1 and 5 1500 mm x1500 mm x 1mm size samples have been made. The mechanical properties of the alloys investigated at room temperature are reported in [50-52]. Microstructural analysis has been carried out on the deformed sheets by optical microscopy (OM, Leica MEF4M).

3. Results and discussions

The deformation of the alloys has been carried out along their rolling direction adapting an existent milling device which moves the forming tool in a controlled way. According to the nature of the plate employed different process parameters have been experimented, taking into account the differences in the thickness of the sheets. For the realization of both the punch and tool has been started from a 3D CAD model. The punch, made in quenched C40 steel, used to deform the sheets is a solid hemispherical tool with a diameter of 20 mm. The radius of the punch is one of the most important parameters able to influence the surface finishing and the formability of the sheet to be processed. Lower radius has a higher influence on the formability compared to higher one; with higher radius the surface contact between the sheet and the punch is higher and the forces involved are greater. On the contrary, using a punch with low radius, the surface contact and the deformation area is lower allowing the application of a higher pressure on the sheet and consequently guarantee a greater formability of the piece because the force applied remain localized. However, with a very low radius there is the risk to compromise the rigidity and the stability of the tool. In order to perform the deformation, the punch has to show higher hardness than the sheet and at the same time to avoid the catastrophic failure of the hemispherical head high hardness has to be associated to good ductile properties. The friction at the sheet and punch interface has to be controlled in order to obtain a good surface finishing properties: the lower the friction, the higher the surface feature will be. The geometry of the tool can be easily interchanged, while the diameter has to be fixed because it is dependent of the dimension of the milling machine. This later aspect can be considered a single constraint in the forming machine structure. To guarantee all these aspects, it has been decided to prepare the solid hemispherical punch in C40 hardened steel with a diameter of 20 mm guaranteeing a continuous contact between the forming toll and the metallic sheet. The full die has been realized in epoxy resin. The most important elements of the device used for the forming are the metallic base, the blank holder and the system used to move the blank holder along the vertical axis. The blank holder has been made using several metallic rods assembled with screws and nuts, which can be swapped in case of necessity. Four inferior uprights and four superior columns have been used to sustain the whole structure allowing the insertion of the columns and the accommodation of the tubular guide which are indispensable to guarantee the movement of the blank-holder. The movement can be realized by means of a hydraulic apparatus or manually too, but it has to be contemporary with the movement of the tool which makes the deformation. The presence of the blank-holder is important to sustain the metallic sheet and to guarantee a proper positioning and tensioning of the sheet during forming. Figure 1 reports the CAD design of the punch and of the epoxy full die matrix, where the full die height corresponds to the maximum achievable height for the sheets (100 mm), the configuration of the punch inserted in the milling machine, the schematic illustration of the full set-up employed and finally the real test-rig used for the ISF realization. Linear as well as helical tool paths have been investigated, and during the full process, the sheet has remained clamped into the blank holder; for the tightening the ductility of the metallic sheet has been taken into account.

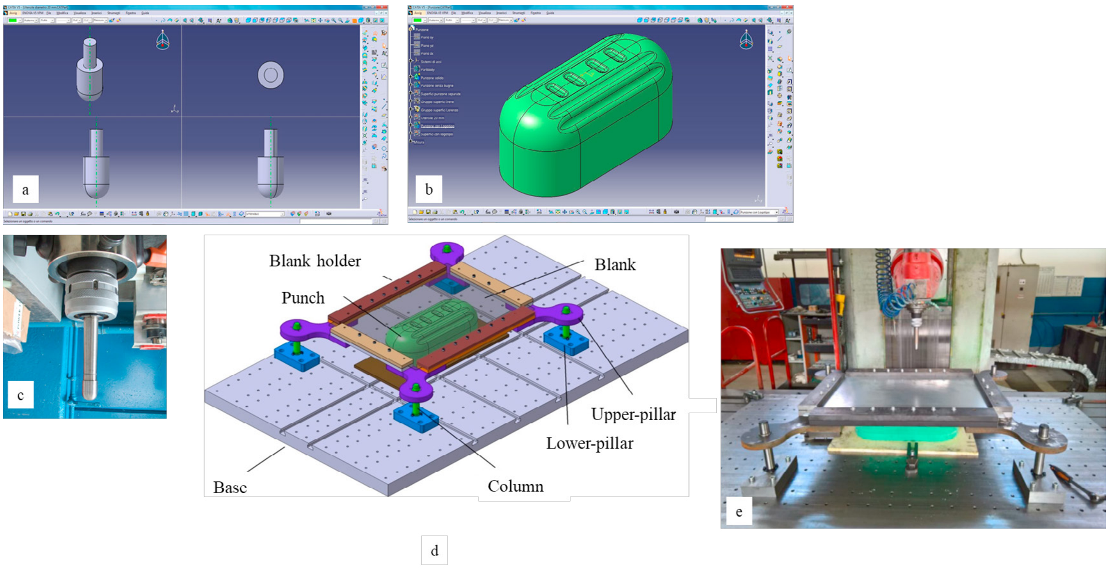

Fig. 1. - CAD design (a) of the punch and (b) of the epoxy full die matrix (800x980 mm^2, h=100 mm); (c) the punch inserted in the milling machine; (d) the schematic representation of the full set-up; (e) photograph of the test-rig used.

Following the validation of the system used for the forming process (structural rigidity, sheet support), some deformations have been performed on the different alloys selected. The research has started using the alloy with higher workability to check the dynamics of the process with no any failure of the tool employed in this step. In the following, the experiment has been moved to the alloys showing poorer workability (minor % elongation). For all alloys, the movement along the z-axis (orthogonal to the surface) has been fixed to a constant value (the tools moves down with a small increment of 0.2 mm).

DX54 has been clamped into the blank holder then formed with the hemispheric tool copying the die shape. The tightening value has been fixed according to the sheet formability (80 Nm), while the tool path selected is a linear one. As lubricant, a water-oil suspension has been employed. The rotation rate has been fixed to ω=1000 rpm, while the tool feed rate has been stepwise varied with the following values υ=1000, 2000, 3000 mm/min. For all these values the evaluation of the surface quality has been carried out. For the forming, a current moving program used for roughing at constant z has been optimized and the plastic deformation has been completed layers by layers. The geometry of the punch has been divided in many parallel planes which are perpendicular to the z axis. When the tool has finished the first layer starts the following one by a vertical increase along the z axis. The actual working cycle did not allow the forming of the inner parts which have different curvature. Figure 2 reports the images concerning the scheme of the forming process, where the red lines indicate the path performed by the tools during the forming process.

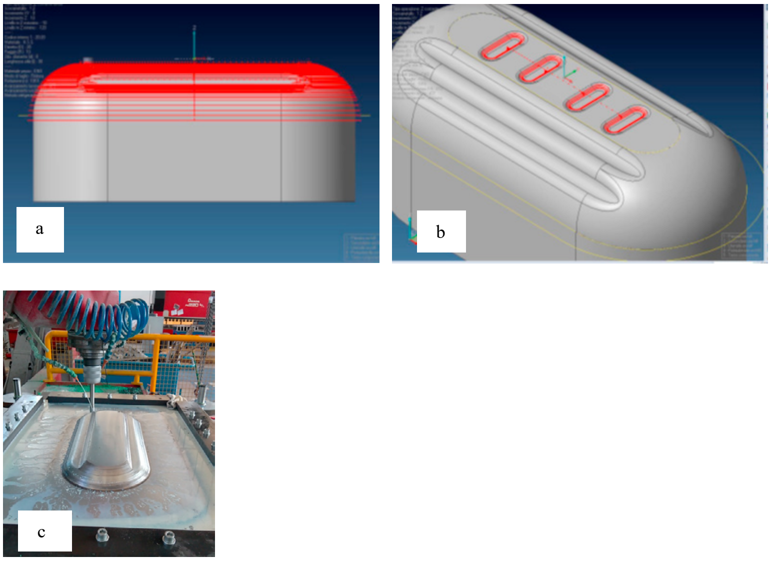

Fig. 2 CAD design of the path performed by the tools during the forming; (a) general view, (b) details of the route performed (c) image of the effective forming route

Different feeding rates determine different surface qualities of the sheets (Fig. 3a). On one hand, the higher is the feeding rate the poorer is the surface finishing properties and the wear phenomenon are more accentuated, as reported in Fig. 3. When the tool feed rate is higher than 3000 mm/min, the forming has been impossible causing the total failure of the sheet. Overheating of the surface occurs which in turn determines the failure during the forming. On the other hand, the time required for the process are higher using a low feeding rate. For the reasons exposed, 2000 mm/min was selected as a trade-off value for the further deformations. Considering a depth of 100 mm, it has been demonstrated the integrity of deformed surface and a good surface finishing for the first 90 mm; after 90 mm, fracture of the alloy occurs on the horizontal planes. The point of the axial increase of the forming can be considered as initiation site for the crack nucleation leading to its propagation and finally determines the failure of the piece (Fig. 3b).

The aluminum alloy has minor ductility compared to DX54, and for this reason, some of the working parameters assumed for the first experiment have been modified. First of all, considering its lower plasticity, the tightening has been reduced progressively to 50, 10 and 5 Nm, in order to assure the sheet deformation during the deformation. In addition, the tool path has been changed from linear to helical in order to induce minor stress into the sheet.

Assuming the highest tightening mode, the metallic sheet shows some limitations in the movement during forming inducing some stresses within the alloy which determine its failure when the forming depth is about 35 mm. The situation changes when the tightening is 10 Nm: in this case, even if the materials flow is not optimal, the maximum penetration depth is about 53 mm. The clamping force seems to be significantly correlated to the formability of the alloy. When the metallic sheet is closed into the blank holder it has to show a sufficient freedom in order to be formed with no any damage. Lowering this parameter, the development of the figure with a height of 72 mm has been performed, while over this value failure of the alloy takes place.

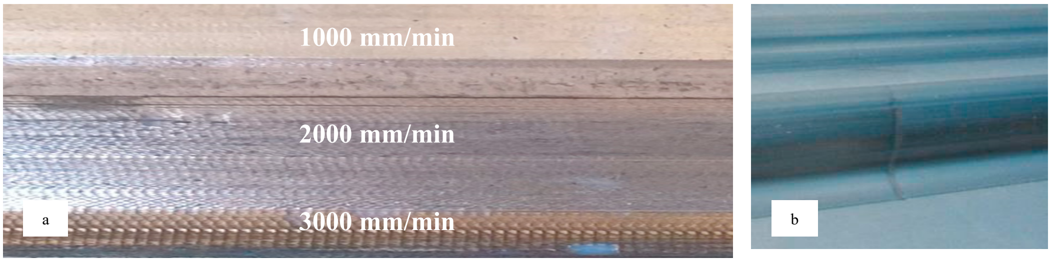

Fig. 3 Images showing the effect of the feeding rate on the surface quality of the sheet (a) and the presence of crack during forming (b)

The parameters used for the Al alloy have been adopted for the Ti alloy grade 1; even if this alloy shows lower yield strength and higher elongation at brake compared to the Al alloy tested, its failure occurs when the figure deformed has a height of 46 mm. From the analysis performed and results obtained it comes out that such parameters are not the most important which influence in vigorous mode the formability of the alloys. Anyway, it has been demonstrated that Ti grade 1 can be shaped using such technology inside the working window presented earlier and rationally coordinating the action of the tool between the different zones along the sample to be shaped a better spreading of the force applied has been attained.

Ti6Al4V alloy has low deformation rate and for this reason clamping force has not been applied to avoid early falling-out of the material due to the excessive stress generated. Additionally, due to the difficult workability of such alloy, 1000 mm/min tool feed rate has been used, even if this lead to prolonging the time. For the excessive spring back that Ti6Al4V alloy shows, in many areas the sheet forming is not performed successfully. Additionally, along the whole sheet an important twisting and bending has been observed (Fig.4). Such phenomenon determines a very irregular geometry, where the figure in the central part reach only 6 mm vertical growth, while at the edges it arrives to 15 mm. Even if the forming has been realized employing the best process conditions obtained till now, the maximum height of the figure is the lowest one obtained among the alloys experimented during the research. This is mainly due to the low elongation and to the low formability of the alloy. ISF can be used for such alloy only for small size figure, or following the modification of its composition through the addition of some elements able to moderate the spring back of Ti6Al4V.

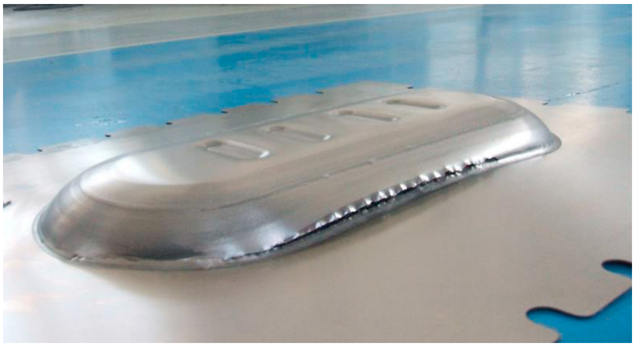

Fig. 4 Photograph of the deformed Ti6Al4V sheet

4. Microstructural analysis

The metallic sheets have been cut into small samples separating the most deformed zone. The effect of the stresses on the microstructure has been reported in Fig. 5. Using a linear movement of the tool along the steel sheet, reaching a final depth of 90 mm, the maximum deformation was obtained. Comparing the as received alloy and the deformed one, an elongated grain have been observed along the stress direction supporting the great tendency of such material to deformation. Al alloy sheets show lower deformability trend; the reduction of tightening in combination with the linear movements of the tool leads to obtain 35 mm of depth of forming at the middle of the sample and at the end of the forming fracture occurs. Using a helical tool movement, the achievable grade of deformation is higher and a significant grain refinement can be observed. The intermetallic phases assumed an elongated shape along the forming direction. Ti grade 1 shows a lower deformation rate, reaching 46 mm height and an anisotropic deformations of the grains are visible. Ti grade 5 alloy has a slight and irregular deformation behaviour, according to some literature data too [53].

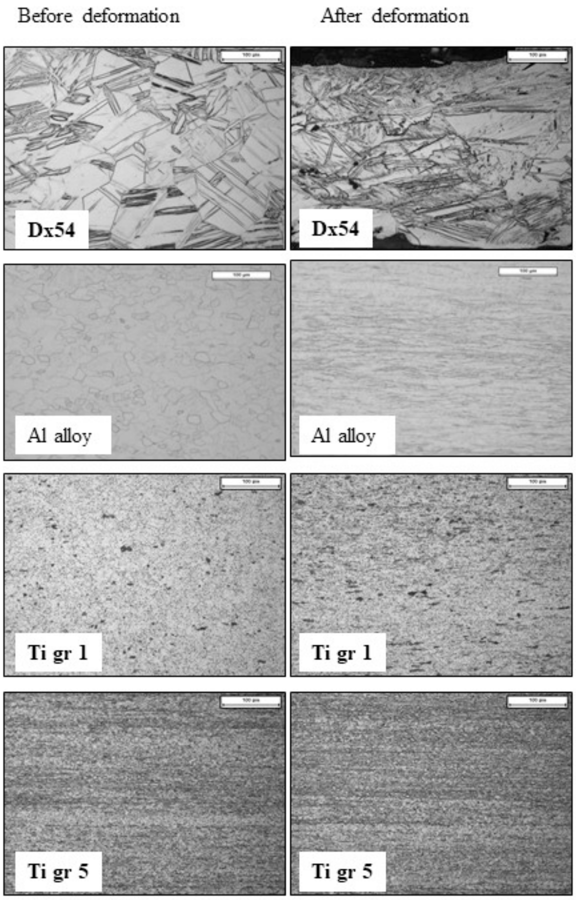

Fig. 5 OM microstructures of the sheets before and after deformation

4. Conclusions

The target of investigation presented in the present paper was oriented on the use of Incremental Sheet Forming process on different metallic sheets with the purpose to individuate the correct process parameters, which could better meet the need of the small medium enterprises involved in the research. In particular, concerning the growing production experience with the possibility to show the direction to the next improvements by employing such forming procedure for automotive (and other) component production one can obtain an important benefit, from both metallurgical and economical/environmental points of view.

From one hand, the possibility to use a common milling machine, in a readapted form, which is actually already employed for other purpose was demonstrated. There is a clear evidence of the relation between the tool feed rate and the surface finishing: as the speed of the tool decreases, the surface finishing is enhanced. The lubrication of the tool is similarly important and above a certain limit the cooling of the tool is required in order to avoid the degradation of the mechanical characteristics. The emulsion used helps also this task. Clamping of the sheet to be formed has to be not so intense, in order to allow the natural flowing of the sheet; in fact, with lower closing strength higher height was reached.

On the other hand, among the experimented alloys, steel is the most deformable material by such forming procedure; As Al alloy concerns, its formability is highly influenced by the process parameters, the formability depth is double using lower fixing forces. For Ti grade 1, Incremental Sheet Forming can be considered as good alternative method in case of the figure with minor height, while in case of Ti grade 5, the proposed technology at room temperature and employing the devise offered is inadequate to obtain good surface quality product, due to the remarkable spring back and poor elongation of the alloy.

Some on-going research are oriented to develop a possible equilibrium for the spring back of Ti6Al4V, to analyse in detail the relationship between the effect produced by the clamping on the microstructure of the alloys and to develop some mathematical models to predict the force effectively made by the punch.

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