ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

NUMERICAL STUDY ON INCREMENTAL SHEET FORMING APPLIED ON AN IMPACT ATTENUATOR MODEL

Saulo André do Carmo Cunha [1]
Carlos Aurélio da Silva Carvalho [2]
Márcio Eduardo Silveira [3]
Departamento de Engenharia Mecânica , Universidade Federal de São João del Rei - UFSJ
Praça Frei Orlando 170, Centro, São João del Rei – MG, Brazil. Cep: 36307-352
[1] saulocunha75@gmail.com
[2] carloscarvalhoufsj@hotmail.com
[3] mesilveira@ufsj.com.br

Abstract. *Incremental sheet forming is an efficient stamping process to manufacture parts in small lots, prototypes or complex geometry. It consists on the deformation of a metal blank by a progression of localized plastic deformation using a simple spherical tool. One of its main features is the prediction of the sine law which means the reduction of wall thickness is proportional to the decrease in the working angle between the deformed surface and the initial configuration of the plate, generating final structures that are thin-walled components with a high value of energy absorption impact. However, the high rate of strain hardening of the material raised by this process may come to compromise the performance of the component in an impact test. Against this background, the central question that motivates this paper is study by numerical simulation the application of this forming process focusing its implementation on parts manufactured by this method on components of vehicle safety which undergo crash test simulation. For this work, was developed by the finite element method, a model impact attenuator, designed by Formula SAE competition, made by two different procedures: one by bending and welding the plates and the other by the aforementioned forming method. After, this two model impact attenuators, were virtually simulated on crash test and their results were confronted. The influence stamping parameters was evaluated in both cases, showing promising results on the study of the application of SPIF in structural components.*

Keywords: *Incremental Sheet Forming, Impact Attenuator, Finite Element Method*

1. INTRODUCTION

The Stamping Process is a mechanical manufacturing method that comprises a group of proceedings that aim to form a sheet metal blank in a new geometry (Chiaverini, 1977). This process is highly used in industries like automotive, but it has considerable disadvantage of high cost of tolling, that is only alleviated by a large production.

On the actual context of metal mechanic industry, the development of new techniques of rapid prototyping is an established reality; among these techniques Incremental Sheet Forming is an emerging process to manufacture parts that are well suitable for small batch production and/or for complex geometry.

Mounted in CNC machine, this method aims to deform punctually and plastic a sheet metal blank by its movement and/or by the stamping tool, especially in the vertical plane (Jeswiet, 2001).

The applicability of process is being studied in various areas especially in the manufacture of prototypes for the automotive industry (Jeswiet *et al*, 2005) and in the medical area producing cranial prostheses of titanium (Castelan *et al*, 2010)

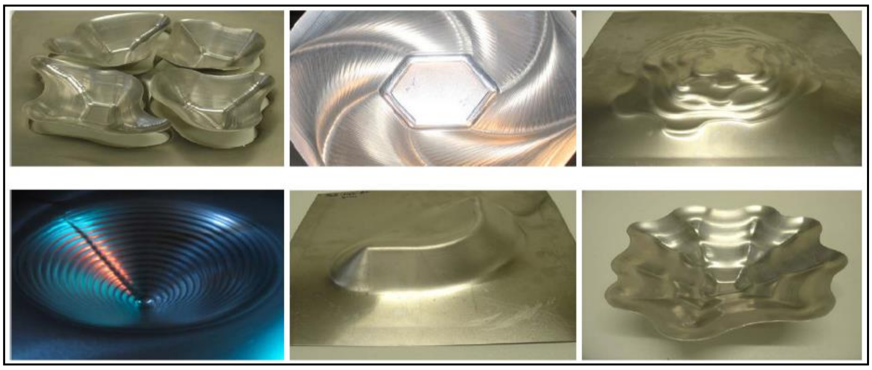

Figure 1. Several parts obtained by Incremental Sheet Forming
Source: TIBURI, 2007, p. 23

Given that there is a need to realize a structural study of parts produced by this process. This work aims to develop two impact attenuators models, one stamped by ISF method and other fabricated by a conventional method (welded plates) and make a comparison by analyzing their structure by a crash test, all done by numerical simulation.

2. INCREMENTAL SHEET FORMING

The two configurations of ISF differ by the points of contact of the stamping tool with the blank. On (Single Point Incremental Sheet Forming) process the sheet metal is fixed in the edges while is formed by the contact of a single indenter. In other hand the TPIF (Two Point Incremental forming) the blank is stamped against a die, punch or a second moving indenter. In all cases the tool path is described by contours or spirals with a depth increment, following the part geometry.

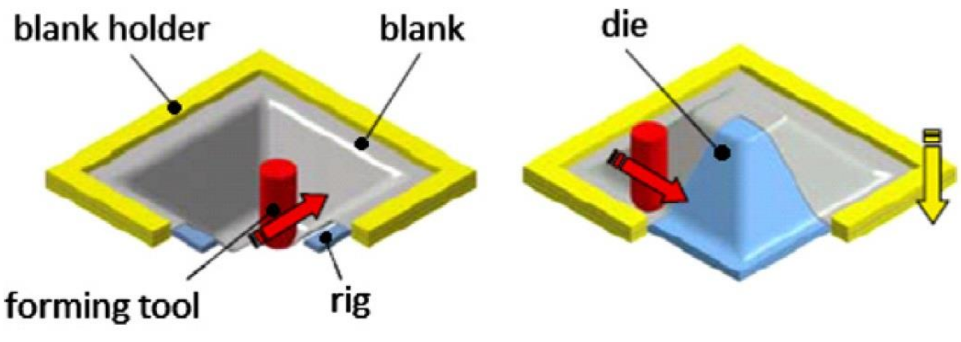

Figure 2. Comparison of SPIF(a) and TPIF(b) processes
Source AZAOUZI, 2012, p.2

In the light of experiments (Jeswiet *et al*, 2005) enumerates the main advantages of and disadvantages of SPIF process:

Advantages

- The parts of the process can be realized directly from an interface CAD/CAM, minimizing the time/cost of production and making it applicable to small lots and rapid prototyping;
- The process does not require use of dies, for most applications;
- High rates of flexibility due of the changes in specific parts of the project are easily implemented;
- Rapid Prototyping in metals, usually difficult to implement, it is easy in this process;
- The small plastic deformation induced contributes to the increased formability checked in using the process;
- A conventional CNC can be in the process;
- The size of the piece being conformed is lonely restricted by the available space on the machine, not requiring larger forces to forming these parts;
- The surface finish is usually very satisfactory;
- The operation is relatively quiet;
- The process allows deep drawings.

Disadvantages:

- Process time is much larger than a conventional deep drawing process. Because of this, to be economically feasible, the SPIF must be applied to manufacturing parts that require small batches;
- The drawing of right angles does not occur in a single pass, but in multi-stage;
- Springback occurs.

About the conformability (Jeswiet *et al,* 2005), states four main parameters: initial thickness of the plate, size of the vertical increment, and diameter of the stamping tool. (Jackson *et al, 2009)* reviewed that experiments and numerical simulations lead to important considerations about the behavior of the sheet metal during the process: for a linear tool path or a tool path with soft curves the material does not deforms significantly along the horizontal plane, but mostly normal to this plane. Thus, the magnitude of strains on the surface of the blank is zero or despicable parallel to the tool direction, and positive perpendicular to the tool direction, and these directions correspond to the minor and major directions of surface strain, respectively, given that, strains on the blank surface perpendicular to the tool direction increase with the increasing wall angle. Due to conservation of volume, the result brings about a relationship between the parameters sheet metal thickness and wall angle known as the *sine law*:

$$t_1 = t_0 \cdot \sin\alpha \quad (1)$$

ISSN 2176-5480

Where t_1 represents the wall thickness after forming, t_0 the original wall thickness and α angle described by the initial configuration of the plate and the deformed surface.

3. IMPACT ATTENUATOR

Formula SAE is a student design competition organized by SAE international. The basic concept behind the event is that a fictional manufacturing company has contracted a design team to develop a small Formula-style race car, and this prototype is to be evaluated for its potential as a production item. The target consumers are the non-professional autocross racers. Each student team designs, builds and tests a prototype based on a series of rules whose purpose is both to ensure onsite event operations and promote clever problem solving.

The Formula SAE prototype has many safety components, and one of the most important is the impact attenuator, a device attached in the front of the chassis car designed to absorb the colliding vehicle's kinetic energy. For the Formula SAE 2013 competition the impact attenuator must be designed for absorb 7350 joules or more attached in a vehicle of 300 kilograms while colliding at 7 meters per second on a rigid wall. Figure 3 b shows the template for this year competition.

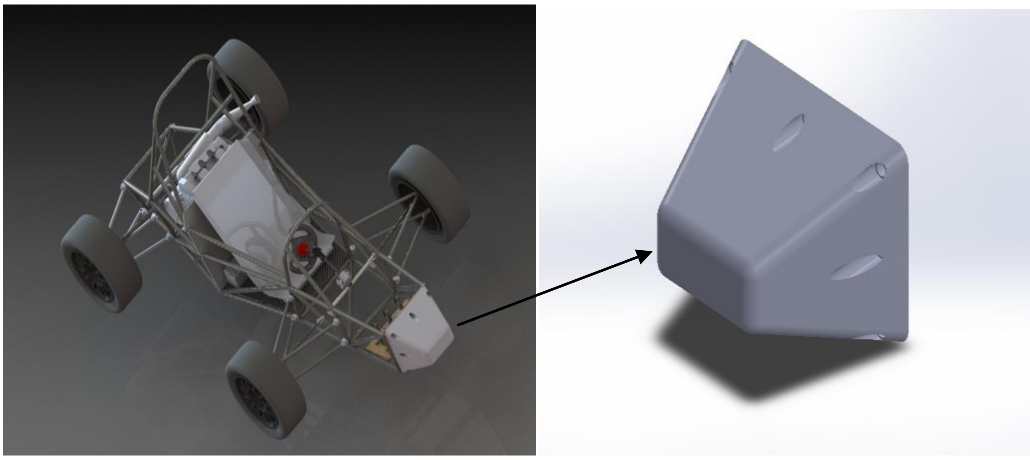

Figure 3. a) Formula SAE semi-finished prototype CAD of FSAE UFSJ. b) Impact attenuator template
Source: The Author

4. FINITE ELEMENT METHOD

The FE method emerged in the 50's as a analytical tool and obtained its promising development on the 60s with a demand of aerospace field. The capability of this method is very wide, with potential to solve problems in the structural area and even fluid and thermal areas. A very useful case of his utility is on impact simulations. The crash tests are highly destructive trials e generally very expensive for the sector of product development. With the use of numerical simulation is possible, still in the virtual phase of design, predict the behavior of a certain component or mechanical system that undergo a crash test. The numerical simulation by FE method has also great capability on the simulation of stamping processes, where is possible to predict with reasonable reliability the initial and final conditions of the processes.

All the conforming processes of sheet metals generate modifications on the properties of the materials and the geometry of the original plate. In the ISF process this alteration is much more prominent than in the conventional stamping process, due to the high conformability generated of it. In the conventional stamping process the thickness reduction can achieve by 30% without failure, depending on the material. On Incremental Sheet Forming the thickness can achieve values higher than 50%. The hardening level of a part fabricated by ISF method is still rarely studied, but numerical simulation has reveled values significantly higher than that obtained by conventional process.

There is some studies establishing a relation between the influence of the stamping process on the performance of the final product (Samessima et al, 2011), (Silveira, 2012). Results show that the residual plastic strain and the reduction of thickness can affect substantially on the simulations that involve great plastic strains, as the crash test simulation.

For structural components manufactured by ISF, it is speculated that this process could affect substantially the performance of the product on a impact test, due to the peculiar mechanism of punctual plastic strain generated by this process. The use of numerical simulation via finite element method may come to elucidate the effects of this recent and promissory process of conformation, in particular the ones that are designed to absorb strain energy while in an impact, like an impact attenuator.

ISSN 2176-5480

5. METODOLOGY

For this work, were proposed two models of impact attenuator, one manufactured by Single Point Incrmental Forming, and other by a bending and welding aluminium plates.

Non-linear simulations – stamping process and impact - were done in the commercial software RADIOSS Block Data using explicit integration in the loading and with formulation robust enough to treat with material and geometrical non-linearity.

5.1 Material

For this simulation the material aluminiun alloy 3003-O of the plate was modeled as isotropic with elastic-plastic characteristics. The strain hardening behavior of materials is a major factor in structural response as metal working processes or plastic instability problems. A proper description of strain hardening at large plastic strains is generally imperative. For many plasticity problems, the hardening behavior of the material is simply characterized by the strain – stress curve of the material.

The incremental plasticity theory is generally used in computational methods. Plasticity models are written as rate – dependent or independent. The description of the material characteristic of the attenuator was made by means of the Johnson-Cook elastic-plastic law (Law 2 in RADIOSS). The stress vs. plastic strain law is as follows:

$$\sigma = (\alpha + b\varepsilon_p^n)(1 + c\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})(1 - T^m) \qquad (2)$$

Where σ is flow true stress, ε_p is plastic strain (true strain), *a* is yield stress, *b* is hardening modulus, *c* is strain rate coefficient, ε is strain rate, ε_0 is reference strain rate, *m* is temperature exponent.

The Johnson-Cook (JC) model assumes that the slope of the flow stress curve is affected by strain hardening, strain rate sensitivity and thermal softening behaviors. Each of these sensitivities is represented by a proper multiplying factor in the constitutive equation. According to this law the material behaves as linear elastic when the equivalent stress is lower than the yield stress. For higher value of stress, the material behavior is plastic. This law is valid for brick, shell, truss and beam elements. Adopted values of above parameter for the aluminium AA 3003-O can be seen in Table 1:

Table 1. Parameters for The Johnson-Cook (JC) model

.

Property	Aluminium alloy 3003-O
Density	2.73 * 10-3 *g/mm3*
Poisson's ratio	0.36
Young's modulus	72600 MPa
Yield strength	42.970 Mpa
Hardening parameter	180.000 Mpa
Hardening exponent	0.210
Strain rate coefficient	0.00747

For this work the effect of the temperature exponent was disregarded.

5.2 Geometry

The components were modeled with plane elements (2D), with six degrees of freedom per node and one point of integration (with Hourglass control). The stamping tool was modeled as a rigid sphere with a diameter of 12 mm.

The sheet metal plate to be stamped had an initial thickness of 1.5 mm and area dimensions of 400x400 mm. For this work a simplified model was proposed with simplified dimensions in order to save computational time:

ISSN 2176-5480

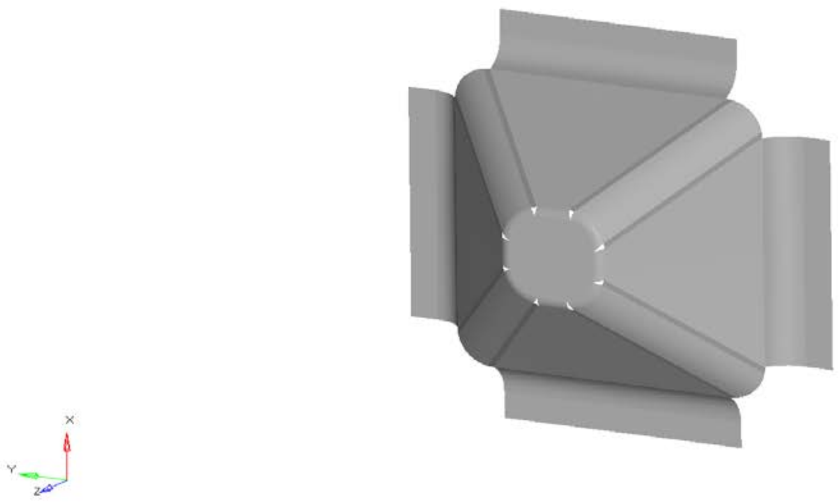

Figure 4. Impact Attenuator Model

The dimensions proposed are:

- 400 mm length;
- 400 mm height;
- 150 mm depth;
- Thickness of the plates: 1.05 mm.

5.3 Boundary Conditions

On the stamping process the plate was clamped on its edges and a semi helical (with a progressive increment on the z axis) displacement programmed to form the required geometry was imposed to the tool. In each contor the stamping tool increase 1mm on depth.

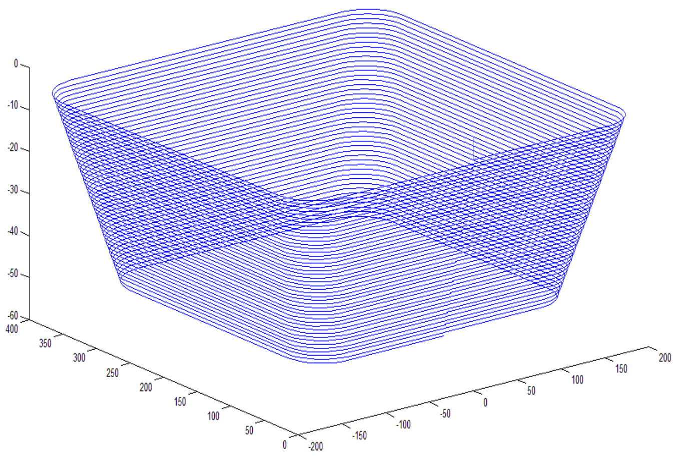

Figure 5. Tool Path Contours

While the process was happening, a rigid block was restricted of all the translational degrees of freedom. After the end on the stamping process, acceleration with the magnitude of 1g was imposed to the block on the direction of attenuator. Therefore, all the effects of the stamping process (thickness reduction, hardening and residual stresses) were measured during the numerical simulation of the impact, without needing to map the results between one and other simulation. The same condition was modeled to the attenuator welded. A rigid bulkhead was added 10 mm behind of

ISSN 2176-5480

the attenuator to restrict the deformation of it. The nodes of the edges of the two attenuators were restricted in all six degrees of freedom.

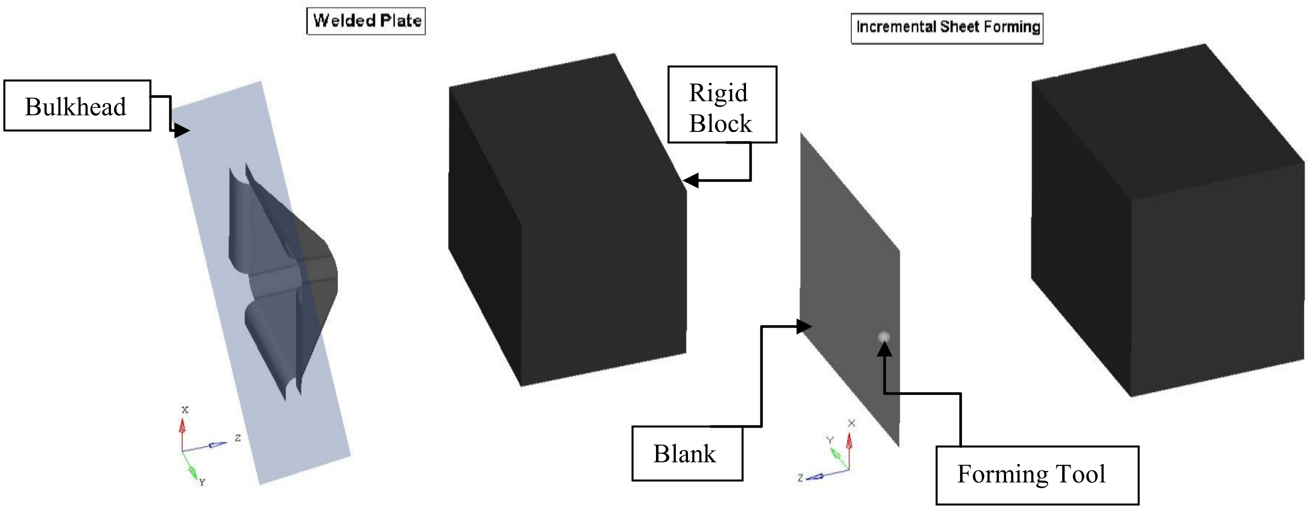

Figure 6. Boundary Conditions

6. RESULTS

In a first phase the results about the effects of the ISF process on thickness reduction and plastic strain were analysed. Unlike the conventional stamping processes, this one provides great modifications on the thickness and strain hardening of the material, and the disregard of these parameters during its application could lead to considerable errors on the simulation results.

It is importat to show that like in the experimental work of (Fritzen *et al*, 2011) we can observe that the final stamped part got a mark on the point of increment of the tool. This means that in this case the results on simulation met the expectations of the real process.

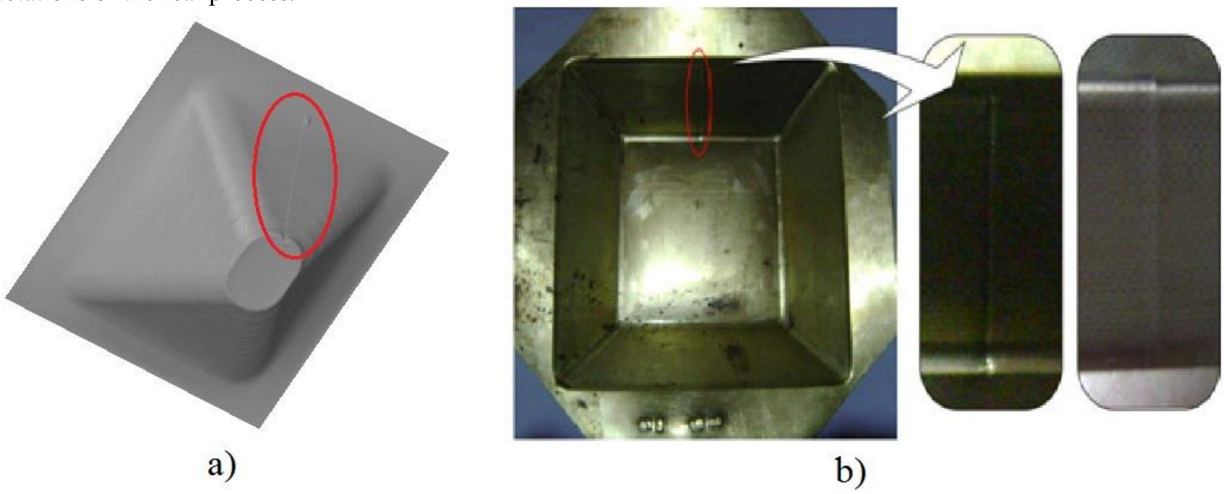

Figure 7 .a) mark of the point of increment of ISF simulation; b) mark of the point of increment of the experimental ISF process (source: FRITZEN, p. 10)

6.1 Thickeness and Plastic Strain Analysis

The results of the thickness of the impact attenuator model stamped by ISF showed that the sine law was respected with a little variation, given that the value predicted by this law is 1.28. The thickness has its minor values at the linear stamped wall and its major values where the tool describes curves of fillet.

The results on plastic strain showed an inverse relationship with the thickness, in other words, the plastic strain is higher on the linear part of the wall and has its minor values on the fillet region.

ISSN 2176-5480

This configuration of thickness distribution could be beneficial in terms of structural analyses, since that the most affected regions for an axial loading would be precisely the corners, regions that ended with the major values on thickness by the end of the ISF process. And the fact that this regions have gotten low rates of plastic strain, could also increase the amount of energy absorbed during the impact.

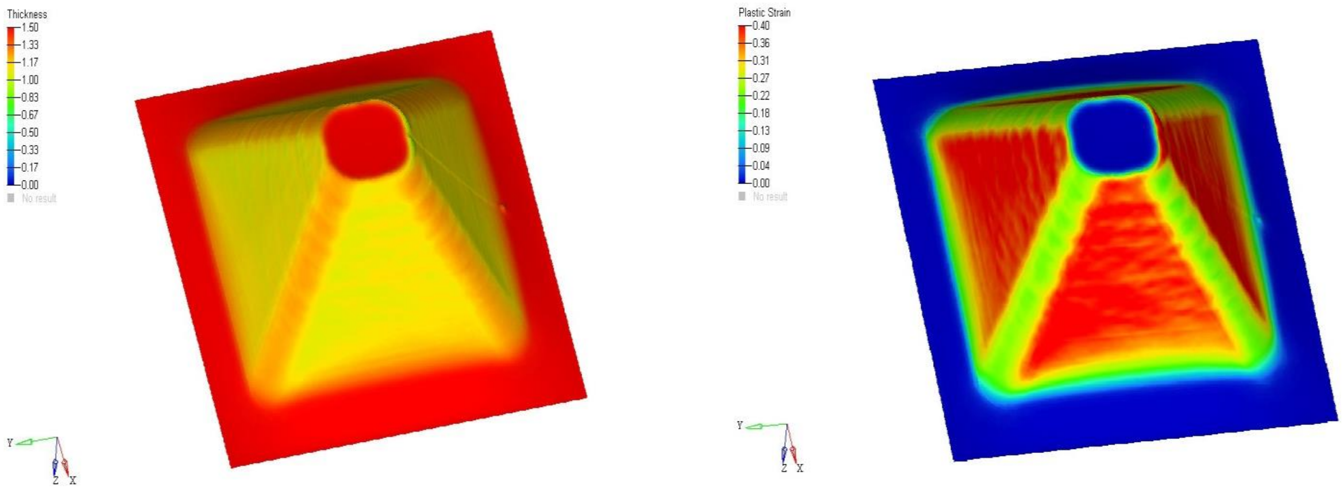

Figure 8.Thickness distribution (left). Plastic Strain contours (right)

6.2 Comparision of Stresses

Figure 9 shows the two models of attenuators – welded plates and by Incremental Sheet Forming - before the impact. It can be observed that the attenuator manufactured by the second method displays regions with residual stresses due the conformation of the processes which it was submitted. It is appropriate to emphasize that for this work the residual stresses due welding and bending processes on the first model were despised.

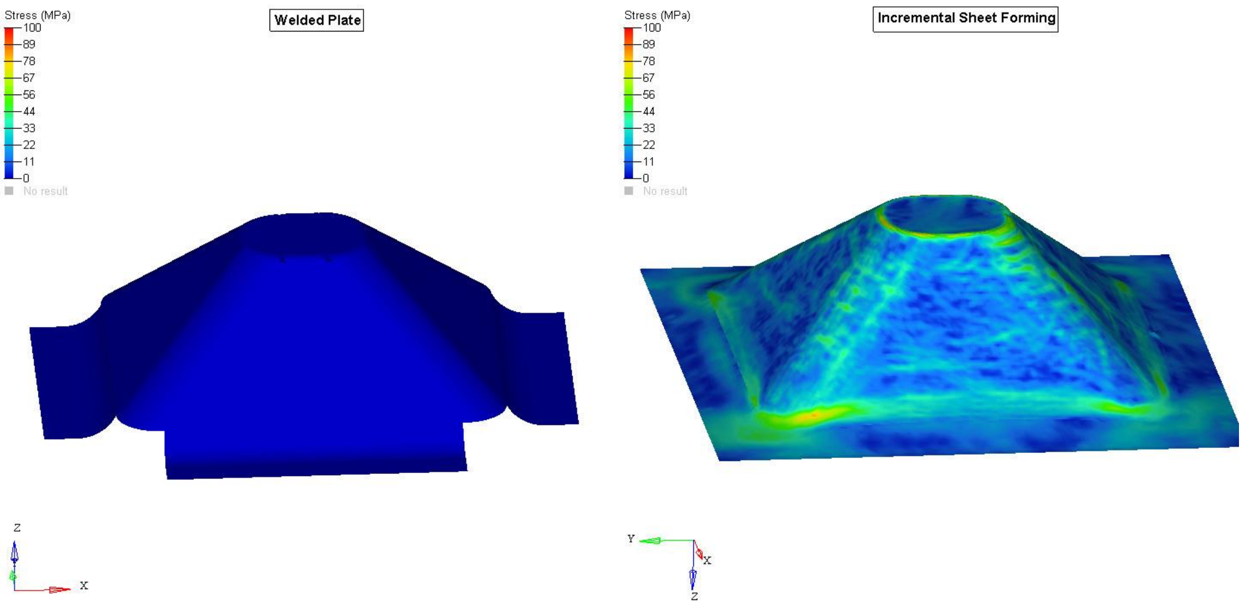

Figure 9. Stress contours before the impact

Figure 10 shows the attenuators after an impact with a total energy of 360 J. It can be noted that the welded attenuator deformed substantially on the top while the stamped attenuator deformed manly on its basis and more discreetly on the top. The corners of the stamped attenuator imposed a major restriction to the deformation. The fact that this one had high rates of hardening due to plastic strains during the conformation process could have affect to its low deformation.

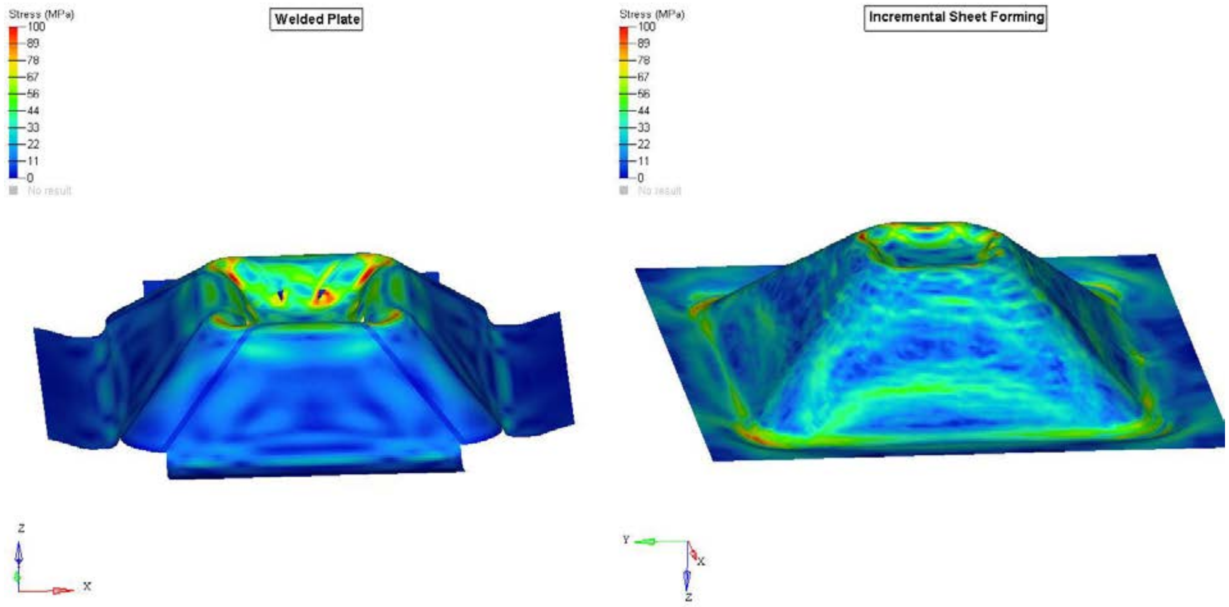

Figure 10. Stress contours after the impact

6.3 Force and Energy Analysis

Figure 11 displays the variation of internal energy of both attenuators models during the impact. It can be observed that the welded structure had a higher peck of deformation energy than the conformed one. This energy is directly proportional to the plastic strain that the component was subjected during the impact.

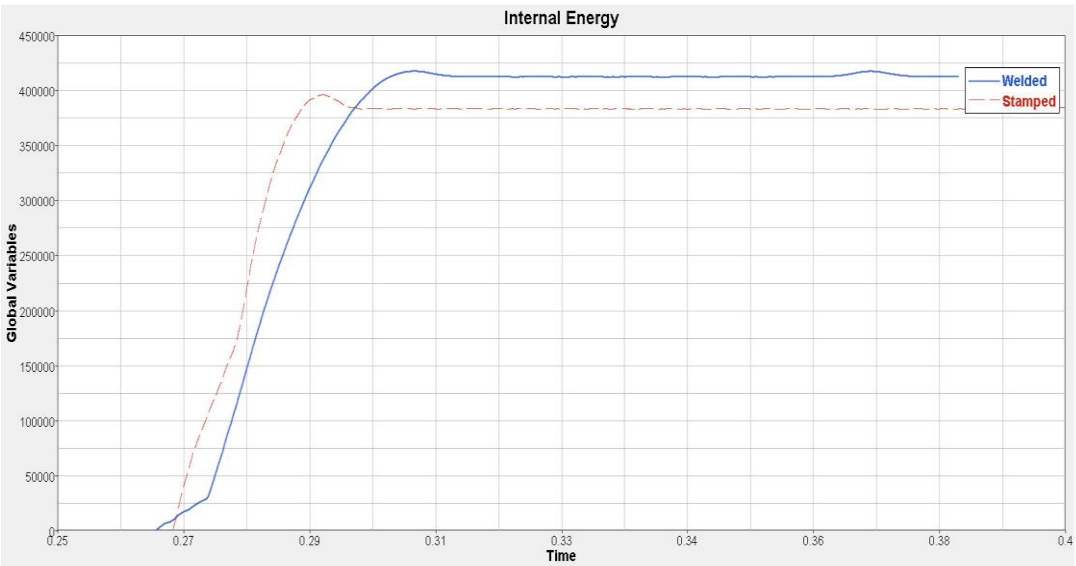

Figure 11. Curves of the variation of energy along time

Figure 10 shows that the variations of reaction force of the block during the impact for both structures. Despite the major peak of force happened on the welded attenuator, this one obtained an average value of reaction force lower than the stamped one, but with longer duration.

In the conformed structure is possible to identify two deformation range while the impact occurred. The first one on the peak of maximum strain was due to the deformation on the basis, and the second range where the force remained relatively stable happened due to strain on the top.

The both attenuators showed this baseline of progressive strain, however on the stamped one, the average value of forces is more elevated, making this one more efficient to absorb higher values of impact energy.

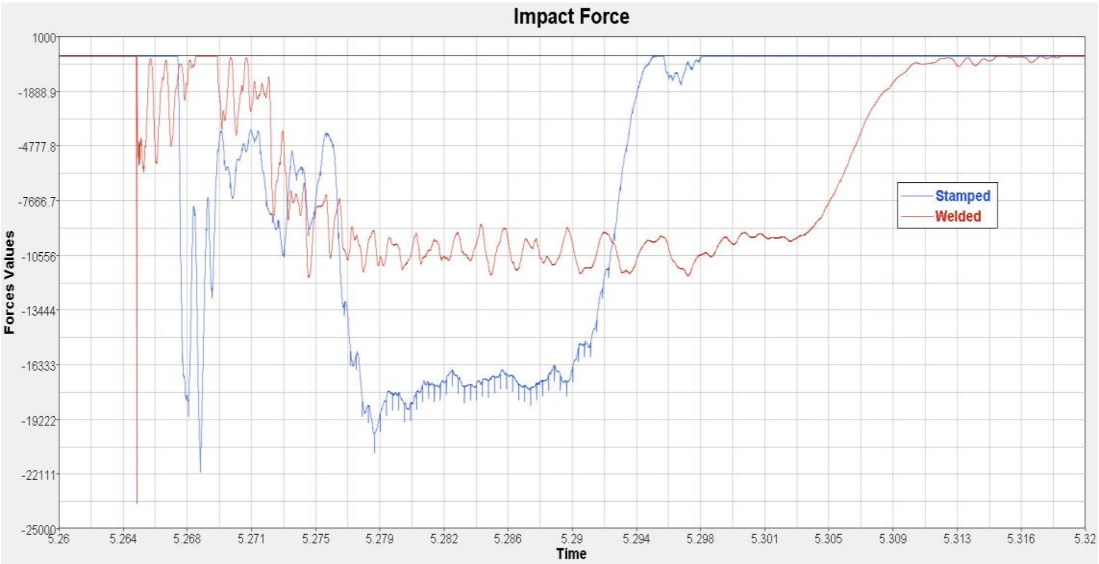

Figure 10. Curves of the variation of force during impact

7. CONCLUSION

This paper had by main objective to simulate by finite element method the manufacturing process of an impact attenuator by Incremental Sheet Forming Method. The data on final thickness and residual plastic strain were analysed indicating that the corners regions were the ones that obtained the higher final thickness values and, therefore, the lower values on residual plastic strain. In structural terms, this configuration proves to be well suitable to components subjected to axial loads, once that the corners have higher moments of inertia, being responsible as well as for the structural harness and for the plastic strain during an eventual impact.

For the purpose of evaluate the performance of the impact attenuator fabricated by ISF method in a crash test simulation, a rigid block was impacted against the attenuator with a equivalent kinetic energy of 360 joules. To avoid a loss of data derived of the conforming process, the ISF process and the impact were made in a single simulation. The results were confronted with an impact attenuator made by a conventional method (by bending and welding the sheet plates) with the same thickness of the cornering areas of the stamped attenuator. The results showed that, for the imposed energy, the conventional model had more deformation than the stamped one, indicating the importance of considering hardening values on the simulation. For further studies, it could worth to evaluate the behavior of attenuators on higher values of impact energy, where the stamped one tends to be more efficient. Also, the adoption of a failure criterion for the simulation became mandatory, because due to the high rates of plastic strain obtained during the stamping process, the attenuator could suffer fractures and cracks during the impact test, losing a part of its capacity of absorb energy.

8. REFERENCES

AZAOUZI, M., Nadhir, L., *Tool path optimization for single point incrmental sheet forming using response surface method.* Simulation Modeling Pratice and Theory 24: 49-58 (2012).

CASTELAN, Jovani. *Estampagem incremental do titânio comercialmente puro para aplicação em implante craniano*. Tese de Doutorado, LdTM, Universidade Federal do Rio Grande do Sul - UFRGS, Porto Alegre, 2010. 114p.

CHIAVERINI, Vicente. *Tecnologia Mecânica, Volume 1*, McGraw Hill, 1977.

FRITZEN, D., Lino S., Anderson D., Castelan J. *Estudo do processo de estampagem Incrmental em chapa de latão 70/30.* In: 31º SENAFOR / 14ª Conferência Nacional de Conformação de Chapas / 1ª Conferência Internacional de Conformação de Chapas, 2011.

JACKSON, K., Alwood, *The Mechanics of Incremental Sheet Forming,* Journal of materials processing technology 209 (2009), pp.1158–1174

JESWIET, J., *Incremental Single Point Forming*, Transactions of North American Manufacturing Research Institute, vol. XXIX, 2001, pp. 75-79.

JESWIET, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., Allwood, J., *Asymmetric Incremental Sheet Forming*, Annals of CIRP, v54, Issue 2, 2005, pp. 130-157.

SILVEIRA, M. E., *3D scanning applied in the correlation of large plastic deformation. Exacta* (São Paulo. Impresso), v. 10, p. 247-258, 2012.

SAMESIMA, F. T., AVILA, A. F., SILVEIRA, M. E., PASSOS, F. M., LEMOS, M. S., COTA, D. O. *Influence of metal forming on the material properties and correlation with experimental tests* In: XXXII IBERIAN LATIN-AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING, Ouro Preto, 2011.

TIBURI, Fábio. *Aspectos do processo de estampagem incremental***.** 2007. 96f. Dissertação (Mestrado)- Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais – PPGEM, UFRGS.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.