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Numerical Analysis of the ISF Process on Sheet with Locally Modified Material Flow Stress

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Abstract

The strategies of product making are considering how they affect the environment. In this scenario, production is pushing to new strong and lightweight materials and to a more suitable mass distribution to use the right material in the right place. An optimal design can be reached by both a proper material selection and use considering the stress distribution on the parts during their life in service. Flexibility in production is essential to be able to shape the products as designed. Incremental sheet forming (ISF) is a flexible manufacturing process, which allows processing various lightweight alloys. Severe sheet thinning is one of the main ISF limitations hindering the quality of the formed components and the efficiency of the production. These limitations result in an appeal weakening of ISF for industrial purposes. To overcome that, the material flow during ISF should be directed considering the strain level of the formed areas. Herein, the research aims at incrementally forming sheets, whose properties were modified locally by heat treatments. For example, the sheet properties can be tailored by laser light, which goes to modify the microstructure of the alloy in specific areas, considering the strain path given to the sheet. The goal is the inhomogeneity reduction of thickness distribution of the sheet. To investigate the problem in a wide range of variability, a numerical model has been set up. Specifically, a flat mesh was first defined and, subsequently, the material properties have been assigned to shell elements considering the differences in the material flow stress ascribable to the grain structures. The material data were extracted by literature. Conical frustums with helical tool path were numerically produced. An intensive understanding on how the ISF mechanism is influenced, if the sheet properties are locally customized, is provided.

Keywords: ISF; thinning; material properties; FEM.

1. Introduction

The demand of customized products with low environmental impact is increasing in recent times. The more appropriate manufacturing process plays a key role as well as the smart mass and strength distribution. In this context, incremental sheet metal forming (ISF) represents a promising and economical manufacturing process [1] for low volume and complex shapes.

The research has already explored various aspects of this process with the objectives of improving the surface integrity and performance of the products [2,3], but also some dependent aspects such as the reduction of tool wear [4] and/or the production times [5,6].

However, the mechanical properties of components manufactured by ISF are affected by severe sheet thinning. In fact, the most important drawback of incremental forming, which limits its application to structural parts, is the excessive thinning due to the localized forming zone [7,8].

Various approach has been devolved to overcome this limitation. Azaouzi et al. [9] focused the attention on the tool path optimization in order to reduce the manufacturing time and homogenize thickness distribution of an asymmetric part. For the same purpose, some other studies have been performed

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during the time. Attanasio et al [10] based their tool path optimization approach on the application of a variable step depth to increase accuracy and to reduce thinning. Duflou et al. [11] based their strategy of improving the geometrical accuracy and the thickness distribution consequently adding a laser source in the conventional equipment and so performing a heat-variant of ISF. Finally, Taleb-Araghi et al. combined ISF and stretch forming to speed up the process and manufacture parts with a reduced thinning [12].

More recently Ambrogio et al. [13,14,15] demonstrated that the local deformation, typically of ISF, can be controlled by locally changing the strength of the sheet, by additive o subtractive processes. Actually, this approach, based on the ISF hybridization, was previously introduced by Schulte et al [16] in a preliminary attempt to combine ISF with a forming technique in order to obtain parts with a more homogeneous profile.

The main goal of this paper is a further study on the thickness optimization along the shaped wall by introducing a new approach. More in detail, in this work the research has been focalized on the evaluation of thickness distribution of part obtained by ISF process starting from an initial sheet with a locally modified material flow stress. The basic idea is to tailor the sheet properties by a laser source which goes to modify the microstructure of the alloy in specific areas.

To do that, the numerical model has been set up and used to evaluate the material distribution along the wall side of the formed parts changing the position of the laser-treated zone. All the details are discussed in the following sections.

2. Material and method

The research procedure aims to perform a series of numerical investigations of the ISF process on sheets with locally modified material flow stress. For sake of simplicity, a conical frustum was considered as final shape. Three different positions for the laser-treated zone were chosen along the shaped wall. The thickness distribution was evaluated numerically by using both implicit and explicit time integration scheme [17].

The finite element model and the numerical investigation on the thickness distribution are detailed in the following subsections.

2.1. Material

The material considered is AA 6060-T4. The local laser heat treatment of precipitation-hardenable aluminum alloys enables the tailoring of the material properties. In this case, the sheet is softened by short term heat treatment in order to improve the material flow during the forming process. The material data for the AA 6060-T4 before and after the heat treatment were extracted by literature [18].

An intermediate zone of 5mm was also considered on both sides of the laser-treated zone to consider a thermally altered transition sector. In this sector, the material strength was assumed as the average value of the other two zones, as reported in Fig. 1.

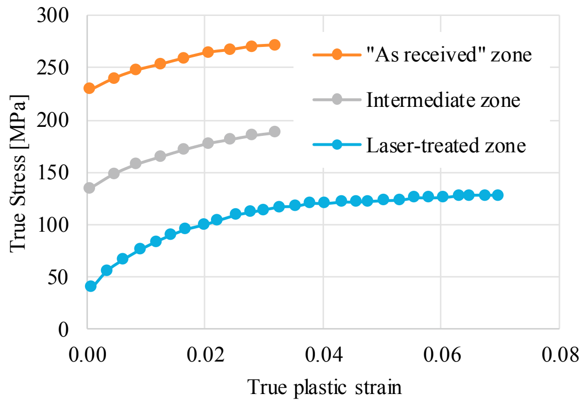

Fig. 1. Stress-strain curves for the three sectors.

2.2. Part geometry

Square sheets (240x240mm^2) with a thickness of 2mm, made of AA6060-T4, are the blanks in the "as-received" condition.

The initial strength of the sheet was locally altered by local heat treatment in specific zones. The heat treatment was performed using a spot size of 5mm and an intermediate zone of 5mm was considered on both sides of the laser-treated zone, as reported in Fig. 2, where A is the inner radius of the inner intermediate zone, B is the inner radius of the laser-treated zone and C is the inner radius of the outer intermediate zone.

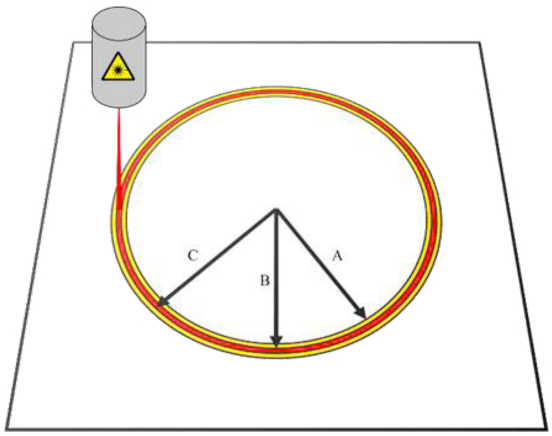

Fig. 2. Geometrical model of the sheet tailored by laser light.

Furthermore, three different positions for the laser-treated zone were considered in the forming zone, as reported in Table 1, thus introducing three distinct case studies.

Table 1. Position of the laser-treated and intermediate zone

	A [mm]	B [mm]	C [mm]
Case 1	75	80	85
Case 2	65	70	75
Case 3	55	60	65

The truncated cone, having a depth larger than the tool punch diameter [7], is considered the most promising benchmark profile to investigate the thickness distribution in steady-state conditions. To pursue this aim, a major base of 180mm, a final depth of 40mm and a wall angle of 50° were the imposed dimensions. According to the considered alloy, the imposed wall angle is larger enough to guarantee the insurgence of localised thinning phenomenon in an evident way but smaller enough to ensure the process feasibility [19].

2.3. Models set-up

In order to investigate the influence of the local heat-treatment on the sheet, two finite element models were developed. The first finite element model was developed with Abaqus/Implicit.

Specifically, dynamic implicit quasi-static simulations were performed. The sheet was meshed with four-node shell elements (S4R) with reduced integration. Five Gauss integration points were set along the thickness. A refined mesh with an approximate global size of 2 mm in the areas deformed by the tool was generated for consistent results, while 3 elements were set along the width of the laser and the intermediate zone. The number of elements is approximately 5500 (depends on laser position). The tool used is a hemispherical punch with a radius of 6 mm and it was modeled as a discrete rigid part. The step depth of 0.5mm between two subsequent partial coils is reached gradually while the tool moves in the circumferential direction. The tool trajectory is simulated as a spiral-cone path through displacement boundary conditions. The contact is modeled as Surface-to-Surface contact, while in contact property the coefficient of friction was set to 0.1. A “Hard” Contact Normal Behavior with Penalty Constraint enforcement method was added to reduce the penetration between bodies and to improve the convergence of the numerical simulation. In order to consider the material difference after the heat treatment, the blank was partitioned to three sections. Each sector has been assigned to its specific material behavior as discussed in Sec. 2.1. The initial configuration of this model is represented in Fig. 3.

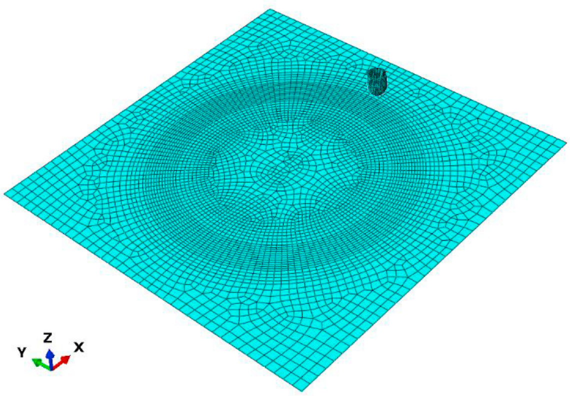

Fig. 3. Finite element model.

Since the ISF implicit simulation is very demanding computationally, a second finite model was developed with Abaqus/Explicit, keeping the same mesh size and design.

The explicit integration scheme is conditionally stable, which implies a limit on the time step size limited by the characteristic element size and by the speed of sound within the material. For this reason, the stable time step is usually small and this implies a long time to complete the process. However, with this integration scheme, mass scaling and time scaling could be used to reduce the computational time. In this work, semi-automatic mass scaling is used, such that the simulation has a time step of 2E-06s. The required tool path was set as velocity boundary condition to reduce the amount of kinetic energy in the model since a displacement-based tool trajectory results in velocity jumps [20]. The punch velocity was artificially increased to further reduce the analysis time. This does not affect the obtained results being the material properties no strain rate depended. The tool velocity was assumed to be 10m/s. The contact is modeled as Surface-to-Surface contact (Explicit) with the “Kinematic contact method” formulation.

All the details of the numerical model are summarized in Table 2.

Table 2. Details of the implemented numerical simulations.

Parameters	Value
Element type	Four node shell elements
Number of elements	5500
Thickness integration point	5
Element integration	Reduced
Hourglass control	Stiffness
Friction	Coulomb, friction coefficient: 0.1
Young's modulus	68 GPa
Poisson Ratio	0.33

The required time to complete the simulation with mass and time scaling was approximately 4h against 170h of the implicit one.

3. Discussion of the results

The first two simulation runs were performed on the square sheet without laser heat treatment to make some considerations on the thickness distribution along the side wall (Fig. 4) with the two different time integration schemes (Fig. 5).

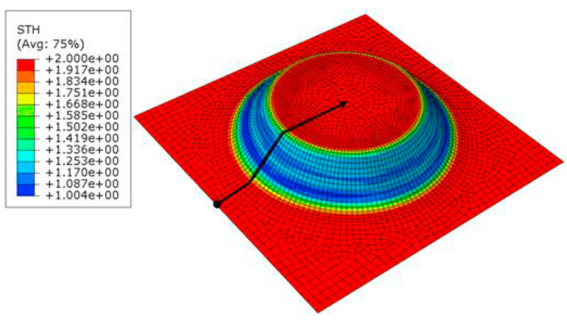

Fig. 4. The selected points where the sheet thickness was evaluated.

The more acute thinning in the explicit run is probably due to the high kinetic energy transmitted through the tool during the movement although the ratio between kinetic and internal energy is less than 10%. The final thickness t_f for single-pass uncompensated tool paths is an approximate function of the wall angle θ and initial thickness t_0 given by the relation:

$$t_f = t_0 * \cos\theta \quad (1)$$

From this relation, the implicit one seems more accurate, but since we are interested in the qualitative trend, without an experimental benchmark at this stage, in the next sections the explicit integration scheme will be considered.

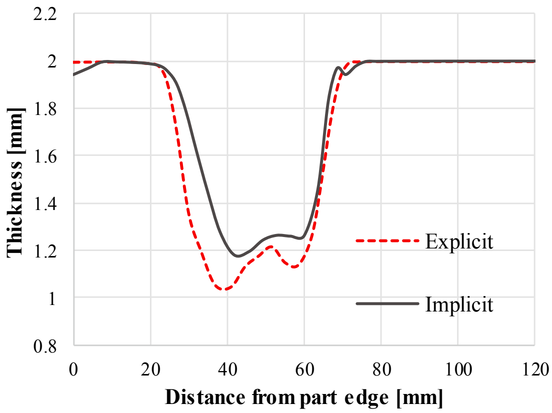

Fig. 5. Explicit vs. Implicit thickness.

However, it has to be highlighted that, the numerical analysis is performed in the same way for all the investigated cases and, therefore the comparison of the various thickness trends is qualitatively not affected by the time integration scheme, despite some oscillations in the geometric profile [21].

3.1. Numerical analysis of the thickness distribution

Explicit simulations were performed to analyze the effect that the local laser heat treatment on the sheet causes on the thickness distribution along the deformed wall side. Figure 6 summarizes the numerical investigation and highlights the comparison between the thickness distribution of the conventional profile and of the tailored ones in the three cases.

As expected, the thickness distribution along the shaped wall of the frustum of cone, although some scattering, is influenced by the local laser heat treatment. First of all, the local softening of the sheet focuses the deformation in this part of the blank, which shows reduced strengths relieving the surrounding zones. At the same time, the adjacent zones undergo a moderated thinning. For all three cases, the numerical thickness trend is higher than the one obtained on the conventional sheet along the wall of the cone before the laser-treated zone. For *Case 2* and *3,* the more consistent thinning occurs on the laser-treated zone, while in *Case 1* the minimum thickness is reached in the intermediate zone. This difference could be justified by the position of the laser zone with respect to the thinning phenomena. Indeed, as highlighted in Fig. 6a, the laser position coincides with the minimum thickness of the conventional profile.

Despite the larger and severe thinning in the softened area, the thinning results positively altered in the rest of the sheet where the thicker profile is measured. At the same time, the excessive thinning could be also balanced by playing on the intensity of the laser treatment with multi-objective optimization of the process that should be performed achieving the right process set up. In any case, the conceived approach aimed at a numerical investigation in a landmark case, where the yield strength decreases by 80%, therefore the unavoidable large thinning in the laser zone is just a natural consequence.

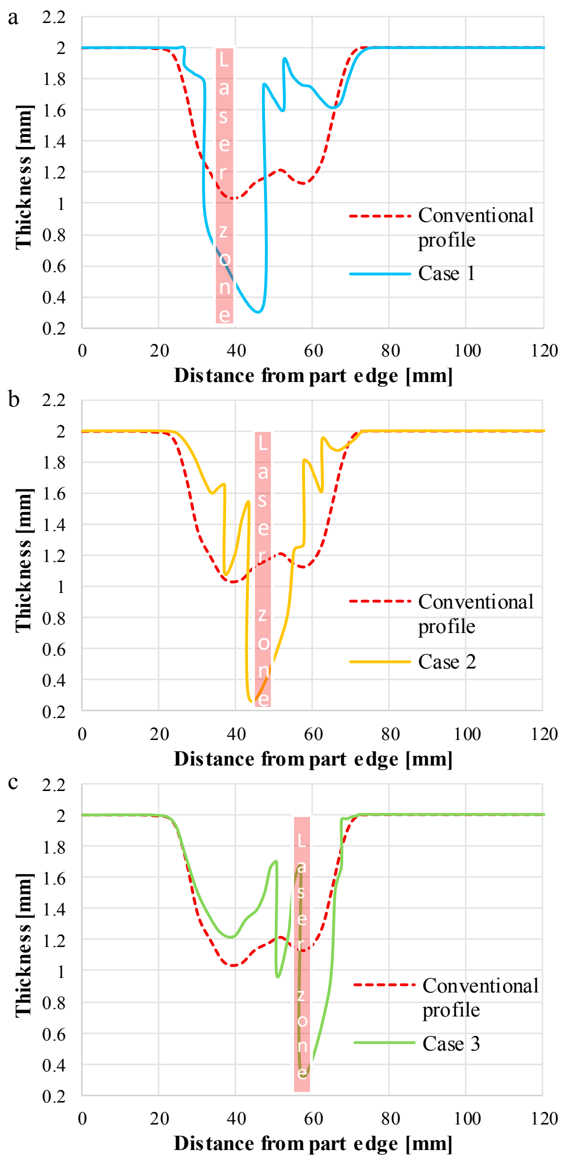

Fig. 6. Thickness s comparison between conventional and tailored blanks in: (a) Case 1; (b) Case 2; (c) Case 3.

Furthermore, it is worthy of note that the large scattering in the thickness profile could be partly ascribed to the numerical model peculiarity. To reduce the oscillation in thickness, indeed, it could be necessary to increase the number of the integration points along the thickness as well as the number of elements in the deformed zone.

This approach highlights just qualitative evidence of the analyzed phenomenon. However, the obtained results are thought of as a starting point useful to the implementation of complete experimental research. Finally, an experimental dimensional check would be appropriate with a view to verify that the final geometry is not altered by the laser softening.

4. Conclusion

As it is well known, the weak point of the incremental sheet forming is the inhomogeneous thickness distribution along the deformed zone. Moreover, the manufactured products are stressed by loads with not homogeneous distribution in all their area. These two questions could be found a common ground if a solid strategy will be developed in order to customize and to alter the thinning distribution of the sheet during incremental forming.

In general, the obtained material distribution depends on the final shape and on the chosen punch trajectory and, therefore, it cannot be customized as required.

In this context, numerical explicit analyses were performed with the aim to simulate the incremental forming of tailored sheets characterized by local laser heat treatment in specific zones.

The numerical evidence has shown that suitable local laser heat treatment on the sheet can be promising to control the thinning on the processed parts extending the formability limits. The reported results must be considered preliminary data, which need to be confirmed first by experimental evidence. Further investigations could be conducted in order to evaluate experimentally the effect of the laser heat treatment on the final thickness distribution in order to quantify the relevance of this behaviour. Simultaneously, a proper characterization of the material flow stress will be needed for consistent results. Once the feasibility will be confirmed, the proposed solution will be extended designing altered thickening to the blank to manufacture.

References

[1] Behera, A. K., de Sousa, R. A., Ingarao, G., & Oleksik, V. (2017). Single point incremental forming: An assessment of the progress and technology trends from 2005 to 2015. Journal of Manufacturing Processes, 27, 37–62. https://doi.org/10.1016/j.jmapro.2017.03.014

[2] E. Uhlmann and C. Hübert, in Proceedings of the ASPE, Raleigh, NC, USA (2007)

[3] H. Ding and Y. C. Shin, Int J Mach Tools Manuf 50 (1), 106-114 (2010)

[4] U. Heisel, J. Wallaschek, R. Eisseler and C. Potthast, CIRP Ann Manuf Technol 57 (1), 53–56 (2008)

[5] M. Ono, Y. Shinbo, A. Yoshitake and M. Ohmura, NKK Technical Review 86, 70–74 (2002)

[6] J. Duflou, B. Callebaut, J. Verbert and H. De Baerdemaeker, CIRP Ann Manuf Technol 56 (1), 273–276 (2007)

[7] L. Manco, L. Filice and G. Ambrogio, Proc IMechE Part B 224 (2011)

[8] Maaß, F., Hahn, M., Dobecki, M., Thannhäuser, E., Tekkaya, A. E., & Reimers, W. (2019). Influence of tool path strategies on the residual stress development in single point incremental forming. Procedia Manufacturing, 29, 53–58. https://doi.org/10.1016/j.promfg.2019.02.105

[9] Azaouzi, M., & Lebaal, N. (2012). Tool path optimization for single point incremental sheet forming using response surface method. Simulation Modelling Practice and Theory, 24, 49–58. https://doi.org/10.1016/j.simpat.2012.01.008

[10] Attanasio, A., Ceretti, E., Giardini, C. (2006). Optimization of tool path in two points incremental forming. Journal of material processing technology, 177/1-3, 409-412

[11] Dufou, R., Callebaut, B., Verbert, J., De Baerdemaeker, H. (2007). Laser Assisted Incremental Forming: Formability and Accuracy Improvement. Cirp Annalls 56(1), 273-276

[12] B. Taleb Araghi, G. L. Manco, M. Bambach and G. Hirt, Ann CIRP 58 (1), 225-228 (2009)

[13] Ambrogio, G., Gagliardi, F., Serratore, G., Ramundo, E., & Filice, L. (2019). SPIF of tailored sheets to optimize thickness distribution along the shaped wall. Procedia Manufacturing. https://doi.org/10.1016/j.promfg.2019.02.109

[14] Gagliardi, F., Ambrogio, G., Cozza, A., Pulice, D., & Filice, L. (2018). Numerical analysis of tailored sheets to improve the quality of components made by SPIF. AIP Conference Proceedings. https://doi.org/10.1063/1.5035033

[15] Serratore, G., Gagliardi, F., Filice, L., Bentrovato, R., & Ambrogio, G. (2019). 3D numerical analyses of SPIF performed on tailored sheets to control their thinning. AIP Conference Proceedings, 2113. https://doi.org/10.1063/1.5112730

[16] Schulte, R., Hildenbrand, P., Lechner, M., Merklein, M. (2017). Procedia Manuf 10, 286-297

[17] Bambach, M., & Hirt, G. (2007). Error analysis in explicit finite element analysis of incremental sheet forming. AIP Conference Proceedings. https://doi.org/10.1063/1.2740918

[18] Merklein, M., Böhm, W., & Lechner, M. (2012). Tailoring Material Properties of Aluminum by Local Laser Heat Treatment. Physics Procedia, 39, 232–239. https://doi.org/10.1016/j.phpro.2012.10.034

[19] Jeswiet, J. et al. (2005). Asymmetric Single Point Incremental Forming of Sheet Metal. CIRP Annals, 54 (2), 88-114

[20] Maqbool, F., & Bambach, M. (2018). Dominant deformation mechanisms in single point incremental forming (SPIF) and their effect on geometrical accuracy. International Journal of Mechanical Sciences. https://doi.org/10.1016/j.ijmecsci.2017.12.053

[21] He, S., van Bael, A., van Houtte, P., Tunckol, Y., Duflou, J. R., Henrard, C., … Habraken, A. M. (2005). Effect of FEM choices in the modelling of incremental forming of aluminium sheets. Proceedings of the 8th ESAFORM Conference on Material Forming.