Materials Research Proceedings 25 (2023) 93-98 https://doi.org/10.21741/9781644902417-12

Numerical model design for accuracy prediction of parts made by hybrid incremental sheet forming

Giuseppina Ambrogio[1,a], Giuseppe Serratore[1,b], Luigino Filice[1,b] and Fabrizio Micari[2,d,*]

[1]Departiment of Mechanical, Energy and Management Engineering, University of Calabria – 87036 Rende (CS), Italy

[2]Department of Engineering, University of Palermo – 98128 Palermo, Italy

[a]giuseppina.ambrogio@unical.it, [b]giuseppe.serratore@unical.it, [c]luigino.filice@unical.it, [c]fabrizio.micari@unipa.it

Keywords: Incremental Sheet Forming, Finite Element Method (FEM), Hybrid Manufacturing

Abstract. Hybrid manufacturing is a promising approach which helps to efficiently improve the performance of conventional manufacturing processes, just contemporary considering different technologies. The suitable combination of Incremental Sheet Forming (ISF) with subtractive or additive processes has been already demonstrated in the past as alternative approach to compensate excessive thinning or low accuracy of the produced parts. Focusing on the last solution, based on the coupled use of ISF and Additive Manufacturing (AM), a new challenge related to the design of a robust numerical model able to predict the behavior of the hybrid-material is still open. In this paper, this issue has been considered and an experimental-numerical validation is proposed.

Introduction

Nowadays the mass customization (MC) is the right technological paradigm that companies have to implement as production strategy if they want to be competitive on the market, because it aims at providing customized products to consumers in large volumes and at costs reasonably low compared to conventional customization processes [1]. Naturally, only in the last twenty years the growth of MC became more evident and wider, thanks to the development of advanced manufacturing technologies and to the increased demand for diversity in the products' range. All these implied the increasing need of production methods focusing further on the individual [1]. During the past years scientific literature offers more technological solutions to implement rapid manufacturing strategy useful for mass customization: dieless forming, additive techniques but specially their hybridization represents a promising approach [2].

Dieless forming is a technique to form sheet metal into three-dimensional shape, firstly introduced in 1994 by professor Matsubara [3] and then engineered by AMINO [4].

As promoted by the founder, the dieless forming is based on the incremental forming principle, pursued by a numerical control machine which drive a hemispherical punch along an assigned and concentric 3D path. The result of this incremental forming methodology is the three-dimensional geometry which reproduce the desired shape without the requirement of additional dedicated and expensive equipment. The simplest configuration of this methodology, named Incremental Sheet Forming (ISF) requires just a CNC machine and clamping frame for the sheet [5]. The sheet is deformed by the punch action but it is also free to move during the repetitive passes, as a consequence rigid movement as well undesired springback are the main drawbacks. Nevertheless, the flexibility and the readiness of this technological solution is not negligible, thus it is a promising alternative for rapid manufacturing.

Starting by a completely different way to interpret the part manufacturing, Additive Manufacturing (AM) techniques represent the modern solution for any type of industry. Within AM family are included all the techniques where objects can be fabricated directly from CAD design without tools or specially designed jigs/fixtures and involves minimal human intervention [6]. Implementing an AM process, the fabrication of unique parts or products with hollow and mould cavities are easily obtainable. Appreciable economic advantages, such as part lightening or reduced time to market, can be achieved by replacing conventional manufacturing with AM techniques in many applications [7]. Design cycle is shortened by a huge extent owing to which products can be quickly brought to market. The application of AM in aerospace sectors showed a mass saving exceeding 50% that combined with the reduced batch dimension typically required places this technique as the most promising. Naturally, AM has own drawbacks that still today penalise the application, such as the long execution time and the total part dimension [7].

More recently, an innovative approach has been introduced founded on the idea to emphasize the impact of the only positive aspects of the manufacturing processes by their integration. More specifically, hybrid manufacturing was formally introduced in 2009, when Schuh et al [8] proposed the following definition: "hybrid means the combination of processes and machines in order to produce parts in a more efficient and productive way" using the *''1 + 1 = 3''* effect and allowing to process materials or shapes which could not be manufactured before or at lower cost. Existing hybrid solutions were summarized in 2014 by Lauwers et al [9], but the development of hybrid process is continuously evolving driven by industrial needs of engineered products and by social aim of higher energy saving.

In 2019, Ambrogio et al. [10] introduced the additive-incremental forming by combining the high flexibility and high readiness of ISF with the versatility of AM. Specifically, the ISF hybridization was promoted pre-treating the blank by AM step with a double aim: for the product accuracy, in order to alter the thinning phenomena and increase the sheet rigidity, or for obtaining more complex 3D shape characterised by concave profile and undercut. Satisfactory results were found but the experimental investigation highlighted an evident weakness in the hybrid process calibration. According to this, the present study is based on the design of a numerical model for helping the additive-incremental forming set up of multi material blanks.

Material and method

The hybrid material model considered is an AISI 304 stainless steel blank thickened locally by an AISI 630 stainless steel crown performed by AM. Specifically, the thickening is a 0.4 mm layer performed by selective laser sintering (SLS). Thanks to the flexibility of the AM process is possible to design and produce tailored blanks without any shape limitation and then, thanks to the flexibility of the ISF process is possible to produce the desired parts with improved geometric accuracy and/or mechanical performances. The chemical and the mechanical properties are reported respectively in Table 1 and Table 2.

Table 1 - Chemical composition of the utilized stainless steels.

Material [%]	C	Mn	P	S	Si	Cr	Ni	Other
AISI 304	0.07	2.0	0.045	0.015	1.0	17-19	8-10	N (<0.11)
AISI 630	0.07	1.5	0.040	0.030	0.7	15-17	3-5	Cu (3-5)

Materials Research Proceedings **25** (2023) 93-98 https://doi.org/10.21741/9781644902417-12

Table 2 - Mechanical properties of the utilized stainless steels.

Materials	Hardness Vickers	Young's Modulus [GPa]	Tensile Strength Yield [MPa]	Tensile Strength Ult. [MPa]	Elong. at break %
AISI 304	205	195	295	660	40
AISI 630	310	197	869	993	20

The AISI 304 is characterized by a better formability while the AISI 630 is used as a reinforcement. The experimental methodology started with a preliminary step performed for thickening the blank by the material deposition, layer by layer, with single films of thickness 40 μm. A sintering laser system printer was adopted and a circular and homogeneous ring was overlapped on the blank. The total thickness of the sintered material is equal to 0.4 mm. Specifically, the sheet is characterized by a side of 180 mm and a thickness of 1.1 mm, while the circular crown is characterized by an internal and external diameter of 70 mm and 140 mm, respectively. Fig. 1 shows the back-side view of the manufactured part in the working area of 140 mm x 140 mm.

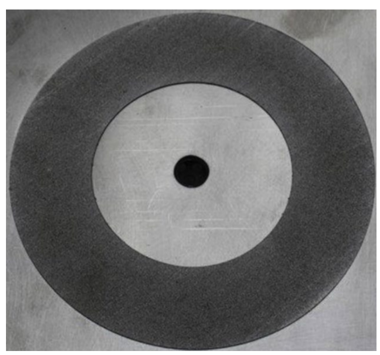

Fig. 1 - Back-side view of the reinforced sheet.

After this preliminary phase, a truncated cone with a base diameter of 70 mm, a slope angle of 50°, and a final height of 30 mm was manufactured by ISF. Three replications were performed by imposing the following parameters during ISF: tool diameter of 12 mm, depth step of 0.5 mm, tool rotation of 300 rpm, and feed rate of 2000 mm/min.

Finally, after the manufacturing phase, the obtained parts were postprocessed and scanned by a MINOLTA laser system in order to catch the geometrical accuracy. Specifically, to remark the suitability of the ISF hybridization the same geometry was also performed by the conventional approach and working on the simple material blank.

Numerical model

A numerical model (Fig. 2) with the commercial software Abaqus was developed to model the behavior of a multi-material sheet formed with the hybrid additive-ISF process. According to the experimental background, the numerical model on hybrid material considered an AISI 304 stainless steel blank thickened locally by an AISI 630 stainless steel. A linear hardening elastoplastic behavior was considered based on the mechanical properties reported in Table 2. The tool was modeled as rigid body with R3D4 and R3D3 shell rigid elements and the blank, composed of two different bodies, as a shell deformable body with S4R shell elements with 5 integration points along the thickness direction. A surface-to-surface finite-sliding contact model was used to the define the contact between the tool and the blank. The friction between the tool and the blanks

Materials Research Proceedings **25** (2023) 93-98 https://doi.org/10.21741/9781644902417-12

was modelled according to the Coulomb's formulation considering a coefficient of 0.1. The periphery of the blank was pinned and the tool path was generated with a CAD/CAM software. The connection between the base blank and the sintered layer was modelled considering a fully constrained contact behavior. A tie constrain was employed to model the permanent bond of the circular crown on the base blank to obtain no relative motion between them. This constraint assume an ideal bond and it prevents the separating or relative sliding between the nodes of the tie constrained surfaces.

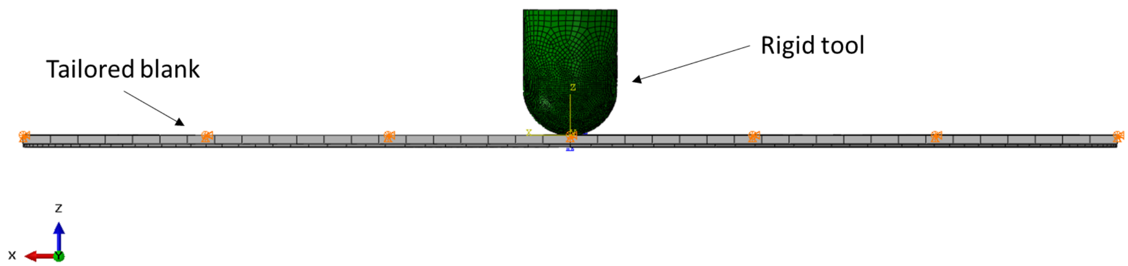

Fig. 2 - Lateral view of the simulation setup.

The numerical problem was solved with the explicit solver to evaluate the final profile and thickness. A semi-automatic mass scaling was employed with a target time increment equal to 2e-6 s. Fig. 3 depicts the modelled simulation assembly considering only the working area of 140 mm x 140 mm:

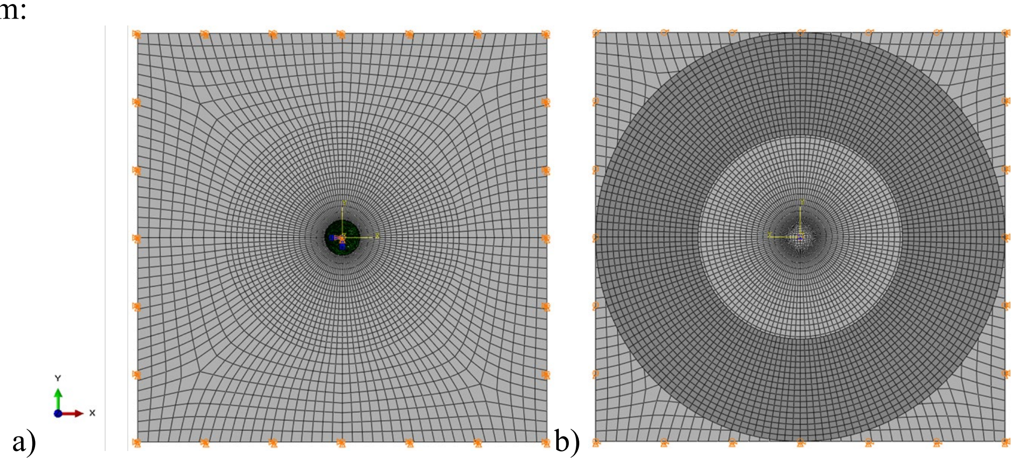

Fig. 3 - Front view (a) and Backside view (b) of the simulation setup.

Subsequently, a second step was simulated after the forming phase removing the tool and the boundary conditions to consider the spring back-effect. After to the model tuning, each simulation lasted 550 min running on an Intel Xeon W-2175 CPU.

Discussion of the results

This section deals with a comparison between the section profile of the truncated cone in terms of deviation from the ideal profile. In this way, the first experimental result was obtained comparing the sections along the part transversal section. As highlighted in Fig. 4 the hybrid and multi-material approach enhances the part accuracy.

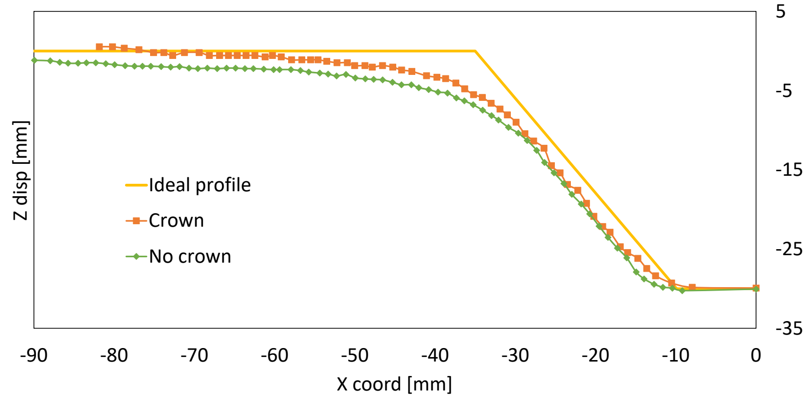

Fig. 4 Comparison along the transversal section between parts obtained by conventional ISF (i.e. no crown) and hybrid additive-incremental forming (i.e. crown).

Fig. 5 shows the results obtained with the circular crown while Fig. 6 without reinforcement. These results show that the developed model could be effectively used to predict the final shape of the manufactured parts even in the case of tailored blanks via AM technique. Although slight difference between numerical and experimental result, due for example at the deformation during the cutting of the sample, or due to the resolution of the 3D laser scanning system, an improvement is obtained with the addition of the circular crow, as expected from the previous experimental investigation [10].

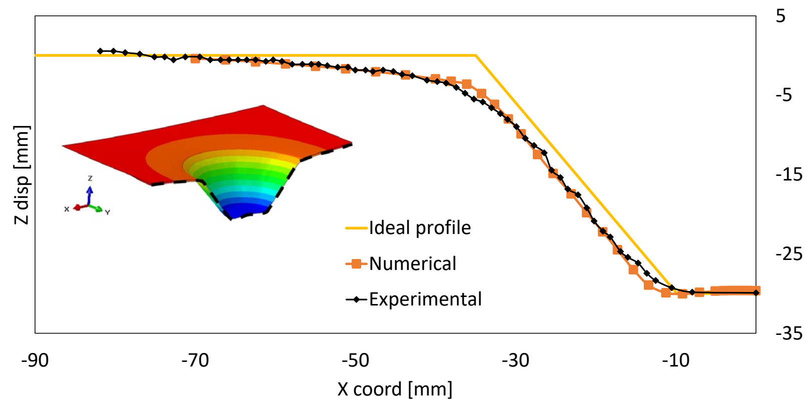

Fig. 5 - Section profile of the truncated cone with circular crown.

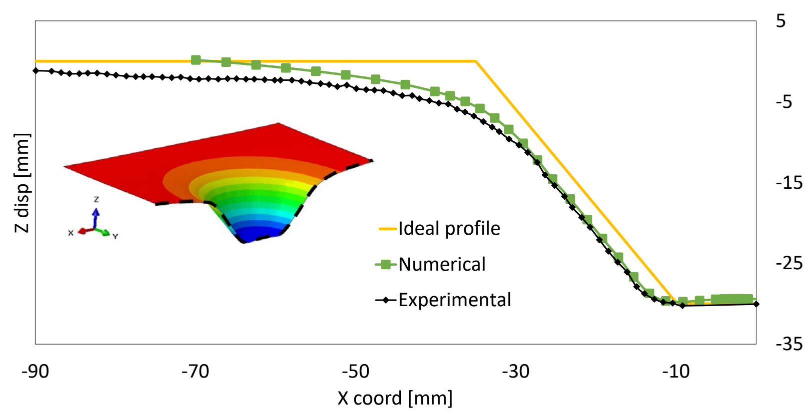

Fig. 6 - Section profile of the truncated cone without circular crown.

Other than what is shown Fig. 5, the deviation between numerical and experimental results in Fig. 6 is mainly due to the pinned boundary condition, since alone the working area is modelled. In the experimental results there is the stringback effect of the clamped zone which was not modelled. This emphasizes the beneficial effect of the reinforcement which improves the clamping condition of the blank, and which approaches the ideal condition of the numerical model.

Summary

In the present work, a simplified numerical model is proposed with the aim to develop a tool able to predict the final shape of a hybrid manufacturing process obtained combining ISF and AM. Incremental forming, in fact, is not yet a consolidated industrial process due to some drawbacks which reduce its suitability. Among them, accuracy is probably one of the most critical. The use of hybrid ISF-AM process may reduce substantially the final shape inaccuracy, but a proper design of the added volume has to be carried out, thus a robust numerical tool is strictly required.

In this paper the tailored blank has been simulated by Abaqus and a significant improvement of the final accuracy has been predicted.

As the future work, this approach will be further developed by means of cohesive elements to tune and experimental outcomes, in order to assess the process feasibility also avoiding any breaking on the interface between different materials.

References

[1] G. Da Silveira, D. Borenstein, F.S. Fogliatto, Mass customization: Literature review and research directions, Int. J. Prod. Econ., 72 (2001) 1–13. https://doi.org/10.1016/S0925-5273(00)00079-7

[2] D. Deradjat, T. Minshall, Decision trees for implementing rapid manufacturing for mass customisation, CIRP J. Manuf. Sci. Technol., 23 (2018) 156–171. https://doi.org/10.1016/j.cirpj.2017.12.003

[3] S. Matsubara, Incremental backward bulge forming of a sheet metal with a hemispherical head tool-a study of a numerical control forming system II, J. Japan Soc. Technol. Plast., 35 (1994) 1311–1316.

[4] M. Amino, M. Mizoguchi, Y. Terauchi, T. Maki, Current Status of "Dieless" Amino's Incremental Forming, Procedia Eng., 81 (2014) 54–62. https://doi.org/10.1016/j.proeng.2014.09.128

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

[6] M. Srivastava, S. Rathee, V. Patel, A. Kumar, P. Koppad, A review of various materials for additive manufacturing: recent trends and processing issues, J. Mater. Res. Technol., (2022). https://doi.org/10.1016/j.jmrt.2022.10.015

[7] M. Srivastava, S. Rathee, S. Maheshwari, T.K. Kundra, Additive manufacturing: fundamentals and advancements, CRC Press., 2019. https://doi.org/10.1201/9781351049382

[8] G. Schuh, J. Kreysa, S. Orilski, Roadmap „Hybride Produktion", Zeitschrift Für Wirtschaftlichen Fabrikbetr., 104 (2009) 385–391. https://doi.org/10.3139/104.110072

[9] B. Lauwers, F. Klocke, A. Klink, A.E. Tekkaya, R. Neugebauer, D. Mcintosh, Hybrid processes in manufacturing, CIRP Ann., 63 (2014) 561–583. https://doi.org/10.1016/j.cirp.2014.05.003

[10] G. Ambrogio, F. Gagliardi, M. Muzzupappa, L. Filice, Additive-incremental forming hybrid manufacturing technique to improve customised part performance, J. Manuf. Process., 37 (2019) 386–391. https://doi.org/10.1016/j.jmapro.2018.12.008