Additive-incremental forming hybrid manufacturing technique to improve customised part performance

Giuseppina Ambrogio[1,a], Francesco Gagliardi[1,b,*], Maurizio Muzzupappa[1,c], Luigino Filice[1,d]

[1]Department of Mechanical, Energy and Management Engineering, cubo 45-C, Ponte P.Bucci - University of Calabria, Arcavacata di Rende (CS) 87036 Italy

a) giuseppina.ambrogio@unical.it, b) francesco.gagliardi@unical.it, c) maurizio.muzzupappa@unical.it d) luigino.filice@unical.it,

* Corresponding Author - E-mail adress: francesco.gagliardi@unical.it,

Full postal address: cubo 45-C, Ponte P.Bucci - University of Calabria, Arcavacata di Rende (CS) 87036 Italy

Journal of Manufacturing Processes Volume 37, January 2019, Pages 386-391

https://doi.org/10.1016/j.jmapro.2018.12.008

Abstract

Hybrid manufacturing is a new production strategy based on the combination of various processes to manufacture components more efficiently in terms of quality, productivity, and/or sustainability. Combinations of subtractive, forming, and additive manufacturing processes can follow one another to produce the desired parts. Hence, both part complexity and performance can increase significantly. The highlighted strategy has been tested by considering two different processes that are typically utilised for small batches of customised parts. Specifically, selective laser sintering has been used to thicken sheets locally, which are subsequently formed by single point incremental forming. This process combination can result in the development of a rapid prototyping technique that exploits the peculiarities of both the utilised processes, and thus allows for the manufacturing of more complex and/or higher quality parts, in a more flexible manner. In the research herein reported, various solutions have been tested to analyse the impact of the proposed hybrid manufacturing strategy on the a) dimensional accuracy, in terms of deviation from the nominal shape, b) quality, in terms of

thickness distribution, and c) part complexity, in terms of the obtainable three-dimensional shape, of stainless-steel-formed sheets.

Keywords: Hybrid manufacturing; Additive manufacturing; SPIF

1. Introduction

An emerging trend in manufacturing is part customization. This is one of the needs that has motivated the manufacturing industries to address the remarkable challenges in a historical time known as the ‘‘Fourth Industrial Revolution” [1].

In 2011, most of the $11.3 trillion in value-added manufacturing was produced worldwide by subtractive processes or by injecting material into a mould [2]. In recent years, additive manufacturing (AM) is beginning to dominate, where the material is aggregated rather than formed in a mould or cut away. The use of AM technologies, in fact, is no longer confined to the production of models and prototypes [3]; however, currently, end-use parts are also manufactured.

In addition to the cost and quality of the manufactured parts, the efficiency of the industry works is measured considering a green and sustainable policy [4]. The collected energy data have been summarised for three manufacturing categories, i.e. conventional bulk-forming, subtractive, and additive processes [5]. This summarization has highlighted how the specific energy consumption (SEC) for each process category depends on the productivity. Additive processes contain the highest range of SEC, and has been assessed to be 100-fold higher than that of conventional bulk-forming processes. The subtractive category is characterised by intermediate values.

Considering the strengths and weaknesses of each of these manufacturing categories, hybrid solutions have been proposed combining two or more processes belonging to the same or different manufacturing categories [6,7].

Recently, the advantages of additive and subtractive techniques have been capitalised to manufacture parts with specific properties and shapes. In particular, additive techniques have been used to produce rough parts, and are subsequently finished by machining [8]. Newman et al. [9], in 2015, proposed a process planning method in conjunction with a developed framework to enable the strengths of additive and subtractive technologies to be combined.

Additional studies have been performed to integrate AM techniques into the production chain to test the feasibility of AM combined with conventional manufacturing processes such as sheet or bulk metal forming [10,11]. In 2017, Bambach et al. [12] analysed the capacity of combining metal forming and AM as a new process chain from the viewpoint of energy consumption. The research focused on the quantification of energy required to perform the highlighted processes and their combinations.

The motivation of this research is derived from the growing interest, highlighted above, in hybrid manufacturing. The goal of this work is to investigate the production strategies that can be used in combining an additive and a sheet forming process. In particular, as recently patented by Hölker–Jäger et al. [13], the single point incremental forming (SPIF) [14] was the explored sheet forming technique to be combined with an additive technique to emphasise the concept of flexibility in manufacturing.

In the first section herein, we demonstrate how metallic sheets can be thickened locally by an AM technique. The proposed strategies for general industrial applications are summarised in **Fig. 1**.

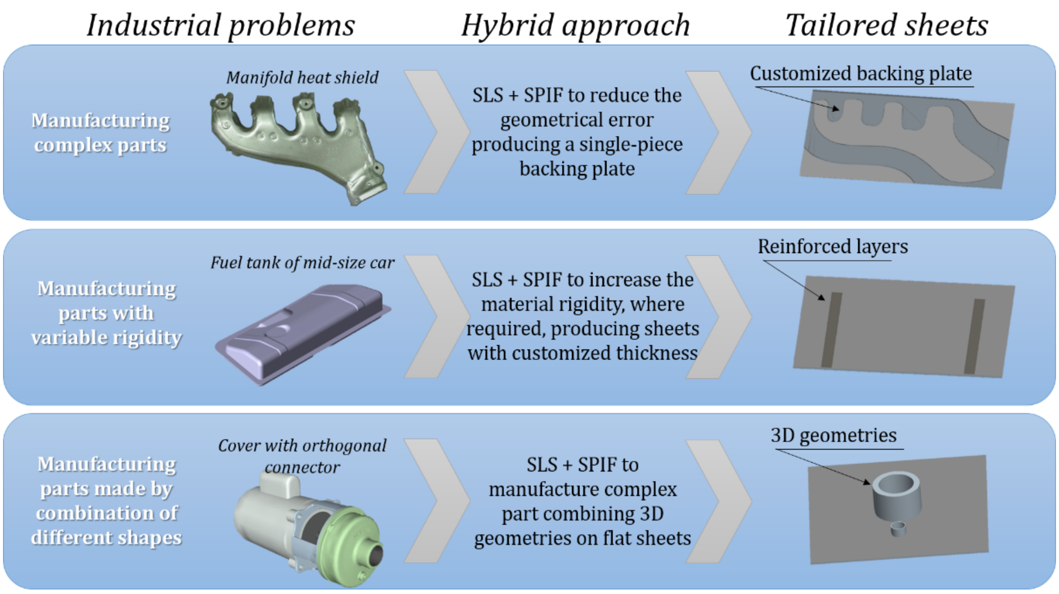

Fig.1. Combination of SLS and SPIF: the proposed strategies

Specifically, selective laser sintering (SLS) [15] was the utilised additive process, and the influence of the laser power density on the quality of the performed reinforced sheet was indicated. Subsequently, the possible uses of the thickened sheets in SPIF were investigated highlighting the capabilities of the proposed hybrid manufacturing solution. Two of the primary SPIF drawbacks were considered, i.e. the accuracy and the localised thinning of the components. A customised backing plate, created by exploiting the production flexibility from SLS, was designed such that the shape of the produced parts is as close as possible to the ideal shape. Furthermore, the minimum thickness resulted on the wall side at the end of the same forming phase was increased using a thickened tailored sheet, where the deformation is expected to be more relevant. Finally, the hybrid solution was utilised to increase the achievable part shape complexity. One side of a tank was manufactured together with its connection tube without using joining techniques, but exploiting and combining the strengths of the two explored processes.

2. Material deposition on metal sheets by SLS

SLS utilises laser as the power source to sinter powdered material, by aiming the laser automatically at points in space demarcated by a three-dimensional (3D) model and binding the materials to create a solid structure [15,16]. The flexibility of the AM process allows for the production of tailored sheets without any consistent limitations in shape as it occurs instead, for rolling [17] and orbital forming [18]. This incremented production elasticity is the strength of the proposed hybrid technique exploitable in creating different solutions. The additive process was performed using both sheets and powder made by stainless steel, i.e. an AISI 304 and AISI 630, respectively. These stainless alloys were chosen because, although they exhibit similar chemical compositions (Table 1), they are characterised by their specific mechanical properties (Table 2). When combined, they can improve the effectiveness of the proposed manufacturing solutions [19]. Briefly, the AISI 304 is characterised by a better formability that allows for an easier processing. However, this alloy presents lower corrosion resistance and mechanical properties than the AISI 630.
The used SLS machine is based on the powder-bed solution; therefore, the roller requires a perfectly flat surface such that the powder can be spread to avoid any dangerous collisions. Hence, the metallic sheet has to be placed and affixed on the same level on the worktable as the SLS machine. Therefore, a pocket with the same dimensions as the sheet was machined inside the worktable, and the sheet was affixed within it using countersunk head screws. A strict connection between the sheet and worktable was required. This is due to the laser source, which, while heating the powders, increases the temperature of the sheet, as well. The latter, owing to its anisotropy and bounded area, could warp, thereby affecting the quality of the process. The sheets were blocked in the middle and along their sides (**Fig. 2**a). Subsequently, material deposition could be performed (**Fig. 2**b), layer by layer, with single films of thickness 40 μm.

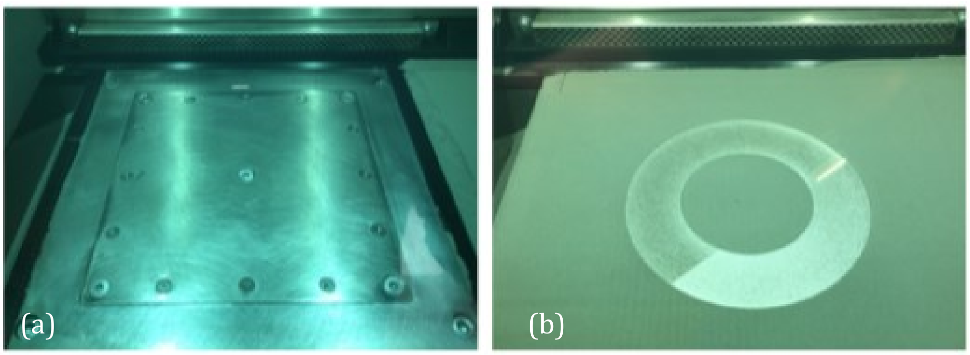

Fig. 2. (a) The sheet fixed inside the SLS machine's work cube and (b) a sequence of the material deposition.

A tradeoff occurs between extremely high and extremely low energy conditions. In fact, if, from one side, extreme laser energy can lead to sheet warpage and/or to material heat damage, then from the other side, a low energy does not allow for a full powder sintering and can yield voids inside the added sintered layers, and/or the easy detachment of the performed material deposition.
The research was performed on sheets of initial thickness 1.1 mm, while a material deposition of 0.4 mm was achieved. An appropriate amount of laser energy per unit time per unit area was, therefore, necessary to process the sheets properly. Specifically, the linear velocity of the laser beam was the process variable used to modify the energy density during SLS. The investigated range was between 1000 and 1600 mm/s. The power and spot size of the laser beam were, instead, set at 195 J/s and 0.004 mm^2, respectively. Thus, the influence of the specific density in a range between approximately 30 and 50 J/mm^3 was analysed. The SLS process window to deposit materials on the processed stainless steel is shown in **Fig. 3**.

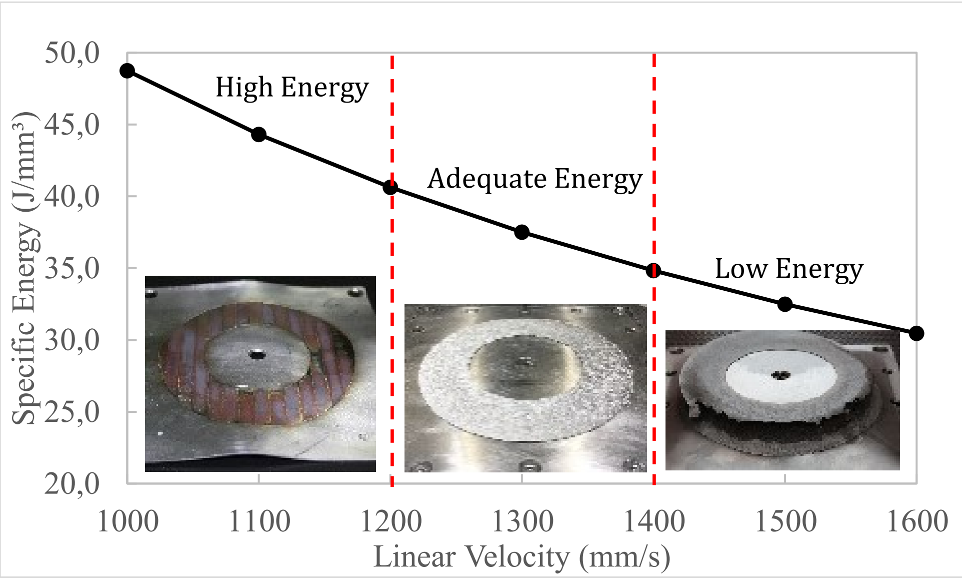

Fig. 3. The process window to make material deposition on the investigated stainless sheets.

For a specific energy higher than 40 J/mm^3, sheet warpage was unavoidable while the material deposition was poor, considering both its density and its adherence to the metallic sheets for an energy lower than 35 J/mm^3. According to that, a linear velocity of 1300 mm/s, and a consequent specific energy of approximately 37 J/mm^3 were set for sintering the processed powders.

The impact of the laser source on the mechanical properties of the sheet for this final process configuration was evaluated by performing microhardness analysis by nanoindentation before and after the AM phase on three reinforced sheets. A load of 490 mN was exerted following five lines along the sheet thickness with measurements that were performed at 50 µm each from the surface to the midplane of the sheet. The average hardness trend is displayed in **Fig. 4** where, for each point, the marked minimum and maximum detected values are shown.

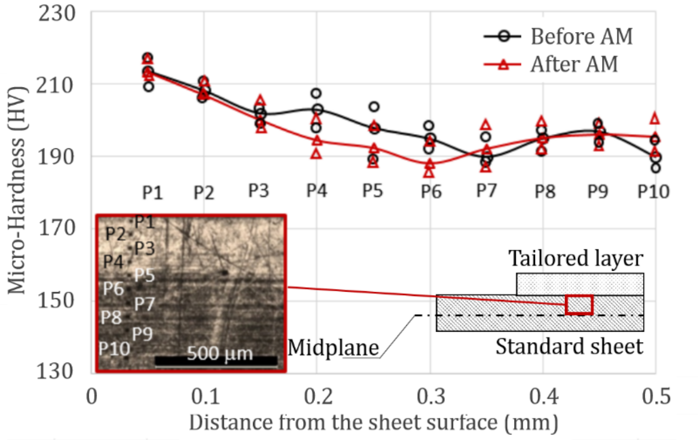

Fig. 4. The micro-hardness values along the thickness of the sheet with and without the effect of the laser source.

No significant variation in material hardness due to the laser effect can be observed, with a maximum standard deviation among the whole detected values lower than 10 HV (relative standard deviation equal to 5%). Furthermore, microhardness was detected on the layer of material deposition using the same measurement strategy described previously. The values along the thickness of the deposited reinforcement are depicted in **Fig. 5**, where the literature hardness for the AISI 630, reported in **Table 2,** was used as a reference value.

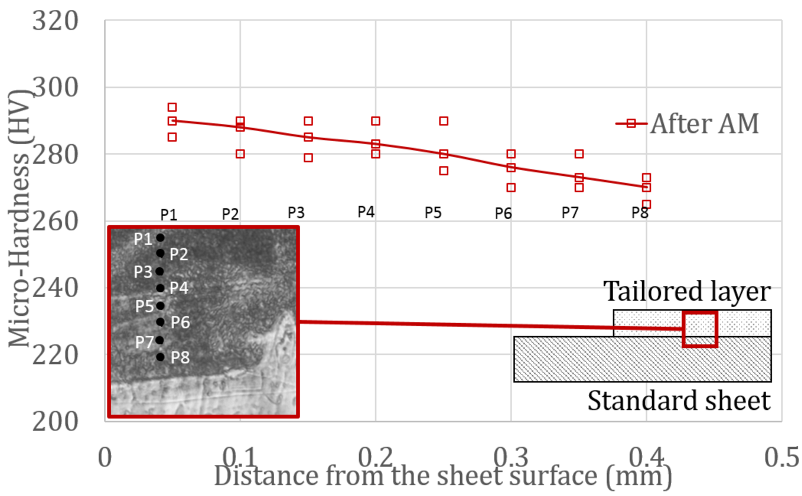

Fig. 5. The micro-hardness values along the sintered layers of the sheet.

Further, in this case, five points were measured and the minimum and maximum values were reported with the average value, indicating a maximum standard deviation of 8 HV (relative standard deviation equal to 3%). In more detail, the sintered layer was characterised by a slight decrement in hardness; this can be ascribed to small porosities on the deposited side. Indeed, the imposed specific energy did not lead a full density of the sintered part, thus justifying the slight hardness deviation from the target value.

Finally, a reinforced sheet was sectioned, and a sample was ground and polished using standard metallography procedures. This sample was observed microscopically from the contact surfaces between the sheet and the sintered reinforcement. Specifically, their connections due to adhesion forces generated by the creation of a molten layer, was strengthened by mechanical interlocking that occurred between the surfaces, thus improving their interactions at micro levels (**Fig. 6**).

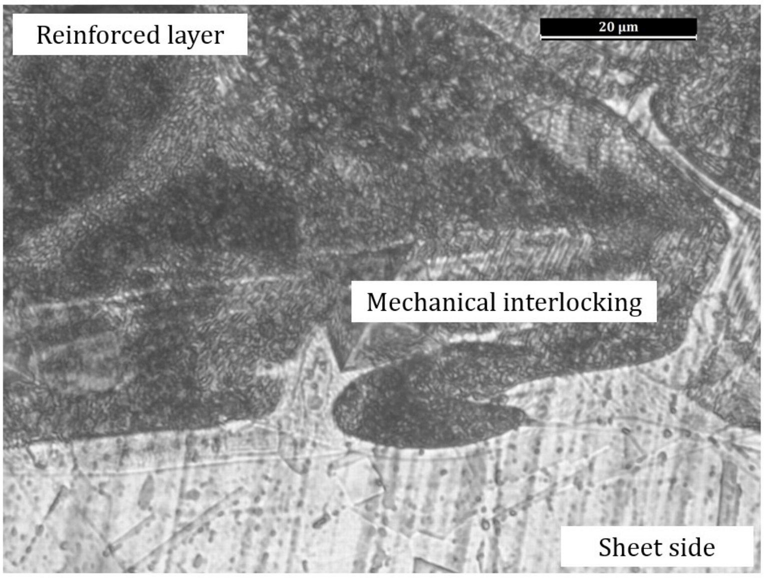

Fig. 6. Mechanical interlocking between the reinforced layer and the surface of the standard sheet.

3. SPIF on tailored sheets produced by SLS

The blanks, thickened locally with metal powders sintered by a laser beam, as described in section 2, were used to utilise the tailored sheets working on them by SPIF. Three possible applications were identified; they led to the testing and analysis of different hybrid-manufacturing variants. These are described and investigated below.

3.1 Strategy to increase the SPIF accuracy – A backing plate made by SLS on the sheet formed incrementally

Achieving good accuracy using SPIF has been challenging [20]. The accuracy of the part can be improved significantly using a backing plate beneath the sheet. The backing plate is inexpensive and its construction is not time consuming if compared with a die; however, it limits the SPIF flexibility. The possibility of combining flexible die-support with SPIF is discussed in the literature. Specifically, Kreimeier et al. [21] presented different strategies in robot-based incremental sheet metal forming using moving support tools that can substitute a full die. In this case, the movements of two robot arms must be synchronised and the working forces monitored, to avoid equipment overstressing. More recently, Min el al. [22] proposed the use of metallic foam as a flexible die-support. They demonstrated an improvement in the geometric accuracy with respect to the traditional SPIF and maintained the good flexibility. Nevertheless, the geometry optimization of the flexible die-support must be performed, and the effect of mechanical properties of the metallic foam has to be considered, especially if complex shapes with sharp angles are to be manufactured.

AM techniques can be a further solution for SPIF to improve its accuracy without sacrificing flexibility. Briefly, a localised thickening of the sheet made by SLS is useful to increase, where necessary, the stiffness of the blank to improve the accuracy of the part. The reinforcement has to be manufactured on the part of the sheet to be trimmed, i.e. on the underside of the production waste. The primary drawback of this solution is the increase in the process costs, which can be derived using an expensive manufacturing solution, i.e. SLS. Nevertheless, this can be reduced by limiting the reinforcement and customizing it to the punch trajectory and to the shape of the part that has to be produced.

The effectiveness of the solution was tested by creating a truncated cone, a profile considered as a benchmark for the research performed on SPIF [20]. Specifically, a truncated cone with a base diameter of 70 mm, a slope angle of 50°, and a final height of 30 mm was formed. A sheet with a side of 180 mm was formed incrementally according to a working area of 140 mm × 140 mm. These dimensions are important because the part accuracy is strictly affected by the distance between the fixing frame of the sheet and the first coil of the punch trajectory. According to Jeswiet et al. [20], this width must be maintained at approximately or lower than 10 mm to minimise the part inaccuracy due to the material springback. In the performed tests, however, this distance was increased intentionally, up to 35 mm, to emphasise the deviation between the real and nominal shapes, and to highlight clearly the advantages of the customised reinforcement. Furthermore, a circular crown with a thickness of 0.4 mm, and internal and external diameters of 70 mm and 140 mm, respectively, was manufactured. This reinforcement was manufactured to locally strengthen the sheet tangent to the working zone, and serves as a customised backing plate. The SLS deposition was performed using the best combination of the process parameters highlighted in the previous section, i.e. a linear velocity, power, and laser-beam spot size of 1300 mm/s, 195 J/s, and 0.004 mm^2, respectively. Thus, the provided specific density was approximately 38 J/mm^3. The SPIF was executed with a punch diameter of 15 mm, a spindle speed of 100 rev/min, a step depth of 0.5 mm, and a feed rate of 1000 mm/min. The truncated cone was formed using sheets with and without material deposition. The reinforced sheet, at the beginning and end of the forming phase, is shown in **Fig. 7**.

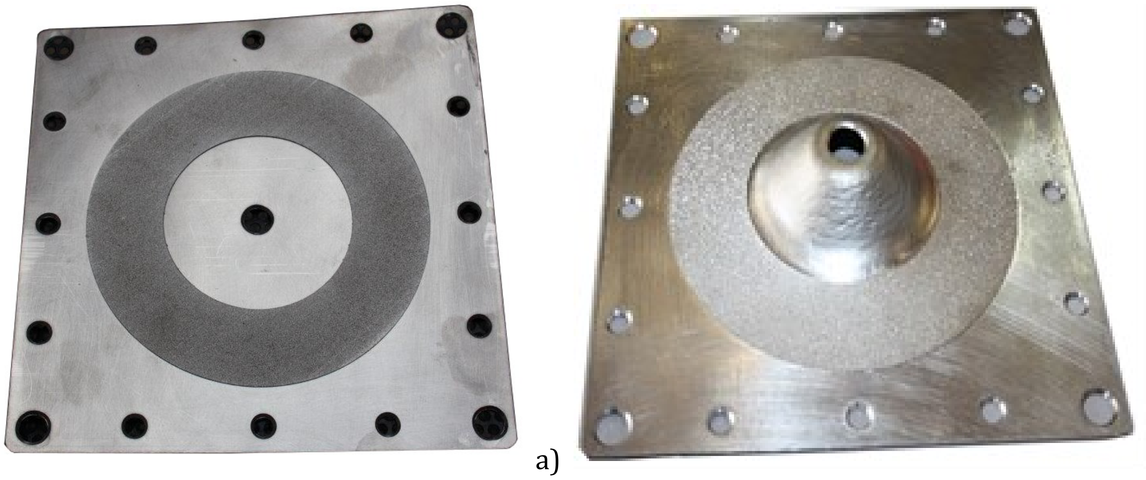

Fig. 7. Back-side view of the reinforced sheet (a) before and (b) after the forming step.

The conical shapes, obtained experimentally from the sheets with and without the additive reinforcement, were compared with the drawn solid geometry. A 3D Minolta laser scanning system, characterised by a measurement error of 0.1 mm, was utilised to detect the surfaces of both cones. The clouds of the points, obtained by the 3D laser, were uploaded into a virtual environment and aligned to the 3D ideal profile. The punctual geometrical errors were measured as the minimum distance between each point and the ideal surface for the whole 3D profile (**Fig. 8a-b**) and for a half cross section (**Fig. 8c-d**).

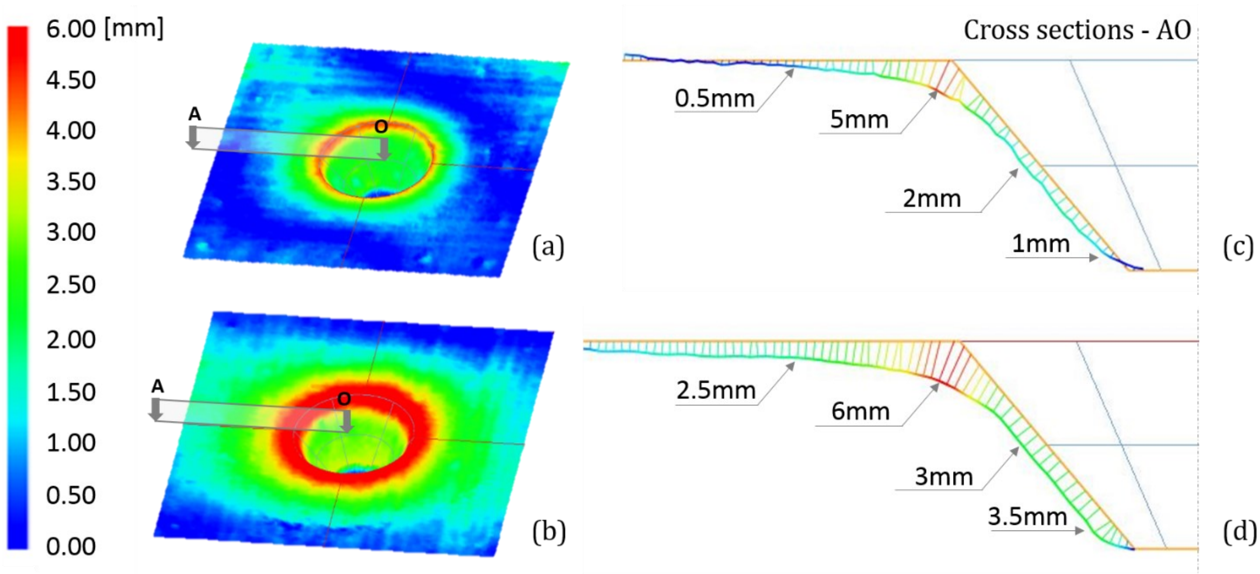

Fig.8. Comparisons between the ideal and the actual profiles obtained with (a)-(c) reinforced and (b)-(d) standard sheets.

From the qualitative standpoint, a reduced deviation can be observed from the conical shape achieved for the sheet with the sintered reinforcement owing to a smaller curvature on the major base, and a better fitting between the effective and desired lateral profiles. Form the quantitative standpoint, the punctual analysis along the 3D profile highlighted a reduction in the average distance from 2.71 mm measured on the standard sheet, to 1.73 mm measured on the reinforced sheet. The quantitative distribution of the geometrical errors is reported in **Fig. 9**.

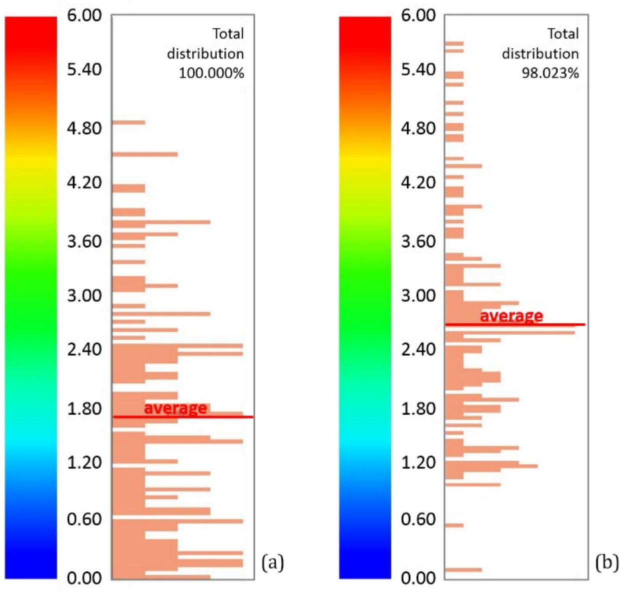

Fig.9. Quantitative distribution of the geometrical errors of the (a) reinforced and (b) standard sheet.

This result, supported additionally by the small values of standard deviation (1.24 mm and 1.19 mm for the conventional and reinforced sheet, respectively), confirms the effectiveness of the hybrid solution to resolve a primary SPIF drawback. For clarity, the same analysis was repeated on an additional samples; however, no significant differences were detected. This strategy is useful when small product batches have to be produced and the cost of a backing plate for each batch cannot be justified. A cost-benefit analysis between this strategy and the one with backing plate is, however, necessary to estimate the strengths and weaknesses of the alternatives in relation to the shape of the component and to the number of pieces to be manufactured.

3.2 Customised sheet thickening by SLS to compensate the localised thinning due to SPIF

In SPIF, as mentioned above, the sheet is fully clamped along its outer perimeter; therefore, any deformation across its plane leads to blank thinning. The material distribution along the formed wall side has been investigated widely because, being inhomogeneous, it could reduce the quality and performances of the manufactured parts. In aerospace applications, for example, where the thickness must not be below a threshold to obtain the component homologation, increasing the sheet thicknesses to greater than is required, is typically the adopted strategy. To improve the material distribution, the solution, herein discussed, can be a viable alternative.

Furthermore, the localised thickening of the sheet as a coating can be performed on the area where a more accentuated thinning is expected. Hence, an offsetting of the variability related to the thickness reduction is obtained by changing the initial material distribution along the sheet plane. The minimum thickness value measured on the formed parts should be greater. The effectiveness of this second hybrid application was tested by forming a truncated cone, for the same reason explained previously. A square sheet with a side of 180 mm, totally clamped for a width of 10 mm, was formed incrementally for this analysed case, as well. The same process parameters were set; however, in this case, the truncated cone was characterised by a base diameter of 140 mm, a slope angle of 55°, and a final height of 30 mm. A circular crown of 0.4-mm thick, was created, thereby resulting in the thickening of the area of the sheet where the punch moves, i.e. internal and external diameter of 80 mm and 140 mm, respectively. The unreinforced sides of the sheet maintain the initial thickness of 1.1 mm. The coated sheet at the end of the forming step is shown in **Fig. 10**.

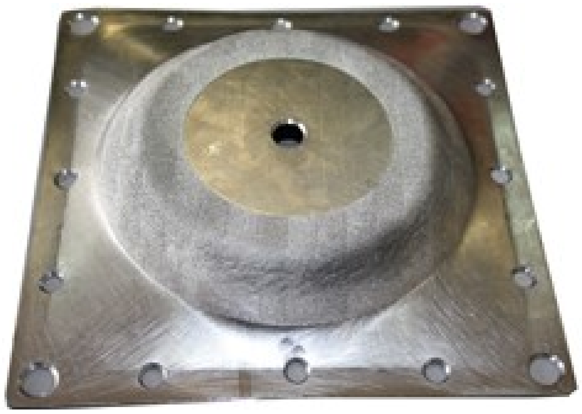

Fig. 10. Back-side view of the coated sheet after the forming step.

Three replications of the same SPIF process (addressed with a tool diameter of 12 mm, a depth step of 0.5 mm, a tool rotation of 300 rpm, and a feed rate of 2000 mm/min) were repeated for each sheet, i.e. standard and tailored sheets. To compare the thickness distribution between the standard and tailored profiles, the SPIFed specimens were cut along their middle plane (**Fig. 11**a). Specifically, a coordinate-measuring machine was used to detect the thickness of the cone wall starting from the outer working zone. One point for each millimeter was measured on the wall profile to obtain an accurate a thickness distribution with a measurement error in the order of microns. Furthermore, two orthogonal sections were measured for each sample. The detected trends were compared with respect to the average measured values (**Fig. 11**b), in which the relative standard deviation was always less than 6%. As expected, a cone wall with a greater minimum thickness value was formed.

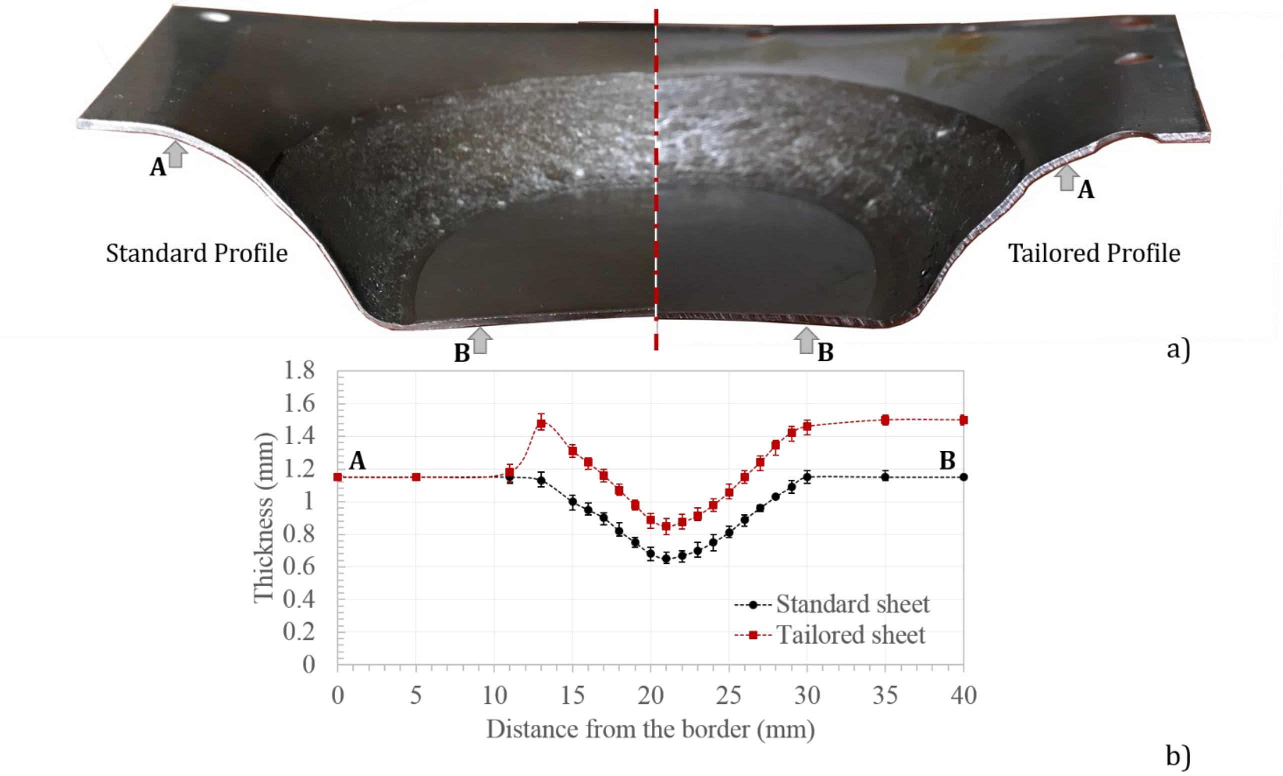

Fig. 11. (a) A midplane section of the cone obtained with a standard and a tailored sheet and (b) comparison of the thickness distribution.

3.3 Hybrid manufacturing by combining SLS deposition and SPIF deformation

Hybrid manufacturing techniques allow for the production of parts, characterised by most varied forms, without using joining methods. Hence, a suitable process chain must be designed to exploit the peculiarities of each utilised working technique. Specifically, AM and sheet forming processes can be combined to create complex shapes of formed laminated parts and 3D functional elements. The proposed hybrid technique is an example thereof. In fact, the required 3D elements on the flat sheet can be manufactured additively as the first step of the designed process chain. Subsequently, the sheet can be formed by SPIF to obtain the desired final shape. The introduction of a flexible forming process enhances the strength of the hybrid manufacturing solution, in terms of an easier and more powerful customised production. The manufacturing solution arising from the combination of SLS and SPIF was tested to produce the upper part of a tank with a connection tube characterised by a well-defined shape. In particular, **Fig. 12**a shows the undeformed sheet with a 3D protrusion; this is only one of the infinite shapes achievable by SLS. Similarly, **Fig. 12**b shows the entire 3D component, where the flat sheet was formed by SPIF without the need for additional tools.

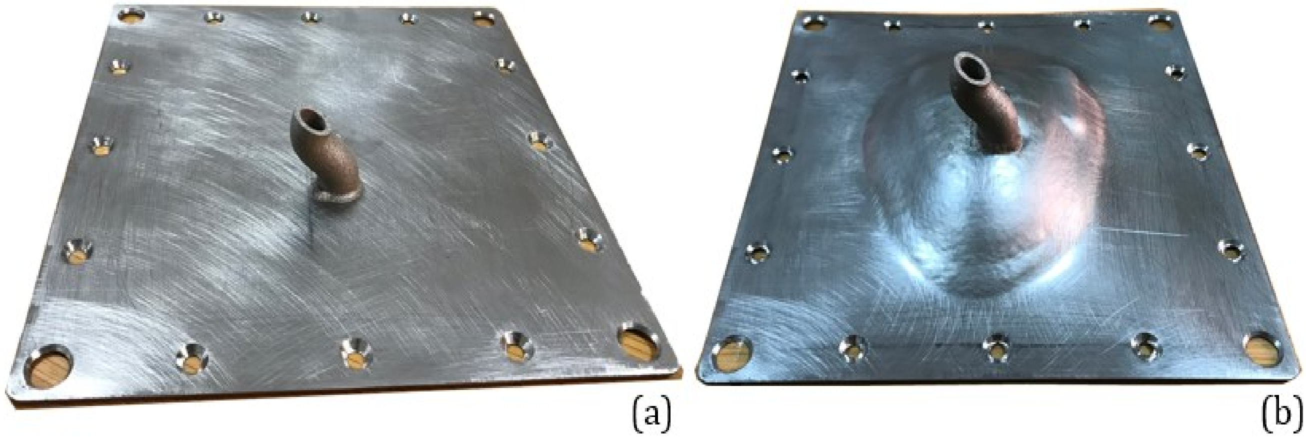

Fig. 12. (a) the undeformed sheet with the 3D protrusion made by SLS and (b) the final component made by the investigated hybrid approach.

The capability of the investigated hybrid manufacturing solutions in manufacturing complex parts is evident, considering the flexibilities of both highlighted processes.

4. CONCLUSIONS

We herein presented a hybrid solution that combined two flexible manufacturing processes. Specifically, the combination of an AM technique and a sheet forming process was proposed to produce parts with higher accuracy, better mechanical properties, and/or characterised by more complex shapes. Three application routes were analysed to: 1) improve the accuracy of the formed part by building a backing plate on one side of the sheet; 2) avoid excessive sheet thinning by sintering material on the area where the deformation is pronounced; 3) increase the typology of the shapes that can be manufactured with a flexible hybrid process solution.

Future research must be performed to explore in more depth the capability of the proposed routes to manufacture customised parts with the desired level of complexity and quality. A subsequent investigation on the setting of non-constant thickening will be performed to link its variability to the deformation level of the sheet to obtain a more homogeneous material distribution.

References

[1] Pereira AC, Romero F. A review of the meanings and the implications of the Industry 4.0 concept. Procedia Manuf 2017;13:1206–14. doi:10.1016/j.promfg.2017.09.032.

[2] Thomas DS, Gilbert SW. Costs and Cost Effectiveness of Additive Manufacturing. Gaithersburg, MD: 2014. doi:10.6028/NIST.SP.1176.

[3] Yan J, Battiato I, Fadel GM. Planning the process parameters for the direct metal deposition of functionally graded parts based on mathematical models. J Manuf Process 2018;31:56–71. doi:10.1016/j.jmapro.2017.11.001.

[4] Tranter JB, Refalo P, Rochman A. Towards sustainable injection molding of ABS plastic products. J Manuf Process 2017;29:399–406. doi:10.1016/j.jmapro.2017.08.015.

[5] Yoon H-S, Lee J-Y, Kim H-S, Kim M-S, Kim E-S, Shin Y-J, et al. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. Int J Precis Eng Manuf Technol 2014;1:261–79. doi:10.1007/s40684-014-0033-0.

[6] Krejcie AJ, Kapoor SG, DeVor RE. A hybrid process for manufacturing surgical-grade knife blade cutting edges from bulk metallic glass. J Manuf Process 2012;14:26–34. doi:10.1016/j.jmapro.2011.09.001.

[7] Zhu Z, Dhokia V, Newman ST. The development of a novel process planning algorithm for an unconstrained hybrid manufacturing process. J Manuf Process 2013;15:404–13. doi:10.1016/j.jmapro.2013.06.006.

[8] Alexander I, Vladimir G, Petr P, Mihail K, Yuriy I, Andrey V. Machining of Thin-walled Parts Produced by Additive Manufacturing Technologies. Procedia CIRP 2016;41:1023–6. doi:10.1016/j.procir.2015.08.088.

[9] Newman ST, Zhu Z, Dhokia V, Shokrani A. Process planning for additive and subtractive manufacturing technologies. CIRP Ann 2015;64:467–70. doi:10.1016/j.cirp.2015.04.109.

[10] Merklein M, Junker D, Schaub A, Neubauer F. Hybrid Additive Manufacturing Technologies – An Analysis Regarding Potentials and Applications. Phys Procedia 2016;83:549–59. doi:10.1016/j.phpro.2016.08.057.

[11] Bambach M. Recent Trends in Metal Forming: From Process Simulation and Microstructure Control in Classical Forming Process to Hybrid Combinations Between Forming and Additive Manufacturing. J Mach Eng 2016;16:5–17.

[12] Bambach MD, Bambach M, Sviridov A, Weiss S. New process chains involving additive manufacturing and metal forming – a chance for saving energy? Procedia Eng 2017;207:1176–81. doi:10.1016/j.proeng.2017.10.1049.

[13] HÖLKER-Jäger, Ramona BEN A. KHALIFA, Nooman Tekkaya E. Method and device for the combined production of components by means of incremental sheet forming and additive

methods in one clamping setup. EP3197633A1, 2017.

[14] Behera AK, de Sousa RA, Ingarao G, Oleksik V. Single point incremental forming: An assessment of the progress and technology trends from 2005 to 2015, 2017. doi:10.1016/j.jmapro.2017.03.014.

[15] Holt N, Van Horn A, Montazeri M, Zhou W. Microheater array powder sintering: A novel additive manufacturing process. J Manuf Process 2018;31:536–51. doi:10.1016/j.jmapro.2017.12.009.

[16] Hopkinson N, Majewski CE, Zarringhalam H. Quantifying the degree of particle melt in Selective Laser Sintering ®. CIRP Ann 2009;58:197–200. doi:10.1016/j.cirp.2009.03.001.

[17] Merklein M, Johannes M, Lechner M, Kuppert A. A review on tailored blanks—Production, applications and evaluation. J Mater Process Technol 2014;214:151–64. doi:10.1016/j.jmatprotec.2013.08.015.

[18] Merklein M, Plettke R, Opel S. Orbital forming of tailored blanks from sheet metal. CIRP Ann 2012;61:263–6. doi:10.1016/j.cirp.2012.03.130.

[19] Joseph R. Davis. Stainless Steels (Asm Specialty Handbook). 1994.

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

[21] Kreimeier D, Buff B, Magnus C, Smukala V, Zhu J. Robot-Based Incremental Sheet Metal Forming – Increasing the Geometrical Accuracy of Complex Parts. Key Eng Mater 2011;473:853–60. doi:10.4028/www.scientific.net/KEM.473.853.

[22] Min J, Kuhlenkötter B, Shu C, Störkle D, Thyssen L. Experimental and numerical investigation on incremental sheet forming with flexible die-support from metallic foam. J Manuf Process 2018;31:605–12. doi:10.1016/j.jmapro.2017.12.013.