

Design for FDM of flexible tooling for manufacturing aeronautical components by incremental sheet forming

G Flores¹, D Palomo¹, A J Martínez^{1*}, M Borrego¹, J A López¹, D Morales¹, G Centeno¹ and C Vallellano¹

¹ Department of Mechanical and Manufacturing Engineering, School of Engineering, University of Seville, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

*Corresponding author: ajmd@us.es

Abstract: Nowadays, industrial production is required to reduce industrialization times and development costs for new products while maintaining high quality standards. In this context, the development of new flexible manufacturing technologies has gained relevance in the last few years. The use of Fused Deposition Modelling (FDM) additive technique has been recently proposed in different industrial sectors for manufacturing rapid tooling (dies) to be used in conventional sheet metal stamping or stretching processes with a significant decrease in costs and time savings. On the other hand, Incremental Sheet Forming (ISF) technology is characterized by an enhanced formability of the parts thus manufactured as well as for the need of a small number of tooling, reducing costs compared to conventional processes such as hydroforming or stamping. In particular, its simplest variant, Single-Point Incremental Forming (SPIF) requires the use of backing plates, which do not require tight tolerances as their only function is to collaborate in the deformation process acting as a support point. Furthermore, the strength requirements are also not a limitation since the forces involved in SPIF are very small given the local nature of the deformation. In this context, the main objective of this work is the design of a modular tooling system, manufactured using the FDM additive technique, that allows the flexible manufacturing of different aeronautical components by SPIF.

Keywords: Additive Manufacturing (AM), Fused Deposition Modelling (FDM), Flexible tooling, Aeronautical components, Incremental Sheet Forming (ISF).

1. Introduction

Nowadays, industrial production is required to reduce industrialization times and development costs for new products while maintaining high quality standards. In this context, the development of new flexible manufacturing technologies, such as Additive Manufacturing (AM) [1-5] or Single Point Incremental Forming (SPIF) [6-12], has gained relevance in the last few years.

The use of Fused Deposition Modelling (FDM) additive technique has been recently proposed in different industrial sectors for manufacturing rapid tooling (dies) to be used in conventional sheet metal stamping [1], stretching [2] or injection moulding [3] processes with a significant decrease in costs and time savings. Durgun et al. [1] proposed the manufacturing of polycarbonate dies by FDM for the small batch production of stamped steel parts, showing the feasibility of this procedure. Leacock et al. [4] analyzed the use of additive manufacturing by FDM to print small parts that could be assembled to form large dies, used for sheet stretching processes at low production volumes. They pointed out a substantial reduction in costs of around 70% when FDM was used to manufacture the needed tooling, compared



with traditional machining processes. The application of 3D printing has also been used to manufacture drilling templates, made of polymer with internal "honeycomb" reinforcements, in aeronautical manual assemblies for lightweighting and cost reduction [5].

On the other hand, it is well known that sheet metal forming processes are of great industrial importance in highly competitive sectors such as the aeronautical industry, which require products to be manufactured with high precision and flexibility, as well as increasing geometric complexity.

Incremental sheet forming (ISF) is a process capable of meeting these requirements. ISF, also known as dieless NC forming, is a relatively recent flexible manufacturing technology, suitable for small and medium production volumes. Despite being introduced in 1993 by Matsubara [6] for rapid prototyping, it is only in the last decade that a real effort has been put into the development of scientific and technological knowledge aimed at achieving its industrial maturity [7-12]. This ISF technology is characterized by a clear improvement in formability in the manufactured parts, which could enable the use of materials of low formability, such as hardened aluminium alloys (-T3, -T4 or -T6) commonly used in the aeronautical industry. It also reduces the amount of tooling required, reducing costs compared to conventional processes such as hydroforming or sheet metal stamping. The simplest variant of ISF is Single Point Incremental Forming (SPIF), in which the sheet is fixed on its periphery and supported on a backing plate (tooling) and a hemispherical tool guided by Computer Numerical Control (CNC) progressively deforms the sheet around the outline of the desired piece. The name 'single point' refers to the fact that the sheet is exclusively in contact with the tool and backing plate during deformation, without the use of a die on the opposite side of the sheet part. Although SPIF requires a minimum number of tooling and provides great flexibility, the use of backing plates is still necessary. However, these do not require tight tolerances as their only function is to collaborate in the deformation process acting as a support point. Furthermore, the strength requirements are also not a limitation since the forces involved in SPIF are very small given the local nature of the deformation mechanics [10-12].

In this context, the main objective of this contribution is the design of a modular tooling system, manufactured using the FDM additive technique, that allows the flexible manufacturing of different aeronautical components, in particular wing ribs and stabilizers, by means of incremental sheet forming by SPIF. The combination of both manufacturing technologies (SPIF and FDM), along with the concept of modular tooling, provides the system with great flexibility in manufacturing and allows a potential reduction in costs and time to market of a particular prototype or product.

2. Design of the flexible tooling for SPIF

The design of the modular tooling system was developed using CATIA V5[®], which is a software commonly used in the aeronautical industry. The concept of modularity consists of a set of interchangeable parts, which, once assembled, will form the backing plate needed in each case for the incremental forming by SPIF of the different sheet components to manufacture. The different parts that make up the modular design are interchangeable or replaceable with a minimal adjustment between elements, providing a reduction in the assembly or setup times.

The design for manufacturing of the tooling was developed considering the FDM additive technique using polylactic acid (PLA). The system design is equipped with a fixed part and a removable modular part customized for each type of aeronautical component (wing/stabilizer ribs). The assembly of the different parts is done by means of a system of crenelated joints, allowing for a robust assembly, while also being easily removable when another tooling configuration is required. This concept enables the introduction and manufacture of new components by printing additional dies, allowing developing increasingly complex rib designs with low development costs in terms of tooling. Similarly, the developed modular system allows the manufacture of large components without the need for 3D printers with a large printing volume.

Figure 1(a) shows the fixed part of the tooling that will act as a support, reference and clamping to the CNC or manual machine tool. As can be seen, this part has a crenelated design that allows the coupling of additional dies or backing plates for adapting to the specific size and geometry of the rib to manufacture. It also has various grooves in different orientations in order to allow more versatility in

the positions of the T/H (Tooling Holes) of each elemental, through which each set of pieces, i.e. blank holder, sheet, customized backing plate and fixed part of the tooling, will be clamped by means of screws. Figure 1(b) shows the partial assembly of one of the possible configurations. For the sake of clarity, in this picture are omitted the metal sheet and the blankholder. As can be seen, the clamping between the fixed part (lower piece in red) and the backing plate (upper piece in green) will be secured by a pyramid-based system for an adequate transmission of the load between the elements when tightening the fixing screw.

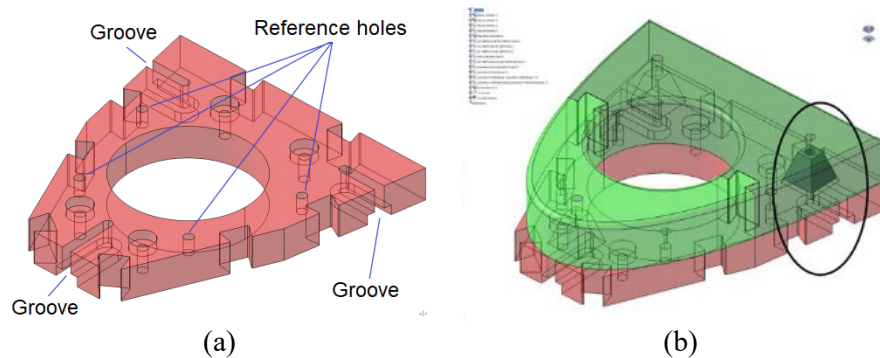


Figure 1. (a) Fixed part of the tooling system. (b) Assembly of interchangeable backing plates on the fixed part and pyramid-based system for clamping.

Figure 2(a) shows the design of several backing plates that allow the manufacturing of different rib configurations when assembled. These designs show the most common features in aeronautical ribs, i.e. hole flanges and concave, straight and convex flanges at the edges. Figure 2(b) depicts the full assembly of one of the possible rib configurations, including the virtual setup before and after the incremental forming by SPIF. In this case, the blank holder (upper piece in blue), the metal sheet and the positions of the three T/H (tooling holes) by which the whole set will be clamped to the fixed part of the tooling system are also included.

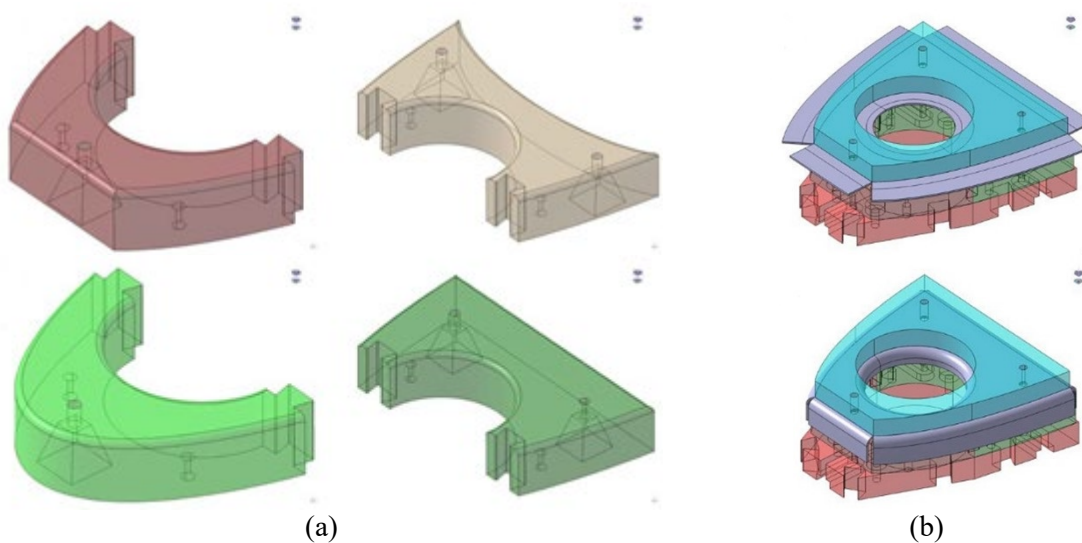


Figure 2. (a) Interchangeable backing plates for manufacturing different aeronautical ribs. (b) Virtual setup before and after the incremental forming by SPIF of an aeronautical rib.

On the other hand, due to one of the requirements of the modular concept consisted of being able to manufacture large-sized ribs and components, figure 3(a) shows an additional piece designed to expand the fixed part of the tooling system and the way to be assembled on it by means of the crenelated system. This additional die of the fixed part is clamped to the CNC machine using screws and it was designed with a groove for a flexible positioning the tooling holes to clamp the set of pieces needed for the manufacturing. Figure 3(b) depicts a virtual setup including an additional customized backing plate (coloured in blue) for the manufacturing of a different rib geometry, shown in figure 3(c). This allows a glimpse of the wide range of manufacturing possibilities achievable with this modular multi-configurable tooling design.

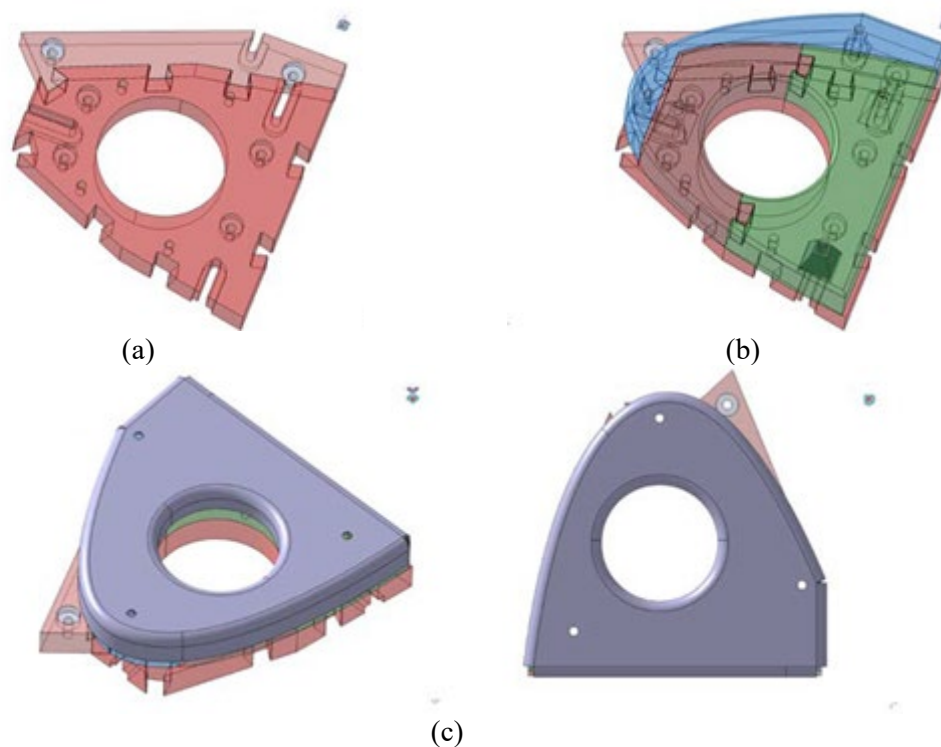


Figure 3. (a) Installation of an additional die for the fixed part of the tooling system. (b) Virtual setup including an additional customized backing plate for the manufacturing of a specific rib configuration. (c) Geometry of the aeronautical rib to be manufactured by SPIF.

3. Manufacturing of the flexible tooling. Process parameters

The manufacturing of the flexible tooling was carried out by means of the FDM additive technique using polylactic acid (PLA). The following elements, previously presented in section 2, were manufactured: fixed part and its additional extension (figure 3(a)), four backing plates (figure 2(a)) and a customized one (figure 3(b)), a blankholder (figure 2(b)) and the pyramid-based system for clamping (figure 1(b)).

It was intended that the process of design and manufacturing of an additional part to the tooling system for including a modification in the aeronautical component to be manufactured or to industrialize a new configuration could be completed in less than 8 hours, the time available in a working day. According to this, the general printing parameters, shown in table 1, were set to meet this objective. In addition, due to the largest mechanical stresses during the deformation process by SPIF are located on the side walls of the backing plates, it was decided to make them thicker than the upper and lower faces, which remained with smaller thicknesses. Thus, the tooling was resistant enough to withstand the loads during the incremental forming, while at the same time saved on material and printing time. According to this, the general values set for the perimeter of the pieces are summarized in table 2.

Table 1. General printing parameters for all parts.

Quality	
Layer height	0.2 mm
Initial layer height	0.2 mm
Line width	0.4 mm
Infill	
Infill pattern	Trihexagonal
Material	
Material	PLA
Printing temperature	210 °C
Build plate temperature	45 °C
Speed	
Infill speed	60 mm/s
Outer wall speed	30 mm/s
Inner wall speed	60 mm/s
Infill speed of the support	15 mm/s
Initial layer print speed	20 mm/s
Initial layer travel speed	15 mm/s
Skirt/brim speed	30 mm/s
Number of slower layers	2

Table 2. Printing parameters for the perimeter of the parts.

Perimeter	
Wall thickness	1.2 mm
Wall line count	3
Top/bottom thickness	0.8 mm
Top/bottom layers	4

An infill density of 25% was used for the manufacturing of the fixed part and backing plates whereas a value of 35% was set for the blankholder, because of the smaller thickness used in the latter. The wall thickness was increased to 1.6 mm and the infill density was set to 35% for both the additional fixed part and the customized backing plate, due to their slenderness compared to the other pieces.

Table 3. Manufacturing times and material consumption for each part.

	Manufacturing time	Material consumption (g)
Fixed part	11 h 08 min	149
Blankholder	08 h 04 min	118
Backing plate 1	05 h 56 min	86
Backing plate 2	09 h 06 min	133
Backing plate 3	08 h 07 min	112
Backing plate 4	05 h 27 min	77
Fixed part extension	05 h 55min	86
Customized backing plate	04 h 48min	67
Clamping system (each)	00 h 25min	4
Total:	68 h	965

Table 3 shows the manufacturing times and material consumption for each of the pieces

manufactured. As can be seen, the fixed part is the one that takes the largest printing time, around 11h. However, it only needed to be printed once since it was designed as the reference element. Each of the parts which allowed the assembly of different configurations of backing plates and also the blankholder were built in less than 8-9 hours of manufacture, as expected/planned. In this sense, and with the aim of reducing times, it is worthy to note that an experiment using printing speeds 50% higher, compared to the data shown in figure 1, was carried out for the backing plate 4. The manufacturing time for was 4h 42min, achieving a time saving of approximately 45 minutes. Additional research for setting the process parameters to reduce the manufacturing times of the interchangeable parts needed for the industrialization of new prototypes of aeronautical ribs will be carried out in a future.

4. Application of flexible tooling for the manufacturing of parts by SPIF

Different configurations of the flexible tooling were setup for the manufacturing of ribs by incremental forming (figure 4(a) and figure 4(b)). To this end, it was necessary to manufacture a metallic tooling (support in white) (see figure 4), which is clamped to the CNC or manual machine and act as a support to tighten the printed plastic tooling. This metallic component has several drills matching the holes designed on the fixed part of the modular tooling system to ensure the tightening of the assembly. As can be seen in figure 4, once the customized backing plates are assembled on the fixed part of the tooling by means of the crenelated system, the pre-cut metal sheet is located by matching the tooling holes (T/U's) with the screws. Finally, the blank-holder is placed and the whole set is clamped and secured with nuts.

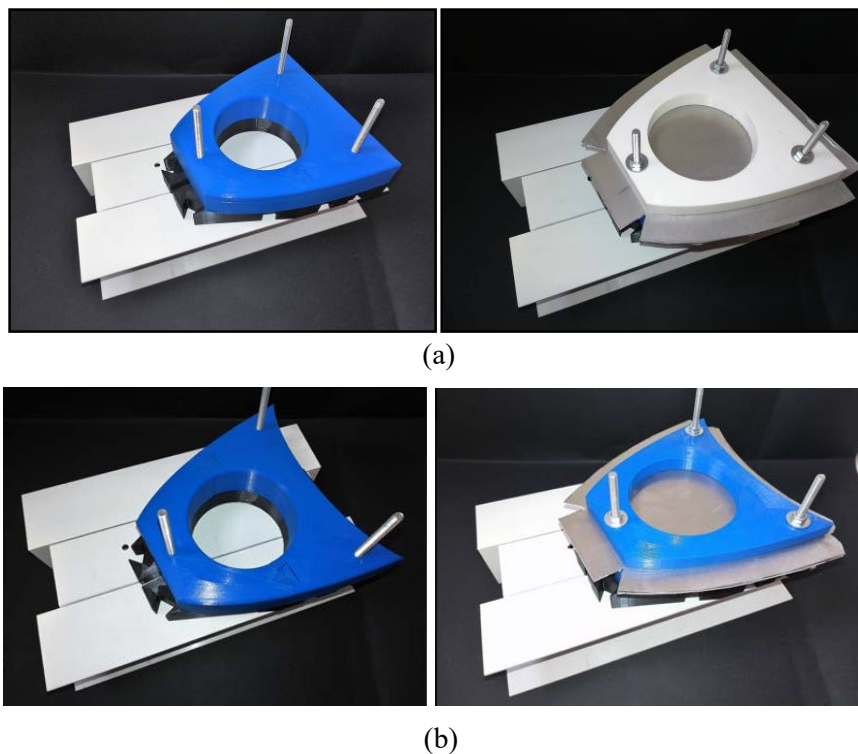


Figure 4. Experimental setups for the manufacturing of two different rib configurations, **(a)** with a straight flange and **(b)** with a concave flange at the rear side.

The manufacturing of any other different rib geometry just would need to change the combination of backing plates, manufactured by FMD. In this sense, figure 4(b) shows an alternative rib resulting from replacing the rear backing plate with a straight flange (see figure 4(a)) for another with a concave flange.

However, it has to be said that, at this stage of the work, the manufacturing of a series of SPIF parts using the proposed modular tooling in the CNC machining center is still a work in progress.

In order to check the technical feasibility of the proposal, a preliminar experiment was carried out in a universal milling machine for the manufacturing by SPIF of a convex flanging with a semi-circular geometry over AA7075-O sheet with a 1.2mm thickness (see figure 5(a)). The step down was set to 0.5mm per pass and a hemispherical tool with a diameter of 12mm was used.

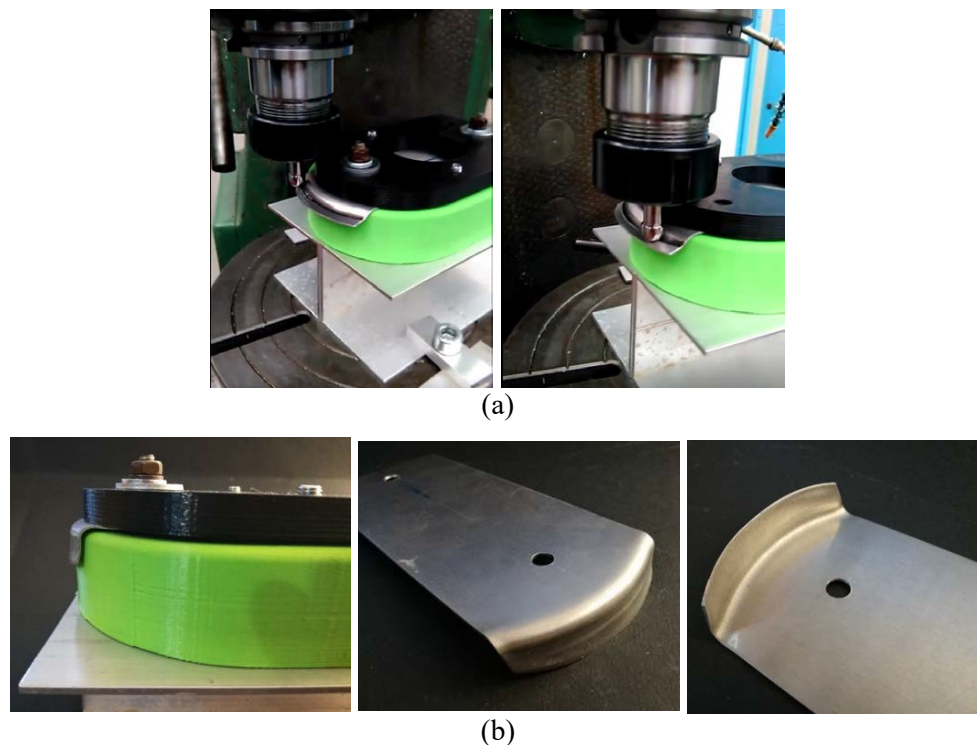


Figure 5. (a) Stages of a semi-circular convex flanging by SPIF. **(b)** Flanged specimen obtained over AA7075-O.

Figure 5(b) shows the successful manufacturing of the flanged part by SPIF. As can be seen, the finish and quality of the piece were good. There was no any mark at the inner side of the sheet close to the stretch-bend region due to the flexibility of the plastic backing plate, unlike what would happen if metallic backing plates had been used. The modular tooling manufactured by FDM was inspected after the deformation process of the sheet, and did not show any surface or structural damage.

The preliminar results obtained in this work can be considered a proof of concept to demonstrate the feasibility of combining the FDM and SPIF technologies along with the proposed modular tooling system, for manufacturing sheet metal parts with a potential reduction in costs and time to market of a particular prototype compared to conventional processes.

5. Conclusions

This paper proposes the design and manufacturing of a modular tooling system that allows the flexible manufacturing of different aeronautical components by means of Single Point Incremental Forming technology (SPIF).

The design for manufacturing of the tooling was developed considering the FDM additive technique using polylactic acid (PLA). The system design was equipped with a fixed part and a removable and interchangeable modular part customized for each type of aeronautical component (wing/stabilizer ribs). The assembly of the different parts was done by means of a system of crenelated joints, allowing for a robust assembly, while also being easily removable when another tooling configuration is required.

A proof of concept of combining the FDM and SPIF technologies, along with the developed modular tooling, was carried out through the manufacturing by SPIF of a convex flanging with a semi-circular geometry over AA7075-O sheet with a 1.2 mm thickness. The preliminar results pointed out the technical feasibility of the proposal and its potential reduction of costs and time to market for a new sheet metal prototype compared to conventional processes. Further work is currently being performed to manufacture by SPIF a series of aeronautical sheet parts in a CNC machining centre.

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