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One-shot drilling of unconventional thin metal hybrid stacks for aerospace applications

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Abstract. The aerospace industry's relentless pursuit of lighter, stronger, and more fuel-efficient aircraft has led to the widespread use of lightweight materials, particularly aluminum alloys, in aerospace engineering. This study focuses on the challenges associated with one-shot drilling without back-up forces of thin parts, a strategy aimed at reducing cycle, avoiding part separation for cleaning after drilling, and minimizing part assembly problems. Despite its effectiveness, problems persist with defects developing at the interface due to the interlayer gap phenomenon. This gap causes metal chips to accumulate and is influenced by both process parameters and the clamping conditions and methodologies. While existing literature primarily associates process parameters with burr measurements, this study delves into the often-overlooked influence of clamping strategies on the occurrence of interface defects. Through experimental drilling on a thin stack of Al7075-T6 and Al2024-T3, various clamping schemes were analyzed to assess their impact on burr height. The results were also correlated with the drill verse, thrust force, and torque. The objective is to increase know-how about these aspects and optimize clamping strategies for effective one-shot drilling, addressing gaps in current research.

Introduction

The aerospace industry has continually led advancements in technology and innovation, consistently striving to design aircraft that are not just lighter and more robust but also exhibit enhanced fuel efficiency. A crucial milestone in this effort has been the extensive adoption of lightweight materials, revolutionizing the field of aerospace engineering and opening up new possibilities. This perfectly fits with the worldwide movement towards adopting manufacturing practices that are more environmentally sustainable. Moreover, there is a persistent endeavour to enhance the efficiency of these materials, with a specific focus on minimizing thickness while preserving optimal performance levels.

Aluminum alloys have been a focal point in the ongoing research for weight reduction and improved performance in the aerospace industry. They demonstrate enhanced structural integrity and increased durability. While Carbon Fiber-Reinforced Polymers (CFRPs) offer a remarkable strength-to-weight ratio, they are accompanied by notable limitations, including susceptibility to impact damage and the necessity for intricate repair processes. As a result, aluminium alloys continue to be utilized, not only for their favourable mechanical properties but also due to their cost-effectiveness and well-established manufacturing processes [1,2].

Different types of aluminum alloys find applications in the aerospace sector, with the most prevalent classes mainly derived from the 2xxx and 7xxx series. Notable examples include the 2024-T3 alloy, employed in applications such as fuselage skin, wing skins, and cowls, and the 7075-T6 alloy, used in fuselage bulkheads, wing skins and stringers [3].

Despite one-shot drilling of non-glued parts being an effective drilling strategy for reducing cycle time and avoiding non-coaxiality issues between holes, it still presents several open points when thin sheets are considered. One of the primary issues involves the gradual increase in thrust force during the drilling process, which can lead to the separation of sheets (interlayer gap), resulting in the accumulation of metallic chips between the parts. The interlayer gap occurs when the upper material undergoes elastic spring back, reverting to its initial shape after drilling. Simultaneously, the lower material bends under the influence of the applied thrust force. These phenomena become more prominent and noticeable for thin materials, resulting in a corresponding reduction in their flexural stiffness. Additionally, Luo et al. [4] and Panico et al. [5] highlighted that the interlayer gap influences the formation of burrs. To maintain structural integrity and assembly quality, it is necessary to remove the accumulated material and interface defects through operations such as disassembly, cleaning/deburring, and reassembly. However, these procedures are time-consuming, do not add value, and can be costly [6], nullifying the benefits offered by one-shot drilling. Although process parameters (rotational speed, feed rate, tool geometry) play a key role in studying the interlayer gap phenomenon, equally crucial is the role of the temporary part-fixing conditions adopted during drilling.

To date, scientific literature has primarily focused on the investigation of a direct correlation between process parameters and the measurement of burr [6,7], leaving largely unexplored the contribution that the clamping strategy of parts offers to the development of defects at the interface of two thin materials drilled in a one-shot configuration. In this study, an experimental drilling investigation was conducted on thin stacks composed of Al7075-T6 and Al2024-T3. For a fixed set of process parameters (i.e., rotational speed and feed rate), three different clamping pattern percentages were investigated (40%, 60% and 80%), also changing the drilling verse (i.e., Al2024-T3 or Al7075-T6). During drilling, the thrust force and torque were acquired. The height of the burr was then correlated with the clamping pattern, the drilling side material, and the thrust force and torque.

Materials and Methods

The experimental one-shot drilling activities were conducted on stacks composed of Al7075-T6 sheet (300 mm x 300 mm x 1 mm) and Al2024-T3 sheet (300 mm x 300 mm x 0.8 mm). These materials were chosen due to their extensive use in the aerospace industry [9].

The stack was investigated in both the Al7075-T6/Al2024-T3 and Al2024-T3/Al7075-T6 configurations (these configurations will be referred as A/B and B/A, respectively) to analyze the influence of the flexural contribution of each material when positioned as the lower reinforcement on the hole quality. In the present experimentation, a coated carbide twist drill with a diameter of 4.76 mm, a cutting-edge height of 1 mm, a point angle of 130° and a helix angle of 25° was used.

The drilling tests were performed in dry condition by using a semi-automated electric drilling unit for industrial applications. The semi-automatic drilling unit is equipped with two independent electric motors, one dedicated to feed motion and the other to rotation (max. power 3 kW and max. rotational speed 8000 rpm). The hole-to-hole handling is performed by the operator, as well as the initiation of the drilling cycle. The drill remains in the drilling position thanks to a collar concentric to the drill bit, which, upon expansion, ensures a tight coupling within the rigid drilling jig (depicted in Fig. 1). The drilling machine is accompanied by specialized software that allows for the management of process parameters and real-time acquisition of current consumption for both motors, thrust force and torque curves over time. The upper and lower edges of each specimen were fixed to the rigid clamping fixture, while the lateral edges were left free to reproduce a typical single structural unit of the fuselage. The experimental set-up is shown in Fig. 1. According to the literature, the drilling of aluminum alloys prefers low feed values and moderate rotational speeds to favor low thrust force and torque values and better hole quality [3]. For this reason, the experimental drilling tests were conducted with fixed process parameters: a rotational speed of 4000 rpm and a feed rate of 0.03 mm/rev. For both stack configurations, three different clamping strategies were tested by varying the fill percentage achieved using a traditional temporary fastener (Cleco fastener). The clamping strategies were chosen from those typically employed during the assembly phase of aeronautical components. The positioning of the holes is in accordance with the 5x5 matrix of holes prepared on the drilling jig, of which only the central row was utilized (see Table 1). The central row was used to mitigate edge effects and to analyse the influence of the maximum flexural contribution of the stack. The experimented clamping percentages were 40%, 60% and 80%, and for each of them, 5 holes were drilled.

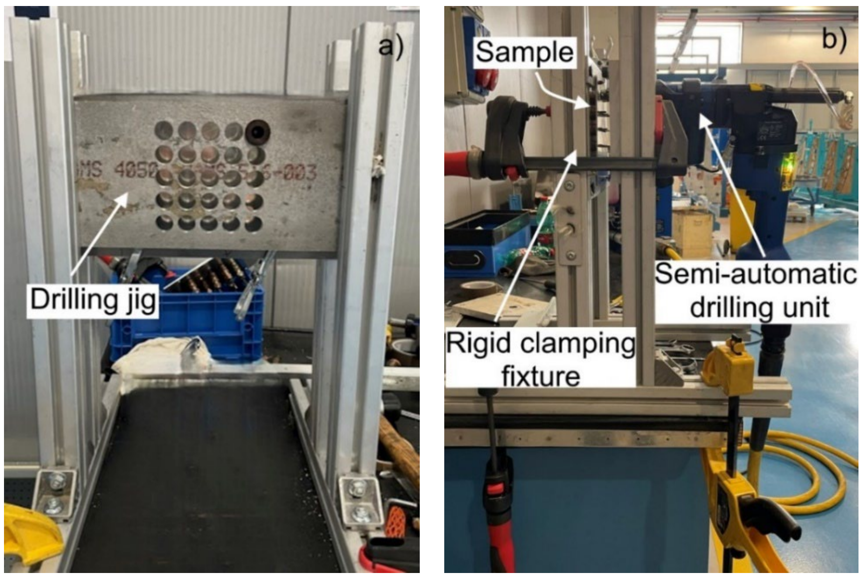
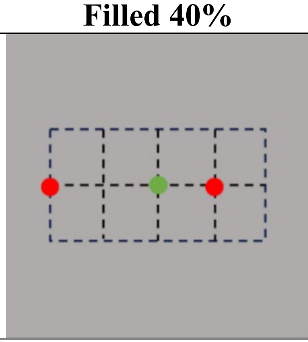
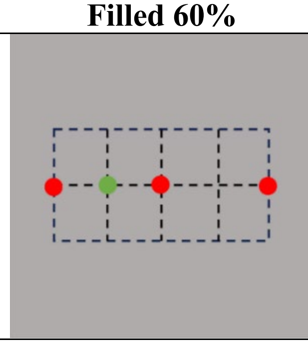
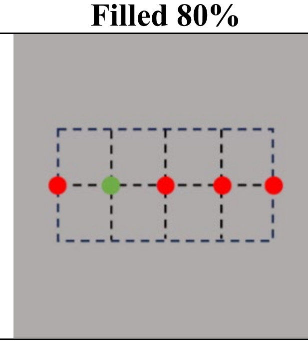


Fig. 1 a) Experimental set-up, front-view – b) Experimental set-up, lateral-view

Table 1 Description of clamping strategies in line with the hole matrix on the drilling jig

Filled 40%	Filled 60%	Filled 80%
		
● Temporary fastener position ● Drilling point -- Free position		

One observable characteristic that influences the quality of holes in aluminum is the presence of a burr. In specific applications such as aerospace, there is a critical need to reduce or eliminate burrs that exceed the specified tolerance range. The burr at the entry side of the hole is usually minor and can be easily removed by chamfering in the process of drilling a single hole. However, in a one-hole drilling configuration, it serves as an indicator of defects at the interface of the two materials in direct contact. This is particularly evident in thin configurations, where the spring back of the first drilled layer and bending of the subsequent layer, induced by thrust force, can lead to a significantly interlayer gap, thus favoring the development of defects at the interface. In contrast, the burr at the exit side is more consistent and may not always be removable due to the configuration of the assembly. To this end, a confocal microscope (Sensofar S Neox) was used to measure the height of the burr on both the top and bottom sides of each hole in both A/B and B/A drilling configurations.

Results and Discussion

Preliminary analysis of thrust force and torque. A typical trend of thrust force and torque curves during one-shot drilling of thin Al7075-T6/Al2024-T3 (i.e., A/B configuration) is shown in Fig. 2.

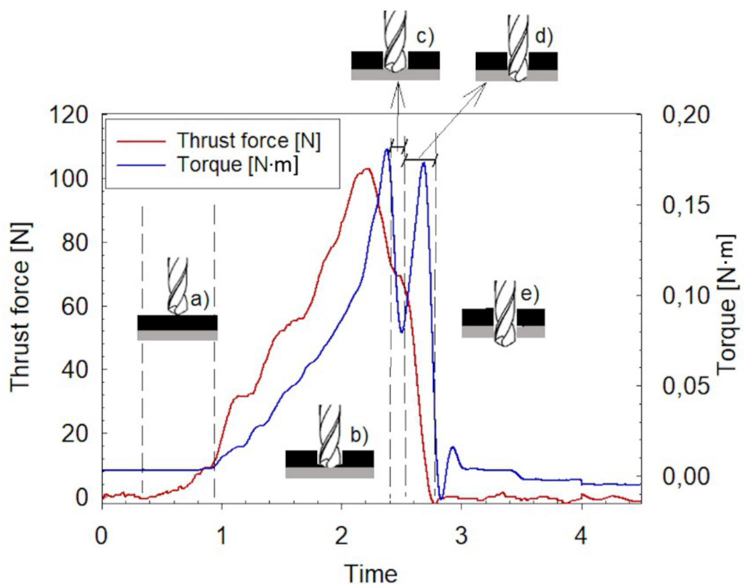


Fig. 2 Time-evolution curve of thrust force and torque during one-shot drilling

For both stack configurations, the qualitative trend is the same, and for the sake of brevity, the curves of B/A configuration are not reported. In detail, the main stages are defined as follows:

(a) The drill bit turns and moves forward in contact with the surface.

Already from this stage, it is possible to observe a peculiarity of the one-shot drilling process of thin materials compared to what is observed for thicker materials. In fact, the increase in thrust force is not concurrent with that of torque, resulting in a pure flexion for a duration of 0.5 seconds.

(b) The increase in thrust force and torque undergoes a change in slope, representative of the onset of the actual cutting phase. Both thrust force and torque reach their respective maxima in this phase. Phase b concludes when the material at the top of the stack has been drilled through its entire thickness.

The distinctive aspect of drilling thin materials, compared to what is observed for thick ones, lies in the duration of this phase, which is closely related to the flexural behavior of the stack. The reduced flexural stiffness offered by the stack and the absence of an external element to counteract the thrust force result in a significantly prolonged tool-material engagement phase, highlighting a phenomenology more akin to forming than cutting.

(c) In this phase, the phenomenon of the interlayer gap develops, which is evident in the abrupt decline in torque. The material at the top of the stack has been drilled, and it elastically returns to its initial configuration. Before the tool engages the next layer, there is a significant deflection caused by the thrust force.
(d) The drill bit engages and advances into the thickness of the material. The torque exhibits a second distinct peak, while there are no substantial variations in the thrust force.
(e) The thrust force and torque return to zero when the tool has completed the drilling process.

The experimental results of the maximum thrust force and torque as a function of the clamping percentage for both drilling configurations are shown in Fig. 3. The thrust force does not exhibit a clear trend in both drilling configurations. This can be anticipated, as under equivalent global boundary conditions, the percentage utilization of temporary fasteners does not provide a substantial increase in the flexural stiffness of the stack. Therefore, a significant variation in the axial force developed during drilling is not expected. As for the torque, for both drilling configurations, there is an increasing trend with the rise in the clamping percentage. Again, it is important to highlight that in numerical terms, there is no substantial variation, as for both stacks, the difference between the minimum and maximum torque values is on the order of a thousandth of N·m.

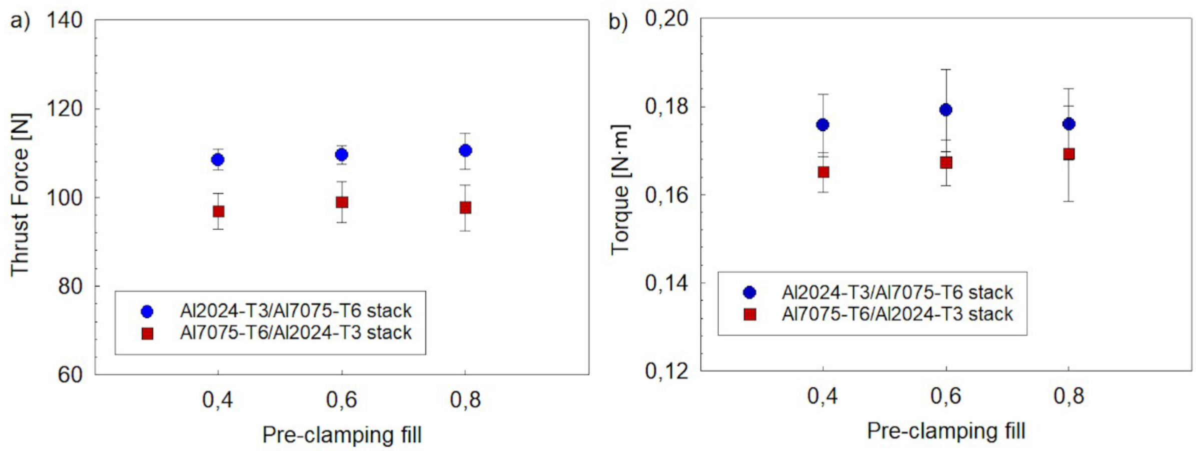


Fig. 3 a) Thrust force values for both Al2024-T3/Al7075-T6 stacks – b) Torque values for both Al7075-T6/Al2024-T3 stacks

Influence of drilling strategy on burr height. Based on a 3D profilometer inspection, the examined aluminum alloys manifested distinct burr morphologies attributable to their different mechanical properties. The 7075-T6 aluminum alloy revealed intermittent burrs, predominantly manifesting as discrete points. This particular variant, identified as a corona burr, is indicative of metallic materials known for their marked hardness and reduced ductility. Conversely, the 2024-T3 aluminum alloy exhibited a continuous, homogeneous, and viscous burr. This type of burr is characteristic of metals that exhibit significant ductility without excessive hardness.
As defined in the previous section, the burr that develops on the inlet side of the stack is typically smaller than that observed on the outlet side and is also automatically removable during the countersinking phase of the hole. For this reason, the maximum burr height was measured on the exit side of the stack and at the interface between the two materials (i.e. burr on the exit side for the upper material and burr on the entry side for the lower material).

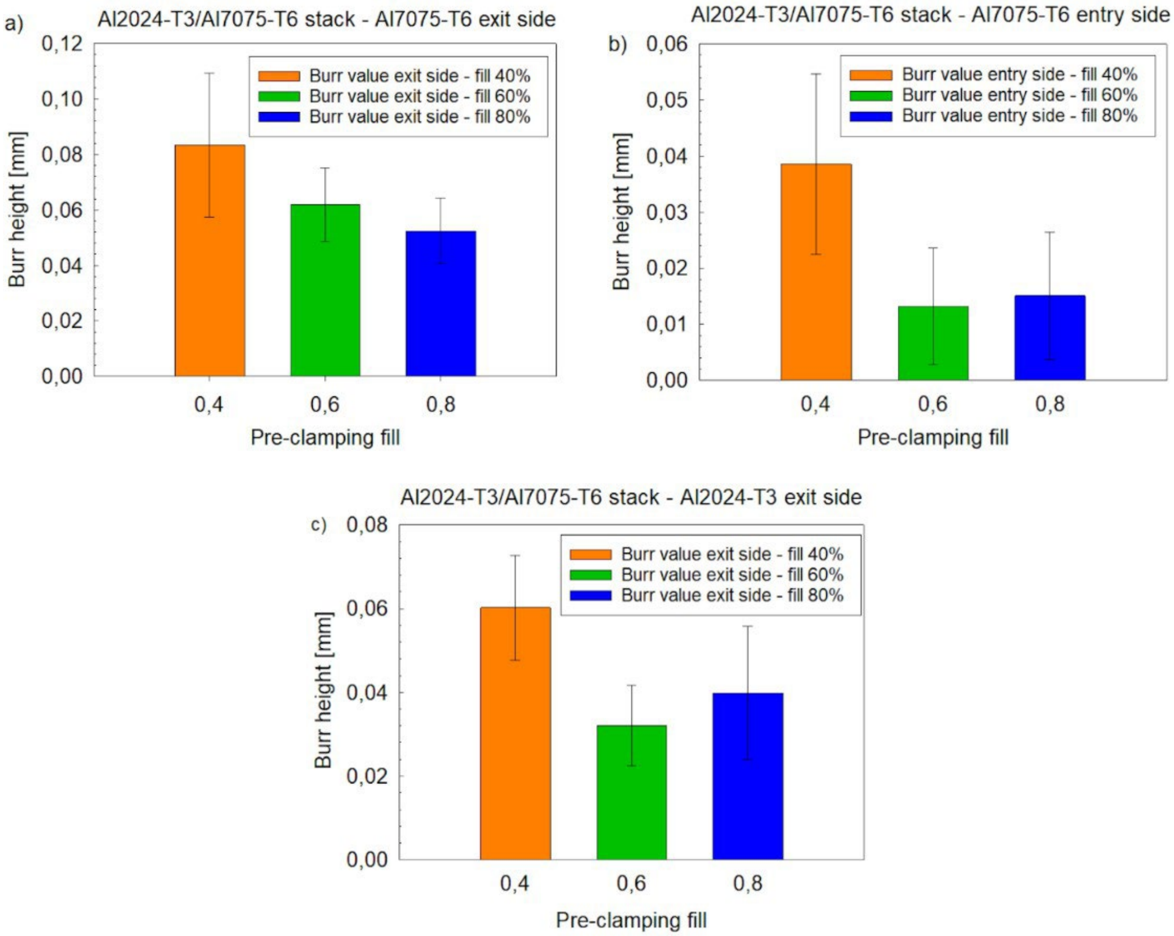


Fig. 4 Maximum burr height value for Al2024-T3/Al7075-T6 stack configuration: a) Al7075-T6 exit side – b) Al7075-T6 entry side – c) Al2024-T3 exit side

In Fig. 4, the mean value of the maximum burr height value acquired for each hole drilled in the one-shot drilling configuration of Al2024-T3/Al7075-T6 is plotted as a function of the applied clamping percentage. In particular, Fig. 4-a refers to the burr on the exit side of the stack, while Fig. 4-b and Fig. 4-c refer to the burr on the entry side of Al7075-T6 sheet and the burr on the exit side of Al2024-T3 sheet, respectively. It can be stated that the burr on the exit side of the stack decreases almost linearly as the adopted clamping percentage increases. As for the burr development on the entry side of the Al7075-T6 sheet (interface region), it exhibits a decreasing trend with an increase in the clamping percentage. This occurs most prominently during the transition from a clamping percentage of 40% to 60%, thereafter remaining relatively constant between 60% and 80%. Essentially, a low percentage of clamping elements and, consequently, a greater distance between two consecutive temporary fasteners results in a higher elastic spring back of the upper sheet, as well as a greater deflection of the lower sheet. This produces a larger interlayer gap compared to cases with a higher clamping percentage. It is important to note that the burr developed at the interface of the two materials can be influenced not only by the process itself but also by contact with the unevacuated chip. With regard to the burr developed on the exit side of the Al2024-T3 sheet, it also shows a decreasing trend with an increase in the clamping percentage, evident from the 40% to 60% clamping and then remaining almost unchanged from 60% to 80%. Similar to the analysis of the exit burr of the Al7075-T6 sheet, the reason is of a structural nature and involves the flexural stiffness of the sheets that make up the stack which will be discussed in detail later.

Similar analyses were conducted for the stack Al7075-T6/Al2024-T3. In Fig. 5, the mean value of the maximum burr height value acquired for each hole drilled in the one-shot drilling configuration of Al7075-T6/Al2024-T3 is plotted as a function of the applied clamping percentage. In particular, Fig. *5*-a refers to the burr on the exit side of the stack, while Fig. 5-b and Fig. 5-c refer to the burr on the entry side of Al2024-T3 sheet and the burr on the exit side of Al7075-T6 sheet, respectively. Each trend observed with the Al2024-T3/Al7075-T6 stack is replicated in the same manner with the Al7075-T6/Al2024-T3 stacks.

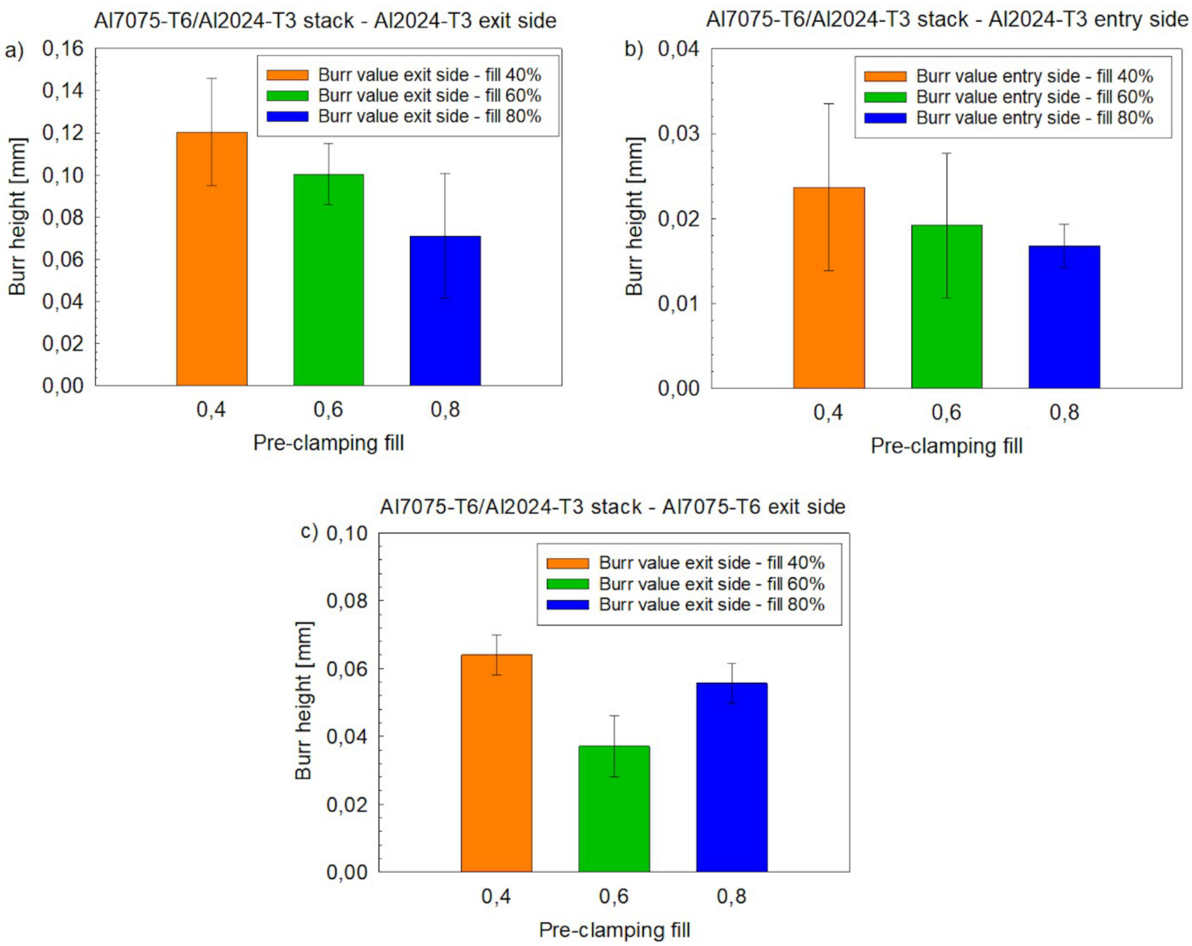


Fig. 5 Maximum burr height value for Al7075-T6/Al2024-T3 stack configuration: a) Al2024-T3 exit side – b) Al2024-T3 entry side – c) Al7075-T6 exit side

For this reason, it becomes interesting to perform a qualitative and quantitative comparison between the maximum burr height values obtained for each stack. Since the measured burr on the entry side (interface region), as known from the literature and confirmed by the current measurements, does not reach significant values, the comparison will be conducted exclusively among the burr values acquired on the exit side of the stack (see Fig. 6-a) and on the exit side of the interface region (Fig. 6-b).

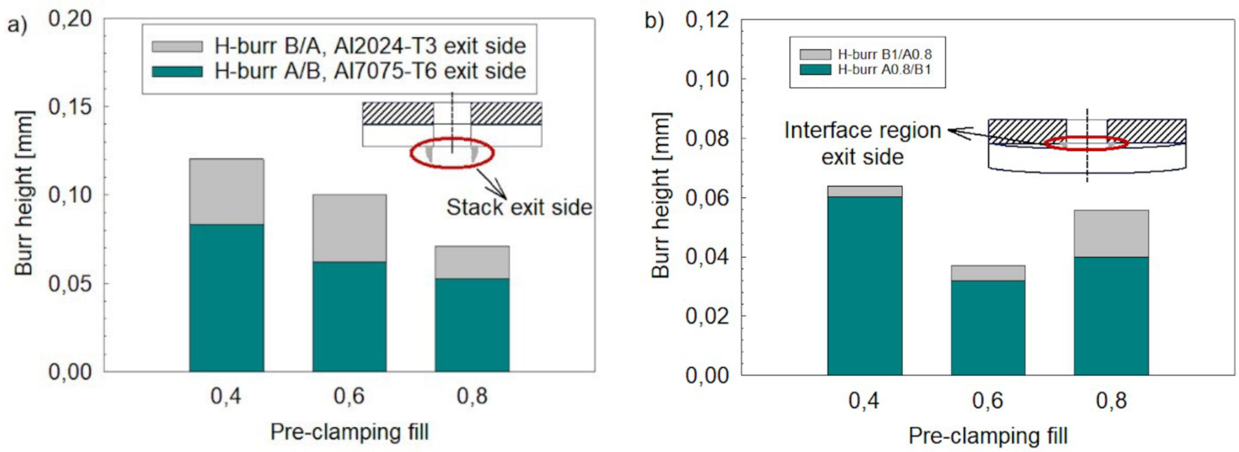


Fig. 6 a) Comparison of maximum exit-side burr height values between Al2024-T3/Al7075-T6 and Al7075-T6/Al2024-T3 stacks – b) Comparison of maximum exit-side burr height values between the materials at the top of hybrid stacks (interface region)

Starting from Fig. 6-a, it can be observed that the burr measured on the exit side of Al2024-T3 in the Al7075-T6/Al2024-T3 stack is consistently greater than that obtained for Al7075-T6 in the Al2024-T3/Al7075-T6 stack. To understand the reason, it is possible to utilize the calculation of the maximum displacement, y_{max}, that occurs in a simply supported beam when loaded at the mid-span:

$$y_{max} = \frac{Fl^3}{48EI}. \quad (1)$$

where *F* is the maximum value of the thrust force; *l* is the distance between two consecutive temporary fasteners; *E* is the Young's Modulus, and *I* is the Moment of Inertia of the cross-sectional area of the beam. For rectangular section, *I* is equal to $bh^3/12$, where *b* is the width and *h* is the height (or thickness) of the section.

Considering the drilling schematic depicted in Fig. 2, the upper material in "phase d" no longer contributes with its flexural stiffness. Therefore, the analytical calculation exclusively considers the second layers (as well as those involved in the burr formation on the exit side of the stack).

As an illustrative case for analytical computation, the drilling performed with a clamping percentage of 40% can be considered. Utilizing the thrust force values depicted in Fig. 3-a, along with the Young's Modulus and the thickness values listed in Table 1, can be used to calculate the maximum displacement that occurs for Al2024-T3 (Al7075-T6/Al2024-T3 stack) and Al7075-T6 (Al2024-T3/Al7075-T6) at the midpoint.
As shown in the following Table 2, it measures 0.8734 mm and 0.5106 mm, respectively.

Table 2 Evaluation of maximum theoretical displacement for Al2024-T3 and Al7075-T6 with a clamping percentage of 40%

Material	Young's Modulus, *E* [MPa]	Thickness, *h* [mm]	Width, *b* [mm]	Thrust force, *F* [N]	Span length, *l* [mm]	Evaluated displacement, y_{max} [mm]
Al2024-T3	73100	0.8	20	96.8569	30	0.8734
Al7075-T6	71700	1.0	20	108.4820	30	0.5106

What has been uncovered highlights a completely new phenomenon compared to what has been achieved by the scientific community thus far. For very thin materials, such as those examined in this study, boundary conditions are not negligible in determining the final quality of the hole. This is because, even though the Al2024-T3/Al7075-T6 stack is subjected to a higher thrust force compared to the Al7075-T6/Al2024-T3 stack (Fig. 3-a), the greater thickness of Al7075-T6 sheet (1 mm versus 0.8 mm for the Al2024-T3 sheet) contributes to a reduction in the deflection of the sheet under the drilling thrust force, resulting in a smaller burr height (Fig. 6-b). This is because the sheet essentially undergoes a kind of deep drawing, and therefore, a greater deflection contributes to a higher burr height.

As for Fig. 6-b, it can be stated that Al7075-T6 (in the Al7075-T6/Al2024-T3) develops a larger burr compared to Al2024-T3 (in the Al2024-T37Al7075-T6 stack). The reason again lies in the flexural stiffness properties of the material constituting the stack. Specifically, when the material at the top of the stack is progressively drilled, the still intact underlaying material acts as a counterforce to the thrust force. In the case of the Al7075-T6/Al2024-T3 stack, considering the consideration related to the maximum displacement calculated with Eq.1, the Al2024-T3 sheet represents a less rigid counterforce compared to the Al7075-T6 sheet in the Al2024-T3/Al7075-T6 stack.

Summary

The study of the hole quality was conducted considering the clamping percentage of the parts and the drilling direction for both Al2024-T3/Al7075-T6 and Al7075-T6/Al2024-T3 stacks. This study led to the following conclusions:

1. The increase in clamping percentage and drilling direction does not significantly influence the magnitude of the maximum thrust force and maximum torque. Thus, when taking into account the power consumption aspect of the semi-automatic drilling unit, significant variations are not observed. It is evident that the increase in the number of clamping elements and, consequently, the number of the pre-holes required for pre-assembly results in an increase in the drilling cycle time.
2. In a thin stack, the quality of holes obtained through one-shot drilling must necessarily be associated with structural considerations related to the flexural stiffness intrinsic to the materials and that conferred by boundary conditions. Unlike studies on one-shot drilling of thick stacks, it is no longer possible to define a direct correlation between the thrust force and the burr height that excludes significant variables for the computation of the flexural stiffness of the constituent materials of the stack.

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