Effect of thermal drilling strategy on the geometrical characteristics of metal – composite joints

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Abstract: *This paper deals with the change of joint geometry of non-ferrous metal sheets and composite plates reinforced with bi-directional glass and carbon fiber by thermal drilling due to the effect of different drilling strategy. Joints formed by direct and sequential drilling were tested. Sequential drilling represents a convenient way to minimize delamination of layered composites during joining.*

Keywords*: METAL-COMPOSITE JOINING, THERMAL DRILLING, DRILLING STRATEGY, DIRECT DRILLING, SEQUENTIAL DRILLING, BUSHING GEOMETRY*

1. Introduction

Thermal drilling is one way of joining materials through bushing forming. Nowadays, the challenges of joining materials with completely different properties such as metallic and composite thin-walled materials are being overcome [1-6]. Such material combinations occur in the construction of ultralight structures in the automotive or aerospace industries. Joints of metals and composites are found, for example, in the construction of A-pillars, engine covers, load plates or front stretchers.

Some specific applications of composites in car bodies are shown in Fig. 1.

a) b)

Fig. 1 *Examples of the application of composite materials: a) Porsche A-pillar, b) MQB platform engine cover*

Thermal drilling provides a way to create a bond between a metal sheet and a continuous fiber-reinforced composite with two significant advantages: no fastener and therefore no added weight, and no disruption to the continuity of the fibers. Making joints without disturbing the continuity of the fibres in the composite is possible only if the matrix of the composite is thermosoftening polymer. It heats up when drilled, softens and the fibres are deflected out of position without breaking when the tool penetrates and the bushing is formed, Fig. 2.

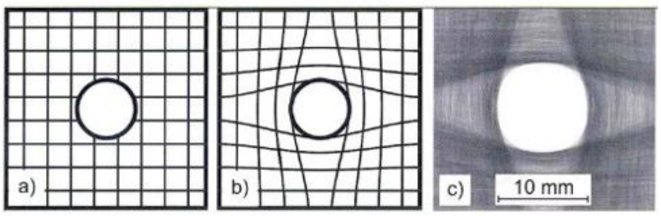


Fig. 2 *Comparison of a hole in a fibre composite formed by a) conventional drilling, b) and c) thermal drilling of a fibre composite with a thermosoftening matrix, adapted from [4,6]*

The mechanical joining of the metal sheet and the composite plate formed by thermal drilling can then look like this, Fig. 3:

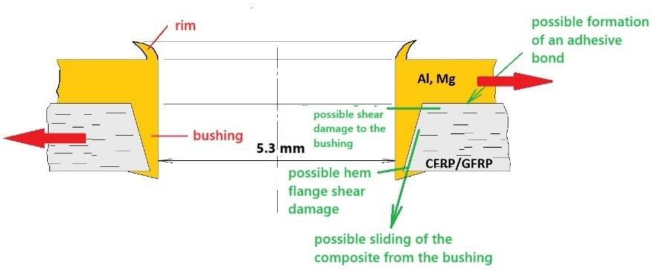


Fig. 3 *Schematic diagram of metal sheet and fibre composite joint made by thermal drilling*

The aim of this paper is to present the differences in shaping the bushing when drilling the metal plate alone, and also when drilling the metal-composite pair by direct and sequential thermal drilling. The objective is to create a bushing with sufficient thickness and length to penetrate through the full thickness of the composite plate to form a mechanical joint and to determine which of the strategies investigated is the most appropriate.

2. Materials and Methods

Materials used in the automotive industry were chosen for the metal – composite joints formation using thermal drilling. Composite materials are progressively replacing conventional metals in automotive construction. They compete with them in terms of comparable mechanical properties and low specific weight - i.e. an advantageous strength-to-weight ratio, also called specific strength.

Characteristics and identification of selected materials:

- Aluminium alloy EN AW-6082 T6 (AlSi1MgMn) – Al alloy supplied in a precipitation-hardened state with relatively high mechanical properties. The alloy was supplied in the form of a 1 mm thick rolled sheet. Hereinfter Al.
- AZ 91 magnesium alloy with the main alloying elements Al and Zn. The alloy was supplied in the form of a 2 mm thick rolled sheet. Hereinfter Mg.
- Composite with polypropylene (PP) matrix reinforced with continuous glass fibres in two perpendicular directions. The thickness of the consolidated composite organosheet is 1.55 mm, which is the result of the compaction of three layers of prepregs. Hereinfter GF.
- Composite with polypropylene matrix (PP) reinforced with continuous carbon fibres in two perpendicular directions. The thickness of the consolidated composite orgaanosheet is 1.55 mm, the result of the compaction of seven layers of prepregs. Hereinfter CF.

The basic characteristics of the materials are shown in Tab. 1-3.

Tab. 1 *Chemical composition of alloys in wt.%*

alloy	Si	Mg	Mn	Fe	Zn	Cu	Al
Al	1.0	0.7	0.44	0.4	0.08	0.06	balance
Mg	0.09	balance	0.14	0.004	0.93	0.02	8.9

***Tab. 2** Mechanical and physical properties of alloys*

alloy	Re [MPa]	Rm [MPa]	A_{50} [%]	density [g·cm^{-3}]
Al	295	340	15	2.71
Mg	280	200	24	1.81

***Tab. 3** Properties of composite organosheets*

Composite	**PP CF50 T200 OS**	**PP GF45 T600 OS**
Matrix	**polypropylene**	
Reinforcement	Carbon fibre	Glass fibre
Type of fibre	Carbon HT	E glass
Weaving	Twill 2/2	Twill 2/2
Surface mass. mats	200 g·m^{-2}	600 g·m^{-2}
Density of weaving	3K	1200 tex
Fibre content by weight	50%/50%	50%/50%
Fibre content in the composite	51%	47%
Surface weight of finished product	301 g·m^{-2}	887 g·m^{-2}
Prepreg thickness	0.22 mm	0.5 mm
Specific weight of composite	1.46 g·cm^{-3}	1.68 g·cm^{-3}
Melting temperature	165°C	165°C
Operating temperature (short-term)	140°C	161°C
Operating temperature (long-term)	100°C	100°C
CTE (23-80°C)	3.2×10^{-6}K^{-1}	11×10^{-6}K^{-1}

The geometry of the test joints as well as the shape and dimensions of the test specimens, determined in accordance with STN EN ISO 12996:2014 using a 5.3 mm diameter tool (Flowdrill Long 5.3 mm), are shown in Fig. 4. The opening (joint) is located in the centre of the overlapped area.

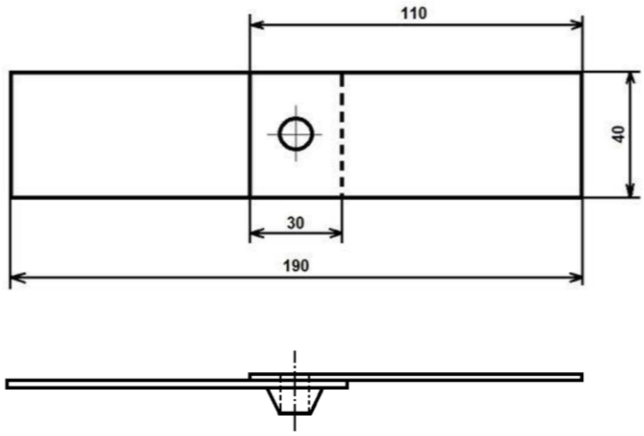
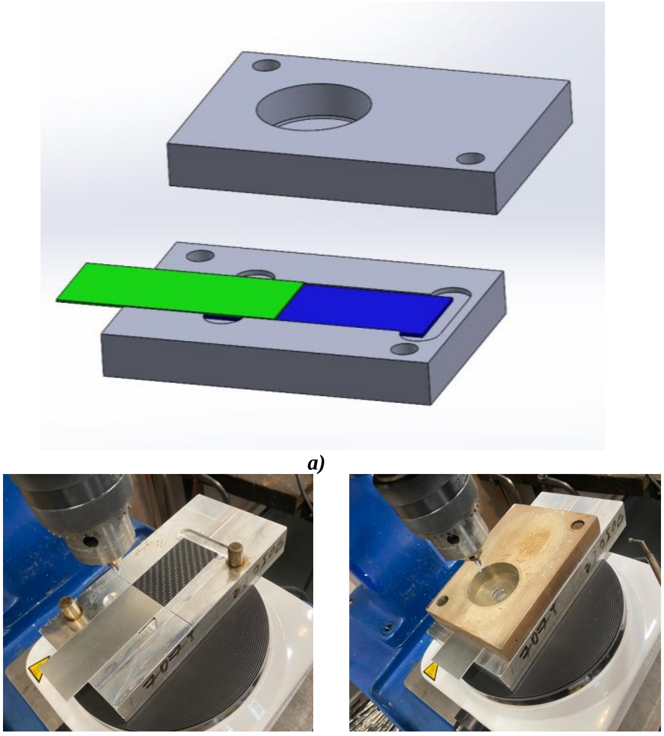


***Fig.** 4 Shape and dimensions of test specimens and joint for the tool ∅5.3 mm.*

The parameters tested in thermal drilling were: rotational speed 2400 min^{-1} and 4800 min^{-1}, feed rate 60 mm·min^{-1} and 240 mm·min^{-1}. Thermal drilling was carried out on a bench drill, the materials were heated and clamped in the fixture. The fixture for setting and securing the relative position of the materials during thermal drilling is shown in Fig. 5.



a)

b) ***c)***

***Fig.** 5 Fixture for joining production: a) CAD model, b) open fixture, inserted materials, c) closed fixture, ready for thermal drilling*

The dimensions of the resulting bushing were determined when the metal plates only were drilled in the fixture, as well as when metal plate is placed on the composite sheet in direct and sequential drilling. Direct drilling means the drilling of overlapped metal-composite materials heated and 165°C at once, Fig. 6. Sequential drilling means that in the first step a opening is made with a tool in the preheated composite, which is overlapped with a metal plate in the second step and drilled again, assuming easier forming the metal bushing in the pre-prepared opening in the composite and less delamination, Fig. 7.

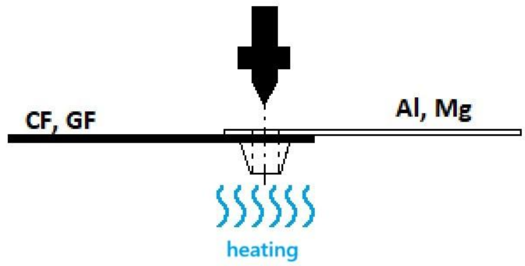


***Fig. 6** Direct drilling*

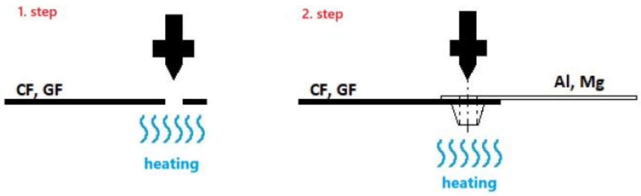


***Fig. 7** Sequence drilling*

After forming the bushings in the metal sheets separately, as well as after forming the joints with the composites, the bushing characteristics - thickness and length - were monitored, Fig. 8. The overall suitability of the shape of the resulting bushing was also assessed - it should have a sharp end, conical shape to be able to penetrate the composite without much delamination of the layers.

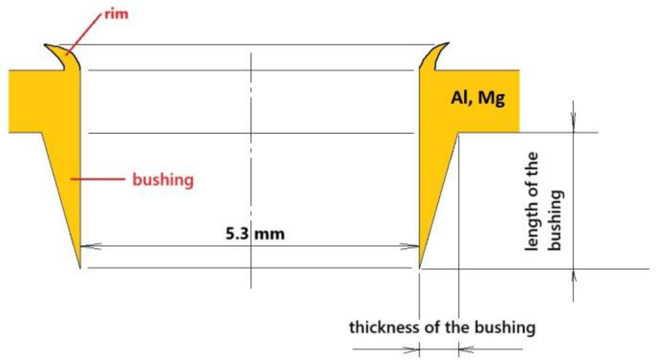


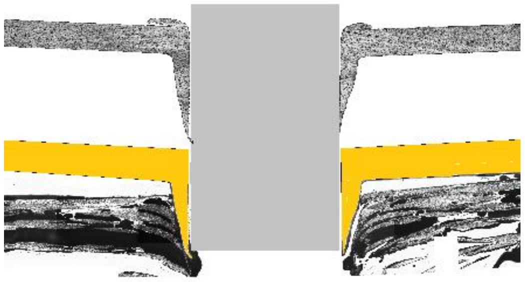
Fig. 8 *Basic bushing characteristics monitored*

Results

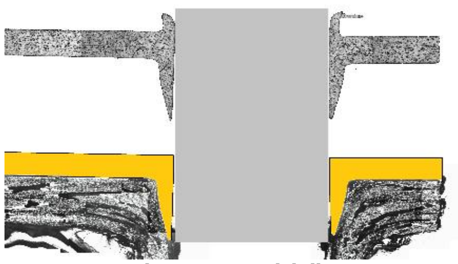
The metallographic study of the bushings was carried out on Al, Mg metal sheets at all process parameters tested, and also for Al and Mg joints with CF and GF composites at all process parameters (two levels of rotational tool speed, two levels of feed rate) and direct and sequential drilling strategies. Example metallographic sections for Al and Mg and their joints with CF are shown in Tab. 4 and 5.

Tab. 4 *Al-CF joints*

thermal drilling of Al sheet



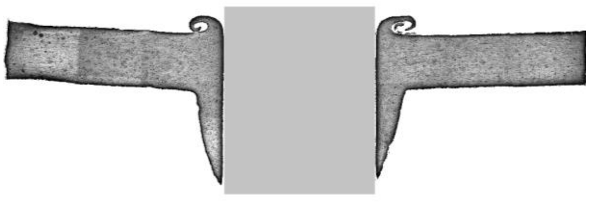
Al-CF joint, direct drilling



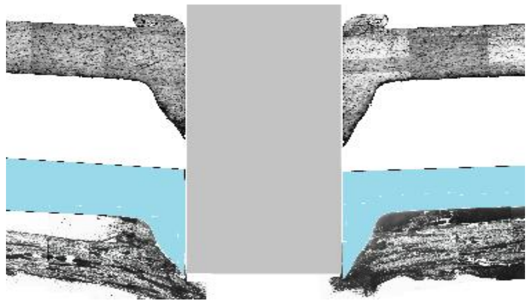
Al-CF, sequential drilling

Table 4 shows that thermal drilling of Al sheet only leads to inappropriate bushing ends, often resulting in bushing fragmentation. When drilling with the composite, either by direct or sequential drilling, the geometry of the bushing was improved. It can be concluded that Al shaping that is constrained by other material or a pre-drilled hole improves the bushing shaping process.

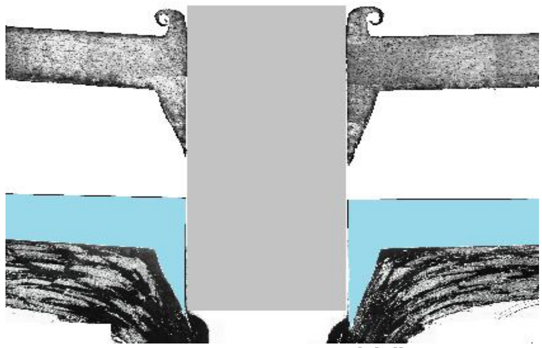
Tab. 5 *Joints Mg-composite CF*



thermal drilling of Mg sheet



Mg-CF joint, direct drilling



Mg-CF joints, sequential drilling

In Mg alloy, on the other hand, a bushing of suitable shape is formed when the Mg sheet is drilled separately, whereas when drilling with the composite by direct drilling, the flow of Mg material into the bushing area is significantly impeded. On the contrary, sequential drilling improves the shaping of the bushing by pre-drilling an opening in the composite, which allowed a sharper and longer bushing to be formed than in direct drilling. The overall results of the bushing characteristics for all material combinations and drilling strategies are shown in Tab. 6 and Fig. 9 and 10.

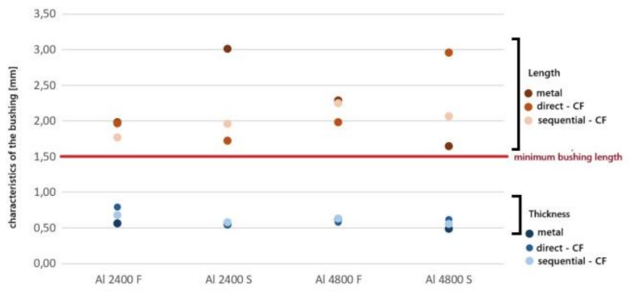


Fig. 9 *Bushings characteristics for Al-CF*

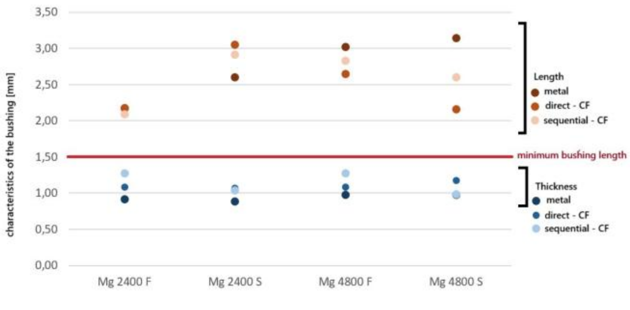


Fig. 10 *Bushings characteristics for Mg-CF*

Tab. 6 *Geometric characteristics of the bushing in metal drilling and direct and sequential joining*

Mat.	Process parameters		Thermal drilling of metallic sheets only		Direct drilling				Sequential drilling			
					CF		GF		CF		GF	
	RPM [min-1]	Feed rate [mm·min-1]	thickness [mm]	length [mm]	thickness [mm]	length [mm]	thickness [mm]	length [mm]	thickness [mm]	length [mm]	thickness [mm]	length [mm]
Al	2400	240	0.57	1.99	0.80	1.98	0.86	2.05	0.68	1.77	0.69	1.85
		60	0.55	3.02	0.56	1.73	0.59	0.80	0.59	1.96	0.59	2.90
	4800	240	0.63	2.29	0.58	1.98	0.67	2.10	0.64	2.25	0.66	2.20
		60	0.49	1.65	0.62	2.96	0.61	2.60	0.56	2.07	0.56	2.46
Mg	2400	240	0.92	2.18	1.09	2.18	1.10	2.29	1.28	2.09	1.33	2.43
		60	0.89	2.61	1.07	3.06	1.17	2.60	1.04	2.92	1.04	3.07
	4800	240	0.98	3.03	1.09	2.65	1.23	2.38	1.28	2.84	1.19	3.02
		60	0.98	3.15	1.18	2.16	1.07	2.74	0.99	2.60	1.01	3.44

Notes:

Inappropriate bushing shape	**Rather inappropriate bushing shape**	**Rather suitable bushing shape**	**Suitable bushing shape**

From Tab. 6 and Fig. 9 and 10, the following observations can be made:

- the thickness of the bushings is not significantly affected by the process parameters of thermal drilling
- a greater thickness of bushings is achieved for Mg alloy (0.89-1.33 mm), which is due to a larger material volume available in drilling area with respect to the 2 mm plate thickness
- for Al alloy, the thickness of the bushings varies from 0.49 to 0.86 mm, which corresponds to a smaller sheet thickness compared to Mg
- the length of the bushings was greater than the thickness of the composite for both Al and Mg, except in one case (Al 2400/60 - GF), i.e. satisfactory
- bushing length is more sensitive to the variation of thermal drilling process parameters, with the feed rate having a more pronounced effect on the bushing length than the RPM. The effect of feed rate on bushing length is clear - slower feed rate (especially when combined with higher speed) allows longer bushing lengths to be shaped, both for Al and Mg.
- The length of the bushings is around 2 mm for Al-CF, between 2 and 3 mm for Al-GF, the length of the bushings is between 2 and 3 mm for Mg-CF, between 2.5 and 3.5 mm for Mg-GF. This can be justified by the less dense weave of the GF fabric, the thicker fibres and the lower number of glass fibre layers in GF compared to CF. This implies that the glass fibres have less resistance to penetration of the bushing.

If we consider not only the dimensions of the bushing but also their shape visually, and mark the cases of suitable shape in green in Table 6, we can determine the appropriate process parameters for the formation of the joints easier. Suitable process parameters for joining Al and Mg sheets with CF and GF composites are following: rotational tool speed 4800 min^{-1} and slower feed rate 60 $mm \cdot min^{-1}$. A suitable joining strategy is sequential drilling.

If a joint is formed with the above mentioned suitable process parameters with sufficient thickness and length of the bushing, the joint can be secured against opening by hemming flange, Fig. 11.

The fibres are closed under the formed hem flange, which in addition to closing the joint also prevents delamination of the composite.

Conclusion

Thermal drilling technology can be used for creation efficient joints of non-ferrous metal alloys and fibre composites with thermosoftening matrix at suitable process parameters. Good joining is also supported by a suitable two-step drilling strategy, but this means an extra operation and an increase in joining time when applied under industrial practice conditions. Therefore, the load carrying capacity of joints formed by these drilling strategies still needs to be mapped.

Fig. 11 *Al-GF joint with hem flange*

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