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RESEARCH PAPER

STUDY OF THE USE OF THERMAL DRILLING IN MECHANICAL JOINING OF MG SHEET AND GFRP/CFRP COMPOSITES WITH THERMOSOFTENING MATRIX

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ABSTRACT

The paper discusses the joining of magnesium based metallic sheet and composites with thermosoftening polypropylene matrix reinforced with bi-directional continuous glass and carbon fibres by thermal drilling technology. The bushing formation has been investigated by separately drilling AZ91 Mg alloy sheet at two rotational speeds and feed rates to find out the parameters at which a bushing with optimum length and thickness, suitable for joining with the composite, is formed. Under these conditions, the joining of the metal sheet and composite was then carried out by simple thermal drilling. During simple drilling, delamination of the composite occurred in the vicinity of the hole, which was resolved by flanging the bushing with a penetration of the tool from the opposite side. When AZ91 was joined to carbon fibres reinforced composite, there was a lack of bushing formation due to the higher resistance of the carbon fibres, which are present in the composite in greater numbers compared to the glass fibres. This problem was solved by sequential drilling, which means that a flowdrill tool was used to create a hole in the composite itself, then overlaid with Mg sheet and again drilled, forming the bushing and flanging the bushing from the opposite side. The sequential drilling resulted in joints with a load capacity of 0.8 - 1.4 kN, which exhibit the characteristics of a hybrid - mechanical and adhesive joint.

Keywords: AZ91 magnesium alloy; continuous fibre reinforced composite; thermosoftening matrix; thermal drilling

INTRODUCTION

Combining lightweight materials of dissimilar material nature (multi-material design) into larger structural assemblies is a response to the demand for emission reduction through weight reduction of components in the automotive industry [1,2]. For this reason, the use of polymer composites in the design of cars or aircraft is expected to increase. Polymer composites provide a unique combination of high specific properties and good recyclability. Thermosoftening composites in formable organosheets can be layered in the desired manner to achieve specific mechanical properties. At the same time, the continuous bi-directional fibres can conform well when moulded and resist different combined load types, providing good crash-absorption [3-5]. The joining of dissimilar materials by fusion bonding is restricted because of the different material nature of metals and composites [6-8]. Adhesive bonding and mechanical joining appear to be a more viable way to proceed [9]. When bonding metals and composites, we can do it without adhesives, whereby the molten polymer matrix takes over the function of the adhesive. Among mechanical joining methods, in addition to the classical techniques of clinching and riveting, various pins, embedded weld inserts, form-locking elements, etc. can be used [10-14]. In mechanical joining, it is crucial to obtain a joint without disturbing the integrity and continuity of the reinforcing fibres. This cannot be achieved by conventional drilling or cutting. In these processes, the fibres are disrupted, and their reinforcing function in the composite and, thus, in the joint is reduced. Preference is given to processes where the thermosoftening matrix can be heated, and the fibres are merely deflected out of position when the metal element is mounted [15].
The paper deals with joining an Mg metal alloy as a thin sheet with a bidirectional continuous fibres reinforced composite with a thermosoftening matrix by thermal drilling [16-23]. We suggest that penetration of the forming bushing through the softened composite, deflection of the reinforcing fibres, and subsequent closing of the joint by hemming flange will occur during thermal drilling.

MATERIAL AND METHODS

Materials

For metal-composite joining, the following materials were used (**Fig. 1**):

- magnesium alloy AZ91, 2 mm thick sheet metal plate (hereafter Mg).
- polymer composite with polypropylene matrix reinforced with bidirectional continuous glass fibre, 1.5 mm thick organosheet (hereafter PP-GF)
- polymer composite with polypropylene matrix reinforced with bidirectional continuous carbon fibre, 1.5 mm thick organosheet (hereinafter PP-CF)

The chemical composition and basic properties of the materials used are listed in **Table 1** and **Table 2**.

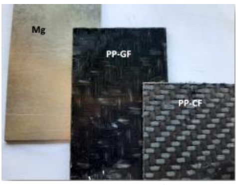


Fig. 1 Appearance of materials used

Fibres weaving style: Twill 2/2

Table 1 Chemical composition of Mg sheet, wt.%

Al	Zn	Mn	Si	Cu	Fe	Mg
8.9	0.93	0.14	0.09	0.02	0.004	Bal.

Table 2 Selected properties of composite organosheets

Fibre	Yarn	Thickness per layer	Number of layers	Matrix	Melting temp.
E-Glass	1200	0.5 mm	3	PP	165 °C
carbon	3000	0.22 mm	7		

Flowdrill tool, machine and parameters

The selected materials were joined using a Flowdrill long Ø 5.3 mm tool. For joining, a simple bench drill machine was used, and two different tool speeds were tested: 2400 and 4800 min^{-1}. The feed rate was ensured manually, slow (approx. 60 $mm \cdot min^{-1}$) and fast (approx. 240 $mm \cdot min^{-1}$).

Test joints - the shape and dimensions

The shape and dimensions of the test joints, shown in **Fig. 2**, were determined based on the diameter of the Flowdrill tool according to ISO 12996:2013.

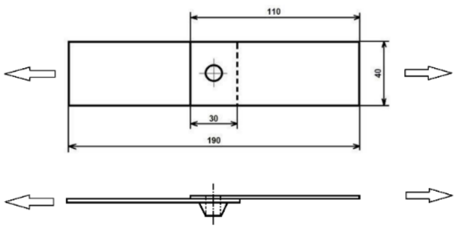


Fig. 2 Shape and dimensions of the test joints, arrows indicate load in tensile shear testing

The procedure for metal flowdrill, making and testing the joints

Firstly, Mg sheet was drilled separately at two rotational speeds and two feed rate values to investigate the Mg alloy's behaviour in thermal drilling. We were interested in the dimensions of the bushing - thickness and length - formed at the tested rotational speeds and feed rates. Based on metallographic analysis, we determined the optimal drilling parameters. The criterion was to obtain a bushing with the greatest possible length, sufficient to penetrate the entire thickness of the polymer composite during joining, and at the same time, a sufficient thickness to affect the load-bearing capacity of the future joint, **Fig. 3**.

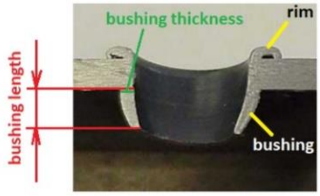


Fig. 3 Cross-section through the axis of a hole produced by thermal drilling

We were also interested in the percentage of material displaced from the original plane of the metal sheet plate (V) by axial force and frictional forming into the bushing region ($V_{bushing}$). We determined this proportion based on metallographic sections, expressing the shape of the bushing by mathematical equations and by integrating along the circle, we calculated the volume of bushing material ($V_{bushing}$). We put this in proportion with the volume of the sheet metal in the area of the hole (V) and expressed it as a percentage, **Fig. 4**.

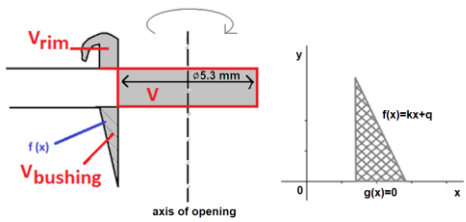


Fig. 4 Procedure of calculating the proportion of material transformed from the metal sheet plate into the area of the bushing

It applies:

$$V = V_{rim} + V_{bushing} \quad (1.)$$

where V_{rim} is the volume of the sheet transformed into the rim and $V_{bushing}$ is the volume of the sheet transformed into the bushing, which can be calculated by integrating the contour of bushing from metallographic section along a circle as follows:

$$V_{bushing} = 2\pi \int_a^b x[f(x) - g(x)]\, dx \quad (2.)$$

Once the optimum drilling parameters for the Mg sheet were determined, joining the Mg sheet plate and composites via the bushing followed.

The procedure for making the joints was as follows: heating the fixture and the materials to be joined in the furnace to 170°C, transferring the fixture and materials to the drilling machine (the temperature after removal from the furnace is maintained locally with a heat gun), fixing, drilling of the overlapped materials, with the Mg sheet in the upper position of the joint.

After the joints were formed, their geometry was investigated metallographically, and their load-bearing capacity was tested on a universal tensile testing machine at a loading rate of 10 $mm \cdot min^{-1}$.

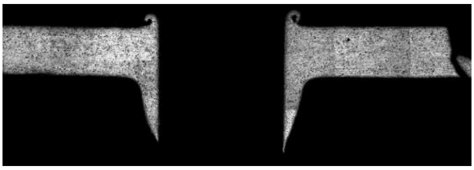
RESULTS

Geometry of bushing made in Mg sheet

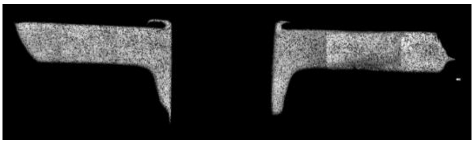
Table 3 shows the geometry of the bushings formed by separate thermal drilling of Mg sheet at two rotational speeds and feed rates.

RPM [min^{-1}] / feed rate [mm.min^{-1}]

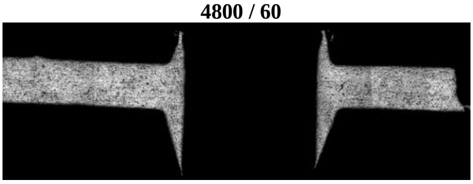
2400 / 60



2400 / 240



4800 / 60



4800 / 240

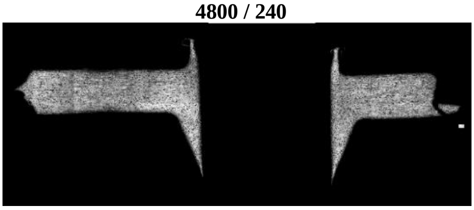


Table 3 Geometry of bushings made in Mg sheet

Table 3 shows that the particular rotational speeds and feed rates slightly affected the shape of the bushing. More detailed differences become apparent after measuring the thickness and length of the bushings and calculating the proportion of material transformed into the bushing area (**Table 4**).

Table 4 Characteristics of bushings made under different process conditions

RPM [min^{-1}] and feed rate [mm.min^{-1}]	Bushing length [mm]	Bushing thickness [mm]	Percentage of material displaced to the bushing area [%]
2400 / 60	2.96	0.96	53.53
2400 / 240	2.8	0.96	68.65
4800 / 60	3.2	0.8	70.34
4800 / 240	2.8	1.0	70.32

The drilling speed of 4800 min^{-1} and slow feed (60 mm·min^{-1}) were selected as the optimum drilling parameters because these parameters produced the longest bushing with sufficient thickness. At the same time, these parameters displaced most of the material from the plane of the metal sheet plate to the bushing area (70.34%).

Geometry of the joints made by simple thermal drilling

Using the above drilling parameters, a joint was formed by simple drilling two overlapped preheated materials Mg + PP-GF. The resulting joint geometry is shown in **Fig. 5**.

Fig. 5 Geometry of the joint Mg – PP+CF

In **Fig. 5**, the resulting bushing has a different shape than when the Mg sheet was drilled separately. This is due to the composite's resistance, an obstacle to the bushing formation. In addition, the composite's delamination is visible, caused by the inevitable gap between the tool and the hole in the fixture (**Fig. 6)**.

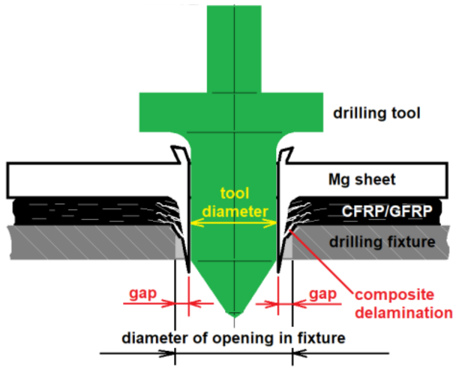


Fig. 6 Schematic diagram of simple thermal drilling process with delamination of composite

The solution to the delamination problem could be to hem flange the resulting bushing that protrudes from the back side of the composite. The hem flange will also ensure that the joint is resistant to opening.

Hemming flange the joint

In order to ensure simplicity of the process, the same flowdrill tool can be used for this purpose but allowed to enter the formed bushing from the back side, **Fig. 7**. The hem flange was formed by a radius between the collar and the cylindrical part of the tool. The whole tool is made out of sintered carbide, so, all surfaces of the tool can be used for forming.

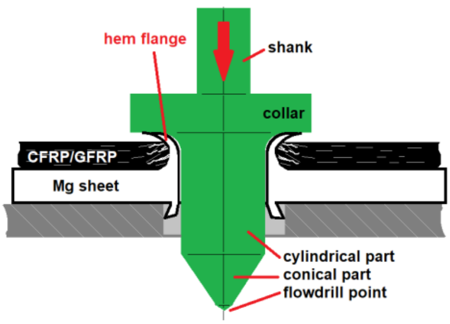


Fig. 7 Hemming flange of the joint

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Geometry of the joints made by sequential thermal drilling

A new problem became apparent when making Mg joints with PP-CF by thermal drilling. The bushing formed had an inappropriate geometry - it was short and thick, making it impossible to create a good-quality joint (**Fig. 8**).

Fig. 8 Geometry of the joint Mg + PP-CF

This is due to the fact that carbon fibre is only half the thickness of glass fibre and the number of carbon fibres in a yarn is 3000 compared to 1200 for glass fibres. Such numerous carbon fibres are compacted into a prepreg with a thickness of only 0.22 mm as compared to the thickness of glass fibres prepreg (0.5 mm). Therefore, when drilling a carbon fibre composite, the resistance of fibres is higher than when drilling a glass fibre composite. This resulted in the formation of a short and thick bushing with inappropriate geometry. The solution to this problem could be a sequential drilling method. Sequential drilling procedure is proposed as follows:

- separate drilling heated composite
- overlay of the composite with Mg sheet metal
- drilling Mg sheet metal
- hemming flange

Geometry of sequentially drilled joints with hemming flange

The geometry of sequentially drilled Mg+PP-GF and Mg+PP-CF joints with hem flange is shown in **Fig. 9**.

Fig. 9 shows that the sequential drilling method helped reduce the composite's resistivity, allowing the Mg bushing to be formed more easily. The hem flange is relatively thin and partially prevents delamination. Around the bushing, a large number of composite fibres are accumulated (fibre-rich zone), which were deflected from the arising hole place.

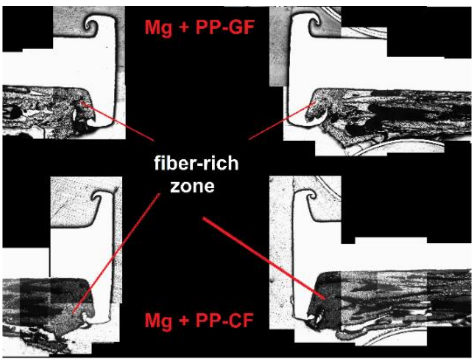

Fig. 9 Geometry of sequentially drilled joints with hem flange

Load carrying capacity of sequential joints with hem flange

Load-displacement curves of joints are shown in **Fig. 10** and **Fig. 11**.

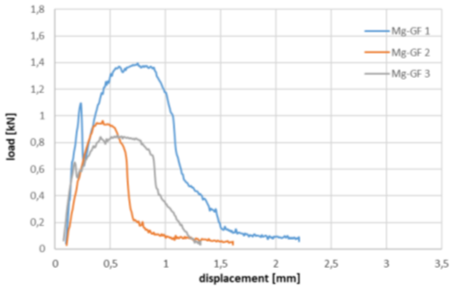

Fig. 10 Load displacmenet curves of Mg + PP-GF sequential joints

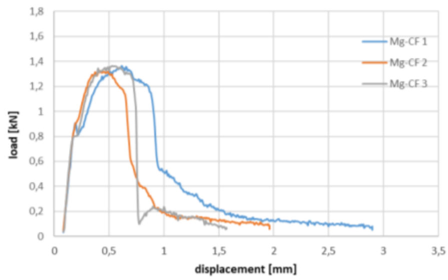

Fig. 11 Load displacmenet curves of Mg + PP-CF sequential joints

From **Fig. 10** and **Fig. 11**, it can be observed that the load carrying capacity of the joints lies between 0.8 and 1.4 kN. However, the hybrid nature of the Mg + PP-GF joints is also evident from **Fig. 10**. A bonded joint is formed between the Mg sheet and the composite heated above the melting temperature of the polypropylene matrix, while the bushing provides the mechanical connection. If the bonded joint is of good quality, it increases the overall load carrying capacity of the joint and this is evident by the peak on the rising part of the load-displacement curve, the detail is highlighted in **Fig. 12**. The contribution of the bonded joint to the overall load carrying capacity of the Mg+PP-CF joints is minimal.

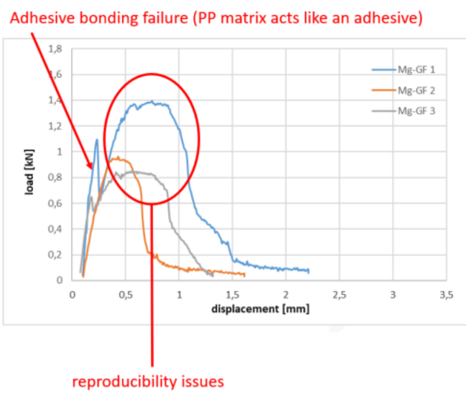

Fig. 12 Load-displacement curves of Mg + PP-GF sequential joints, detailed view

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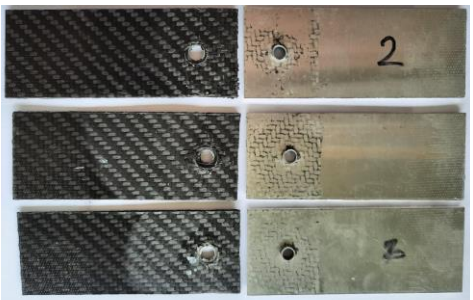
Once the bonded joint is broken (force drop behind the peak), the connection is secured only by the bushing, which gradually breaks after the maximum force is reached (the arched part of the curve around F_{max}). Subsequently, after the failure of the bushing, the force drops and the joint fails.
In addition to the hybrid nature of the joint, the above curves (**Fig. 12**) also show a problem with the repeatability of the joining process - the individual tested joints show a large dispersion in the maximum load capacity achieved (0.8 - 1.4 kN). The appearance of the joints after failure is shown in **Fig. 13**.

a) Mg+PP-GF joints



b) Mg+PP-CF joints

Fig. 14 Appearance of joints after load carrying capacity testing

The hybrid, adhesion-mechanical nature of the joints formed is evident from **Fig. 14**. There are signs of adhesive bonding to the PP matrix on the Mg alloy, however, it is evident that adhesive bonding did not occur over the entire overlap area, which consequently is the source of the large variance in the load carrying capacity of joints.

CONCLUSION

The following findings emerge from the above pilot study:

- The geometry of Mg bushings in joints with composites is influenced by the resistance of the fibres to tool penetration. This resistance strongly depends on the heating regime of the composite during drilling. The viscosity of the polypropylene matrix increases significantly above the melting temperature (165°C), allowing the fibres to move away from the hole axis during drilling. Sufficient heating of the composite (at least 170°C) over a joining area with at least 30 mm in diameter [15] and maintaining the sufficient temperature of the composite during joining is a key condition for forming a joint with minimal disturbance to the continuity of the fibres.
- Hemming flange of the joint has proven to be very useful, preventing delamination of the composite, opening of the joint, not requiring a special tool.
- Sequential drilling facilitates the forming of the Mg bushing by making the hole in the composite in a previous operation. No special tool is required.
- The resulting load carrying capacity of sequentially formed joints varies between 0.8 and 1.4 kN.
- Sufficient temperature and holder pressure lead to a hybrid joint formation - a bonded joint between Mg and composite over the entire overlap area and at the same time a mechanical joint through the bushing

In order to ensure the repeatability and reproducibility of the formation of metal-composite joints, to get the most out of mechanical properties of materials involved, adhesion and mechanical part of joint, it is necessary to optimize and stabilize the designed process from the point of view of:

- the heat conditions during joining (use IR heating instead of a heat gun)
- the holder pressure of the materials during joining
- process parameters (ideally, the thermal drilling process should be carried out on CNC machines, but the need for heating complicates this)

Joining metals and composites via thermal drilling is a promising option for joining structurally completely different materials without fasteners.

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