Application of flow-drill technology for joining thin metal materials

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Abstract: *The paper presents the results of testing the joints of unequal materials using flow-drill technology and a combination of flow-drill technology and adhesive bonding. The formed joints were tested by tensile and shear test according to ISO 12996. The positive effect of adhesive bonding on the load-bearing capacity of the joints and on the stress distribution in the tested materials was observed.*
Keywords*: JOINING DISSIMILAR MATERIALS, FLOW-DRILLING, ADHESIVE JOINING, TENSILE TEST*

1. Introduction

The need for a variety of mechanical joining techniques is increasing in the design of lightweight multi-material vehicle structures. The created joints should meet the requirements for safe and rigid joints, but at the same time with sufficient load absorption before failure. Available techniques for mechanical joining, especially of thin-walled profiles, are flow drill screwing, self-piercing riveting and tack setting. The problem with joining thin-walled materials by means of joining elements, in particular screws, is the small number of turns in thin materials, which break immediately under load [1-6]. A suitable solution in this case is the production of holes by flow-drill technology, where heat is generated by friction of the tool, the material softens and instead of conventional drilling by chip removal, a bush with a length three times the material thickness is formed from excess material [7]. This bush is sufficient support for the screw, it can be used to form a thread.

Although this technology is not primarily used to join materials, but only to locally strengthen the cross-section of one material, if we stack two materials on top of each other and let the tool penetrate both materials, under optimal conditions they will be joined by created bushes. The thickness and continuity of the formed bushes, together with the material properties, will determine the resulting mechanical characteristics of the joint [8-15]. If we combine this technology with adhesive bonding, we can eliminate the concentration of stresses around the joint.

The aim of the experimental work was to create and test the load-bearing capacity of joints of thin sheets based on galvanized and non-galvanized steel and aluminum age-hardened alloy, created by flow drill technology in combination with adhesive bonding.

2. Materials and Methods

Three types of materials were used for joints creation:

- uncoated cold rolled extra deep-drawn steel DC04 (hereinafter **DC**) with thickness of 0.8 mm
- hot-dip galvanized high-strength low alloyed steel TL 1550-220 + Z (hereinafter **TL**) with thickness of 0.8 mm
- age-hardened aluminum alloy EN AW-6082 T6 (hereinafter **Al**) with thickness of 1.0 mm

Chemical composition, mechanical properties of materials used are given in Tab. 1.

Tab. 1 *Mechanical properties and chemical composition of materials*

mat.	YS [MPa]	UTS [MPa]	Elong. [%]	Chemical composition [wt.%]
DC	197	327	39	0.04%C, 0.25%Mn, 0.009%P, 0.008%S, Fe-bal.
TL	292	373	34	0.1%C, 1%Mn, 0.5%Si, 0.08%P, 0.03%S, 0.015%Al, 0.1%Nb, 0.15%Ti, 0.2%Cu, Fe-bal.
Al	290	340	15	1%Si, 0.4%Fe, 0.06%Cu, 0.44%Mn, 0.7%Mg, 0.02%Cr, 0.08%Zn, 0.03%Ti, Al-bal.

According to the diameter of the tool (Flowdrill Long ∅ 5.3 mm), the dimensions of the test specimens for the formation of joints were determined on the basis of the ISO 12996 standard and set to 40×110 mm. Joints with a 30 mm bonding line were made from the prepared test specimens and the hole was placed in the middle of the bonding area, Fig. 1.

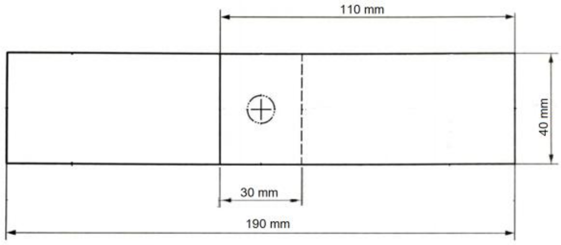


Fig. 1 *Single lap test specimen for combined tensile and shear test*

In the case of joints formed by a combination of adhesive bonding and thermal drilling, a layer of one component, heat curing, solvent free structural rubber adhesive was applied to one of the joined surfaces (Fig. 2), the materials were joined, then a hole was made by thermal drilling and finally the adhesive was cured in an electric oven at 180 °C / 25 min.

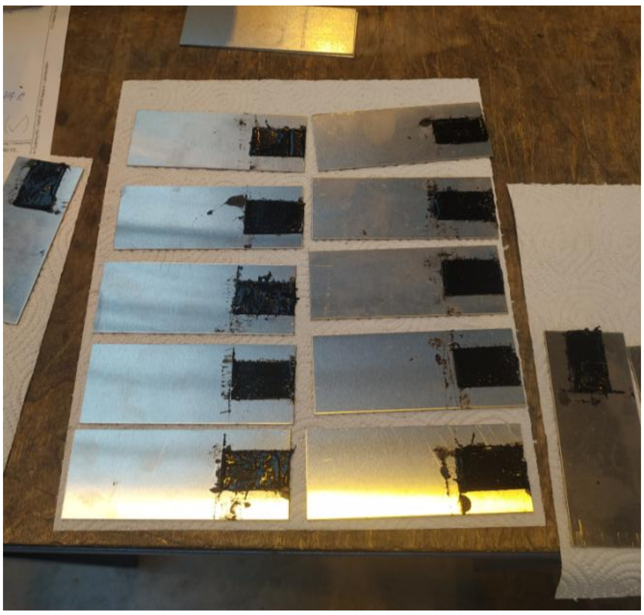


Fig. 2 *Application of adhesive to a defined area*

Joints were made with the following combinations of upper/lower materials: DC/DC, DC/TL, DC/Al, TL/TL, TL/DC, TL/Al, Al/Al, Al/DC, Al/TL. For all joints made of unequal materials, both options (M1/M2 and also M2/M1) have always been tested, as the materials differ in mechanical properties and formability, which can affect bush formation.

The parameters for creating holes by thermal drilling are given in tab. 2.

***Tab. 2** Cutting parameters for holes production*

Peripheral speed	113 m·min^{-1}
Spindle speed	7200 rpm
Feed rate	200 mm·min^{-1} (the movement of the tool ends 0.2 mm below the surface of the top material)
dwell of tool	0.8 sec in the lower position
lubrication	application paste FDKS 100

Joints with a hole, without a thread and without a screw (Fig. 3) were subjected to a tensile shear test on universal testing machine TiraTest 2300. During the test, the maximum force at the joint failure and the load-displacement curve were recorded. The joint loading speed was 10 mm·min^{-1}. After the failure of joints combined with adhesive bonding, the type of joint failure was determined - adhesive, cohesive, mixed.

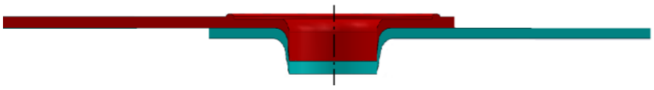


***Fig. 3** Joint cross-section*

3. Results and discussion

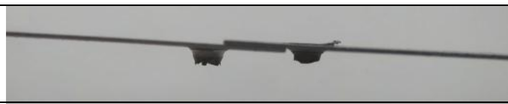
In the production of joints by thermal drilling (without adhesive bonding), it has been shown that some material combinations cannot be joined using the given process parameters. An overview of successfully (OK) / unsuccessfully (NOK) created connections is given in tab. 3. Material combinations where materials have not been successfully joined by thermal drilling have not been further investigated in combination with adhesive bonding, as uncreated or insufficiently formed bushes would not contribute to the strength of the joint combined with adhesive bonding.

***Tab. 3** Overview of successfully/unsuccessfully created joints*

joint		joint		joint	
DC/DC	NOK	TL/TL	NOK	Al/Al	OK
DC/TL	NOK	TL/DC	NOK	Al/DC	OK
DC/Al	NOK	TL/Al	OK	Al/TL	OK

The prerequisite for successfully joining two materials by flow drill technology is that both the top and bottom material will form a continuous bush of sufficient length and both will form a common double bush, with the top material forming the inner layer of the bush, the bottom material the outer layer of the bush. The two bushes together will then contribute to the shear strength of the joint. The reason for the failure of joining some material combinations can be explained by the fact that the top material does not form a sufficiently long bush, or the bush of the bottom material does not have continuous edges but divided by cracks into several segments (petals). The appearance of bushes of joined and unjoined materials is given in Tab. 4.

***Tab. 4** Appearance of bushes created by thermal drilling*

joint	appearance of bushes
DC/DC NOK	
DC/TL NOK	
DC/Al NOK	
TL/TL NOK	
TL/DC NOK	
TL/Al OK	
Al/Al OK	
Al/DC OK	
Al/TL OK	

Tab. 4 shows that unjoined pairs showed low or almost no bush of upper material. In one case (DC / Al), both bushes were formed, but the outer bush formed from the bottom material was broken. According to [12], the quality of the bush formed is affected by the spindle speed and the t / d ratio (material thickness / tool diameter). Too high a spindle speed can lead to damage to the integrity of the bush (see DC / Al, TL / Al joints), especially if the bottom material is an aluminum alloy. The lower the t / d ratio, the less material is available to form a bush with a relatively large circumference (relative to the thickness of the material), as a result of which it is more likely to observe cracking and petal formation.

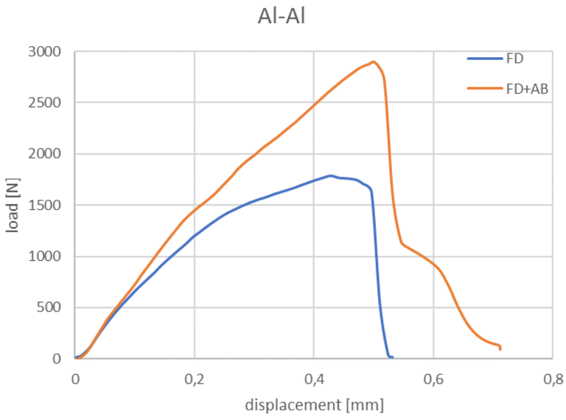
Tab. 5 shows bushes of joints formed by thermal drilling and adhesive bonding.

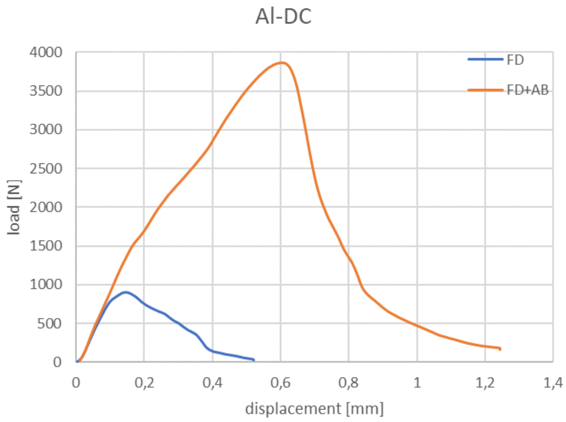
***Tab. 5** Appearance of bushes created by thermal drilling and adhesive bonding*

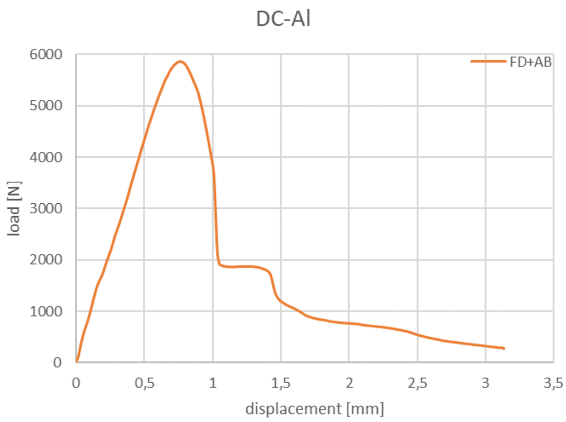
joint	appearance of bushes
Al/Al	
Al/DC	
DC/Al	
Al/TL	
TL/Al	

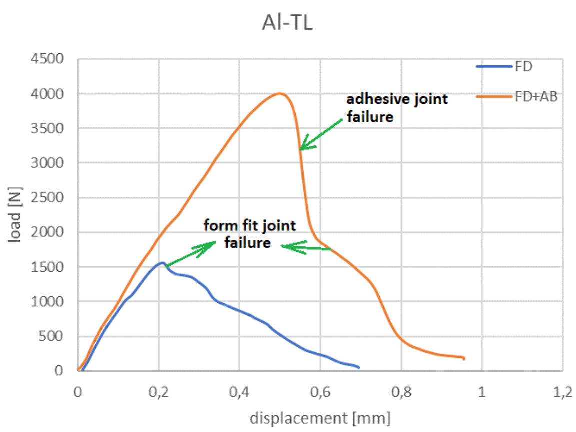
Tab. 5 shows that in joints combined with adhesive bonding, bushes are more integral compared to joints formed without adhesive joining.

Fig. 4 shows the load-displacement curves of the individual material combinations created by the flow-drill and flow-drill technology in combination with the adhesive bonding.









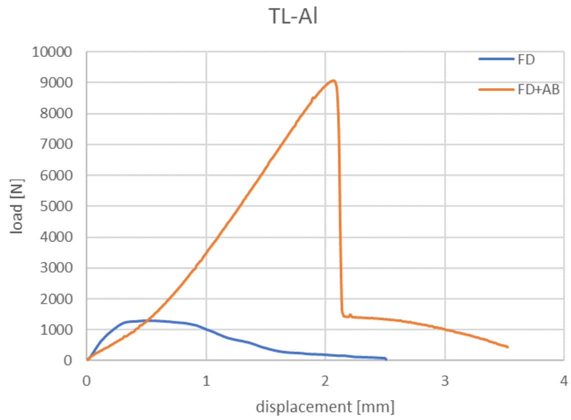


Fig. 4 *Load – displacement curves (FD-flow drill, AB-adhesive bonding)*

The load-displacement curves of the joints formed by the combination of thermal drilling and adhesive bonding reach a maximum after the initial growth, followed by a sharp decrease in the load, which corresponds to a cohesive failure of the adhesive joint. The curve on the descending part generally shows a smaller change in shape at a force which corresponds to the maximum load of the joint created only by thermal drilling, i.e. corresponds to the failure of the bush of the mechanical joint by shearing, Fig. 5. Thus, on load-displacement curves, it is usually possible to distinguish which part of the load-bearing capacity of the joint is provided by the adhesive joint and which part is ensured by the mechanical form fit joint (see Fig. 4 Al/TL load-displacement curve).

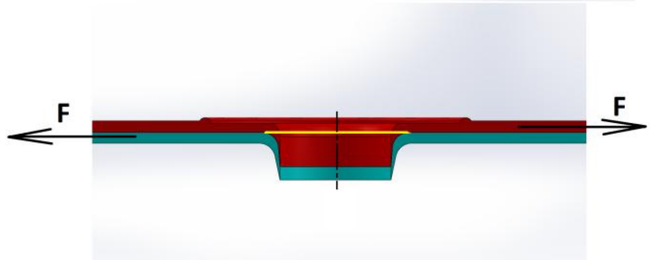


Fig. 5 *Scheme of bush shear failure*

Fig. 6 shows the maximum load at failure of the tested joints.

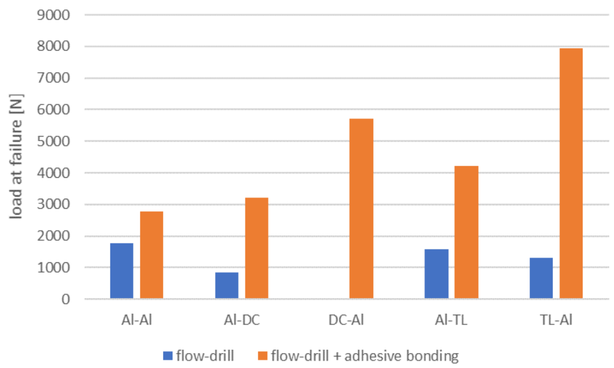
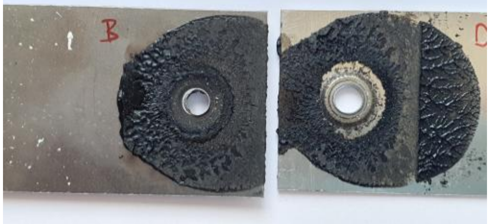
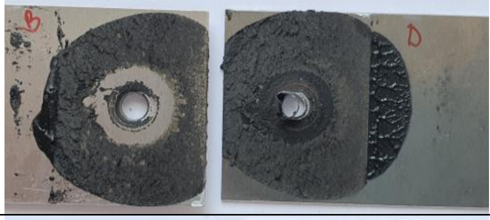
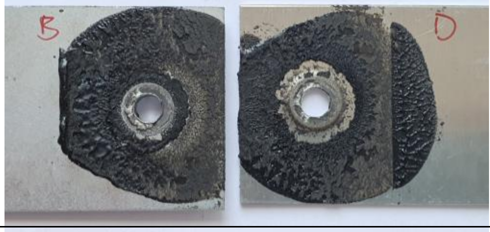
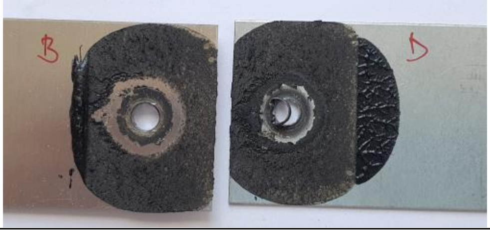


Fig. 6 *Comparison of load-bearing capacity of tested joints*

Fig. 4 shows that adhesive bonding significantly contributes to the strength of the joints in that, in the initial phase of loading, the bonded areas are primarily carrying the load. Only after the adhesive or cohesive failure of the adhesive joint, the bush of the upper material will slow down the final phase of the joint failure process. Tab. 6 shows failure of adhesive-mechanical joints.

Tab. 6 *Appearance of the joint's failure*

Al/Al	
Al/DC	
DC/Al	
Al/TL	
TL/Al	

During the hole formation by thermal drilling, the samples were pressed together, whereby the adhesive applied to the defined surface spread over the circular surface. All joints failed cohesively. There is a narrow intermediate ring around the hole, where the adhesive was adhesively separated from the Al substrate at all joints.

4. Conclusions

The paper presents the results of research into the possibility of joining thin materials by thermal drilling without and with the use of adhesive. Research has shown that all material combinations, where one of the materials is aluminum, either in the upper or lower position in the joint, at given parameters, are suitable for joining. It is also necessary to optimize the thermal drilling parameters because the given parameters led to the formation of a continuous bush in steel materials, while in aluminum cracking and petal formation were observed in the bush. Adhesive bonding has significantly increased the load-bearing capacity of the joints; after the adhesive fails, the final failure of the joint is inhibited by the bush formed from the upper material of the joined material pair.

Recommendations for further research:

- for joining thin sheets, it is possible to recommend increasing the current t/d ratio, which would mean using a smaller drill diameter for the given material thicknesses in order to have a larger supply of material to create a continuous bush.
- Reducing the diameter of the drilling tool would also mean a reduction in the dimensions of the specimens, thus also a reduction in the adhesive-bonded area, which could help to highlight the contribution of the bush cross-section to the bearing capacity of the joint.

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