Analysis of interference fit joints formed by thermal drilling technology with CNC process control

Erik Janoško*, Anna Guzanová, Nikita Veligotskyi
Technical University of Košice, Faculty of Mechanical Engineering, Department of Technology, Materials and Computer Supported Production, Slovakia
erik.janosko@tuke.sk

Abstract: *The paper focuses on the evaluation of the quality of joints of thin-walled dissimilar overlapped materials, formed by thermal drilling without a screw. The shaped interference fit joint is formed by simultaneously forming both overlapped materials, preheated by the friction of a flowdrill tool, and forming a pair of embedded concentric bushings. The joints were made on a CNC milling centre, at constant speed, with tool feed being the only variable. Three tool movement strategies - three movement schemes - were tested. By evaluating the quality of the joints using metallographic sections, the optimum tool movement strategy was selected.*

Keywords*: MECHANICAL JOINING, THERMAL DRILLING, DISSIMILAR MATERIALS, LOAD-BEARING CAPACITY OF JOINTS*

1. Introduction

In many industrial applications, components made of thin plate or thin-walled profiles are widely used. The problem with such structures is the joining, especially when different materials have to be joined (uncoated and galvanized steel, steel with aluminum or composite, etc.) [1].

The Flowdrill process is characterized by the formation of an elongated bushing, which is formed by rotation and pressure of the tool without chip removal [2]. The bushing has a specific shape according to the tool used. This process is also called friction drilling, flow drilling, thermomechanical drilling, etc. The purpose of this method of hole formation is to form a bushing in thin sheets without any addition of material where a sufficient number of threads can be placed [3-6]. Subsequently, a thread can be formed in the formed bushing, thus forming a detachable joint with a connecting element. However, it is also possible to form a mechanical form fit joint of two sheets without a bolt, just by two concentric nested bushings wedged together [7]. In this process, it is necessary to ensure that the resulting bushings of the two materials to be interpenetrated adhere tightly to each other, follow each other's shape, and do not push away from each other due to the spring back effect, which could lead to "opening" of the joint. As this is an atypical application of thermal drilling for joining two overlapped dissimilar materials, there is a lack of information on suitable process parameters in the relevant literature. These vary according to the type of material to be drilled. For example, tool speeds for drilling corrosion-resistant steels are recommended to be reduced compared to those for low carbon steels by 15%, while for Al and non-ferrous alloys it is recommended to increase the speed by 50% compared to drilling carbon steels [8]. The question is what are the appropriate parameters for joining the steel-Al alloy pair, which material should be adapted to. In order to achieve repeatability of process parameters during joint formation, thermal drilling should be done on CNC machines where drilling parameters can be precisely defined and controlled during the toolpath. The heat generated affects the drilling process and depends mainly on the speed and tool feed. Regarding CNC centers, it is more efficient to vary the tool feed than the tool speed, so we decided to take this route in the experiment [8].

The aim of the paper work is to experimentally verify the possibility of using the side effect of the thermal drilling technology (flowdrill) for joining two overlapped thin plates without the use of a bolt, just by forming a pair of nested concentric bushings, while three modes of tool feed will be tested.

2. Materials and Methods

The choice of materials for the experimental program was based on materials currently used in the construction of automotive bodies so that both Fe alloys (galvanized and ungalvanized) and non-ferrous alloys were represented.

Materials selected for experimental works:

- DC04 - extra deep-drawn, uncoated, low-carbon, cold-rolled steel for bodywork. Referenced like DC.
- TL 1550-220+Z - hot-dip galvanised fine grained HSLA steel with excellent cold formability, grade VW (equivalent to CR210LA or HR210LA). Referenced like TL.
- EN AW-6082 T6 (AlSi1MgMn) - precipitation-hardened high strength Al alloy, weldable by MIG and TIG welding technologies. Referenced like Al.

The thickness of steel sheets was 0.8mm, the thickness of Al alloy was 1mm. The chemical composition of the materials used is given in Table 1.

Table 1: *Chemical composition of materials in wt.%*

Mat.	**C**	**Mn**	**Si**	**P**	**S**	**Al**	**Nb**	**Ti**	**Fe**
DC	0.040	0.25		0.009	0.008				bal.
TL	0.1	1.0	0.5	0.08	0.03	0.015	0.1	0.15	bal.
Mat.	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
Al	1.0	0.4	0.06	0.44	0.7	0.02	0.08	0.03	bal.

Table 2: *Mechanical properties of materials (in transversal direction)*

Mat.	**Re [MPa]**	**Rm [MPa]**	**A80 [%]**	**Zn layer [g/m^2]**	**r**	**N**
DC	197	327	39	-	1.900	0.220
TL	292	373	34	104	1.350	0.190
	Re [MPa]	**Rm [MPa]**	**A50 [%]**			
Al	295	344	14			

r - coefficient of normal anisotropy, n - strain-hardening exponent

The shape and dimensions of the test specimens as well as the geometry of the joints calculated for tool Flowdrill long ø 5.3 mm are shown in Fig. 1. The hole is always made in the centre of the overlapped area.

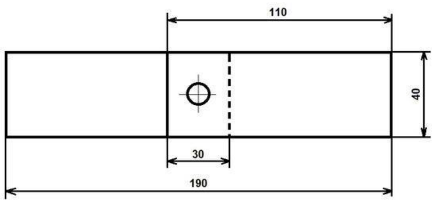
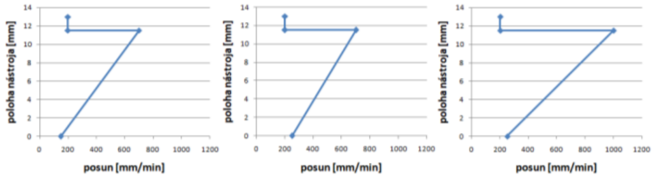


Figure 1: *Shape and dimensions of test specimens and joints designed for FD long ø5.3 mm tool*

The joints were created on a CNC milling centre DMG mori DMU 60evo. According to [8], it is recommended to set a small tool feed at the contact of the tool tip with the material, which should then increase linearly or stepwise, and then the tool feed should slow down again at the lowest reversal point of the tool movement. Based on these recommendations, three tool feed modes were selected and tested on the tool working path, Fig. 2.



a) 150-700-200 mm/min, b) 250-700-200 mm/min, c) 250-1000-200 mm/min
Figure 2: *Selected tool feed modes*

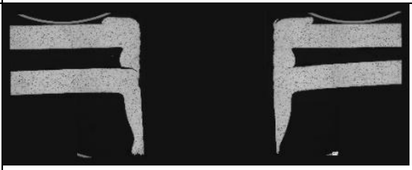
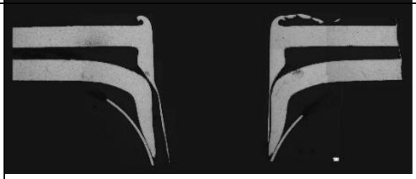
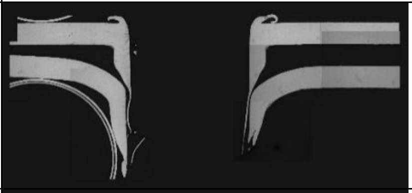
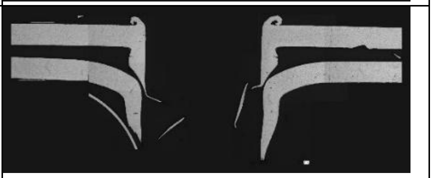
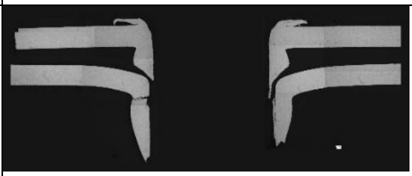
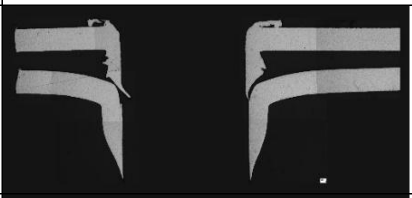
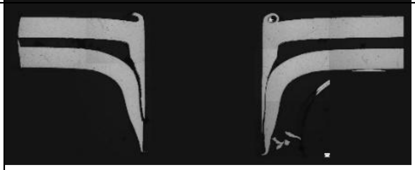
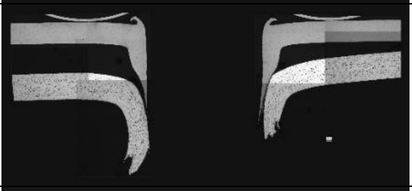
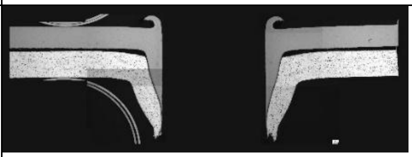
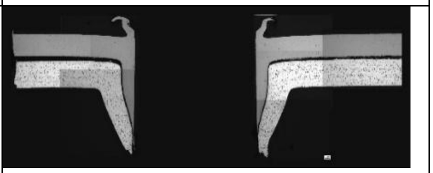
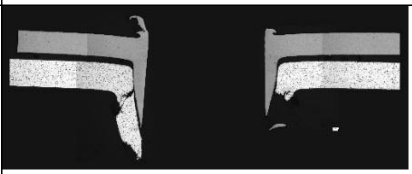
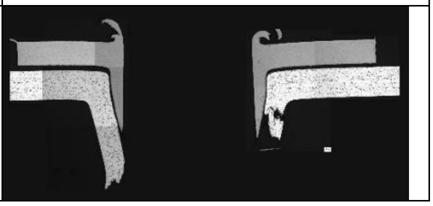
The initial tool feed was 150 or 250 mm/min, gradually increasing to 700 or 1000 mm/min on the 11.5 mm path, finally on the 1.5 mm path the tool feed dropped to 200 mm/min and the tool stopped 0.6 mm below the flange part of the tool to prevent deformation or damage to the collar.

The geometry of the joints as a function of the tool feed mode was then examined by optical microscopy on metallographic sections along the axis of the joint.

3. Results

Table 3 shows the metallographic sections of the joints formed at the three tested tool feed modes on the CNC machining centre.

Table 3: *Metallographic cross-sections of jonts made at three tool feed modes, LM*

Mode:	Tool speed [min^{-1}], initial tool feed – maximal tool feed, tool feed in lowest reversal point [mm.min^{-1}]		
Joints	3800, 150-700, 200	3800, 250-700, 200	3800, 250-1000, 200
Al-Al			
DC-DC			
TL-TL			
DC-TL			
TL-DC			
DC-Al			
TL-Al			

The Al-Al joints failed to establish, increasing the initial and maximum tool feed did not lead to an improvement in connection forming. The DC-DC and TL-TL joints are accompanied by a large spring back effect and too large a bending radius of the bottom plate, which makes it impossible to form nested concentric bushings of sufficient thickness. Instead, there is only an intense thinning of the heated material of inner bushing between the tool and the outer bushing, which acts as a punch and die in the process of forming the inner bushing. For the material combinations DC-TL and TL-DC the situation is similar, however, when DC is in the upper position, due to its high ductility (as an indicator of formability) it thins more intensively and therefore the inner bushing formed from it is too thin. However, if TL steel is in the upper position, it thins less intensely. The best joints were achieved in the steel-Al combination, with minimal spring back effect and tight-fitting inner bushings. As for tool feed modes, it is the DC-Al and TL-Al joints where their effect is best seen. Too little initial tool feed caused the Al sheet to bend and the joint to open. Increasing the initial tool feed from 150 to 250 mm.min^{-1} eliminated this problem, but increasing the maximum tool feed from 700 to 1000 mm.min^{-1} did not produce any significant change in the shape of the bushings.

Fig. 3 summarizes the achieved average inner bushing height, inner bushing thickness at the expected failure location, and microhardness at the outermost part of the inner bushing for each material combination.

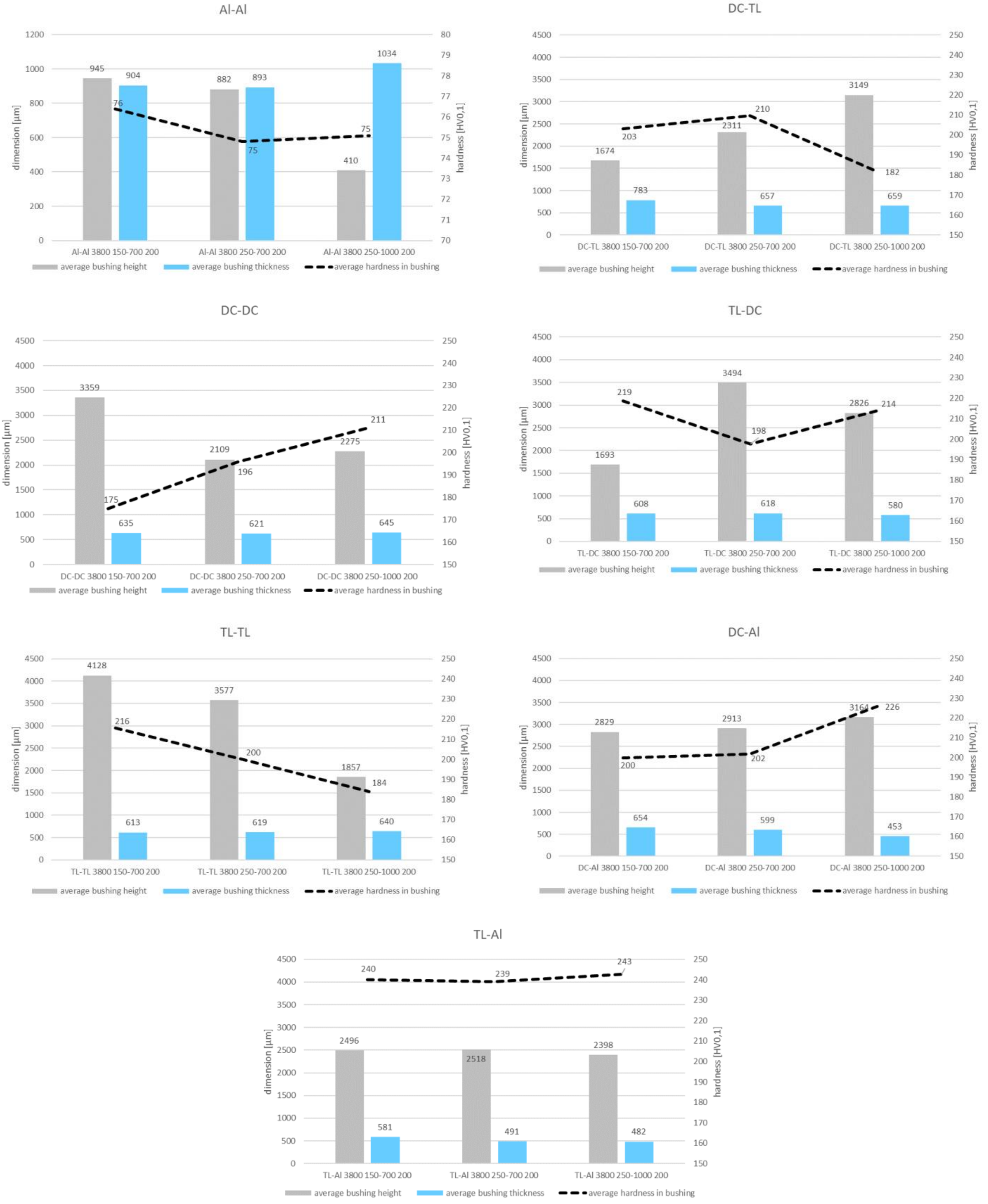


Figure 3: *Average bushing height and thickness, microhardness in the bushing for individual joints*

Fig. 3 shows that deformation hardening occurred in DC and TL steels, which was manifested by an increase in microhardness in the bushing, which represents the most overstrained region of the material in the joint. The DC steel sheet had an initial hardness of

106 HV0.1, after forming to the shape of the bushing, the hardness in the outermost part of the bushing varied between 175-226 HV0.1, depending on the tool feed used. The strain hardening of the TL steel showed an increase in hardness from 131 HV0.1 in the initial condition to values between 184 and 243 HV0.1 in the bushing.

In Al sheet material softening occured, the hardness in the bushing was around 75 HV0.1, while the initial hardness was 119 HV0.1. The Al sheet was supplied in the T6 condition, i.e. it is a solution treated and artificially aged alloy. Its structure consists of a number of Mg_2Si precipitates dispersed in an α-Al matrix. This type of alloys has limited application in terms of operating temperatures to ambient temperature. Any heating may disturb the precipitation hardening effect. At temperatures of 100-500°C, the precipitates can overage, i.e. grow, reducing their strengthening effect; bigger precipitates prevent the movement of dislocations less effectively. Heating above 500°C already leads to dissolution of the precipitates, and if followed by slow cooling, the fragile intermetallic θ phase at grain boundaries may be formed, thus weakening their cohesion. In thermal drilling, Özek et al. [9] found a maximum temperature of Al alloys 1 mm from the hole of about 245°C at comparable tool speeds but significantly smaller tool feed. It is possible to estimate the Al temperature at feed rates up to 1000 $mm.min^{-1}$ to be >300°C, which could have induced a softening of the Al alloy in the vicinity of the hole.

In thermal drilling, not only the mechanical properties determined at ambient temperature play an important role, but especially their change when heated. It is therefore necessary to know the creep curves of materials, the change in the modulus of elasticity of materials with temperature and the physical properties of materials, especially thermal conductivity. Fig. 4 shows the decrease of Young's modulus of elasticity of steel and aluminium when heated.

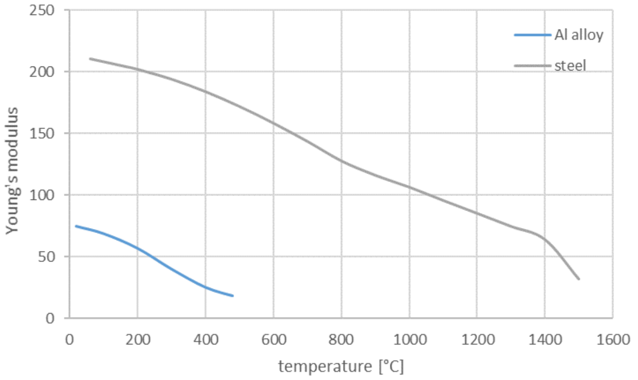


Figure 4: *Temperature-dependent change in modulus of elasticity of steel and Al alloys*

Fig. 4 shows that already at ambient temperature, it takes three times less stress to achieve some deformation of Al than to achieve the same deformation of the same cross-section made of steel. As the temperature increases, this difference increases even more, the Young's modulus of Al decreases more drastically with temperature than that of steel. This is the reason why Al sheet cannot be in the top position when joining with flowdrill technology - it is pushed sideways when heated instead of forming a bushing. Therefore, a material with a higher stiffness (Young's modulus) must be placed in the top position. In the lower position, the aluminium alloy can be placed, which will therefore only be heated indirectly, by conducting heat from the steel into the Al, and will be shaped by copying the resulting steel bushing. In this way, a joint with a suitable geometry, with tightly fitting concentric nested bushings, with certain load-bearing capacity, can be formed. Joints formed by this process can be combined with adhesive bonding.

3. Conclusions

The following main findings can be drawn:

- thermal drilling technology can be used to create a pair of nested concentric bushings capable of carrying a certain level of load
- the best joint geometry is achieved with a steel-aluminium alloy material combination, with the recommendation to place the steel in the upper position of the pair to be joined
- this technology is not suitable for joining steels of the same or unequal grades or for joining aluminium alloy pairs.
- For the most promising joints (DC-Al and TL-Al), no significant effect of the tool feed mode on the geometrical characteristics of the joints was observed, but the displacement modes 3800, 250-700, 200 and 3800, 250-1000, 200 resulted in the formation of tightly fitting concentric bushings with a minimum gap between the plates.
- From the point of view of time saving in joint formation, the following mode can be recommended for joining steels and Al alloys with the above properties and thickness: speed 3800 min^{-1}, tool feed 250-700 $mm.min^{-1}$, at the end of the movement the tool feed decreases to 200 $mm.min^{-1}$.

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