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Effect of Tool Speed when Joining Dissimilar Materials by Flowdrill Technology

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Abstract: This paper deals with the investigation of the effect of rotation speed on the form fit joint of dissimilar materials. Thin -walled materials based on steel and aluminium alloy were joined by thermal drilling. The shape and size of the resulting bushing were evaluated. It turned out that the best material combination for joining by flowdrill technology are joints made of steel and aluminum alloy. Aluminum alloy must always be placed in the bottom position. The best parameters of the formed bushing were achieved with the combination of DC-Al or TL-Al materials, at tool speeds of at least 2400 rpm.

Keywords: joining, flowdrill, thin-walled metal sheets, steel, aluminum

1. Introduction

Joining dissimilar materials is currently a highly topical. Designers are constantly dealing with this issue when designing individual parts of the body, while trying to achieve maximum use of the properties of individual materials, reducing the weight of the body, minimizing emissions in transport, increasing the resistance of the body by strengthening exposed places through the local use of high-strength materials, reducing the cross-sections of less exposed components when ensuring adequate safety of structure, etc. [1-2]. To meet these goals, conventional steels are replaced by non-conventional high-strength steels, as well as other materials with good specific strength, such as aluminum, magnesium alloys or even composite materials [3-4]. Individual vehicle parts consist of several materials, designed with the help of CAD systems and FEM analysis in terms of shape and layout, so that their properties meet the strength and crash-resistant criteria in a specific location of the product - tailor-made production. This approach saves source materials and maximizes the use of material properties [5-6]. However, it is necessary to solve the joining of dissimilar materials that differ from each other in their nature - the internal arrangement of individual elements (e.g. metals versus plastics), or microstructure, mechanical, physical properties, as well as the nature of the response of these materials to different types of loading [7 -12]. Joining dissimilar materials by welding encounters problems, especially when joining steels with aluminum, which differ in melting temperature, very low mutual solubility of elements (Fe-Al) and the formation of brittle intermetallic compounds at the interface of the joined materials. In the case of joining galvanized steels and aluminum alloys, mutual solubility of Zn-Al is better. There are various ways of solving these problems, such as the use of interlayers when welding dissimilar materials, or the modification of technologies to achieve a smaller heat input - CMT welding, welding with high-energy beams - laser, electron beam, etc. Another way to solve the mutual incompatibility of materials is to use other technologies - such as adhesive joining, while it is necessary to take into account the limited temperature of use of such joints and a longer

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production time due to the curing of the adhesive in the joint. Technologies using the principles of mechanical joining, such as clinching, riveting and their numerous modifications, or combinations with adhesive bonding or resistance welding, appear to be very promising. Their disadvantage is that in many cases they require two-sided access to the parts to be joined, but also a different ability of plastic deformation, which is the basis of the formation of form fit joints [13-14]. The founder of thermal drilling technology, as one of the technologies for joining thin-walled materials, even if they are dissimilar, was Jan Claude de Valliere, who in 1923 tried to create a tool that was supposed to make holes in thin-walled steel sheets without cutting, only using frictional heat [15]. The result of his efforts is the friction-forming technology, used mainly when joining thin-walled materials, when the material is not cut at the place of the future hole, but is softened by heat and plastically deformed by the movement of the tool, relocated under the level of drilled material as a bushing into which a sufficient number of threads can be placed to allow mechanical connection to another material. The bushing is a very beneficial when joining thin workpieces, because it locally increases the thickness of the material [16].

In his publication [17], Schmerler discussed the idea of joining two or three overlapped materials using thermal drilling technology without screw, although this technology is not primarily intended for this purpose. The idea is based on the premise that if two or three thin-walled materials are stacked on top of each other and a hole is created using a flow drill tool, coaxial bushings could be formed on the materials being joined, which would be mechanically wedged, creating a form fit joint, Fig. 1.

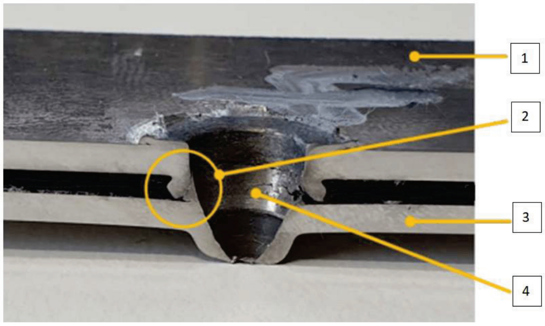


Figure 1: Materials joined by the Flowdrill method: 1- sheet metal, 2- joint, 3- sheet metal, 4- bushing [17].

The article therefore aims to test the effect of the rotation speed on the size and shape of the bushings created during the thermal drilling of a pair of thin overlapped sheets of dissimilar materials. The result should be the determination of the appropriate rotation speed for the successful creation of form fit joints from dissimilar materials.

2. Materials and methods

The following materials were used to create the joints:

– *Cold-rolled non-coated deep-drawn steel DC04, used for the production of interior and exterior car body parts and other extrusions, thickness of 0.8 mm, hereafter: DC.*

– *Galvanized fine-grained high-strength low-alloyed steel TL 1550-220+Z with increased cold formability, thickness of 0.8 mm, hereafter: TL.*

– *Precipitation hardened aluminum alloy EN AW-6082 T6 (AlSi1MgMn), thickness of 1.0 mm, hereafter: Al.*

The chemical composition of the steels is shown in Tab. 1, the chemical composition of the aluminum alloy is shown in Tab. 2. The mechanical properties and surface conditions of the materials used are listed in Tab. 3. Tab. 4 shows the physical properties of materials.

Table 1: Chemical composition of steels, wt.

DC04									
C	Mn	P	S	Fe					
0.04	0.25	0.009	0.008	bal.					
TL									
C	Mn	Si	P	S	Al	Nb	Ti	Cu	Fe
0.10	1.00	0.50	0.08	0.03	0.015	0.10	0.15	0.20	bal.

Table 2: Chemical composition of aluminum alloy, wt. %.

Al								
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
1.00	0.40	0.06	0.44	0.70	0.02	0.08	0.03	bal.

Table 3: Mechanical properties and some specific conditions of materials.

Materials	YS [MPa]	UTS [MPa]	Elongation [%]	Thickness [mm]	Condition
DC	197	327	39	0.8	electrostatically oiled
TL	292	373	34	0.8	Zn coated 100 $g.m^{-2}$
Al	290	340	14	1.0	Solut. treated, artificially aged

YS - Yield Strength, UTS - Ultimate tensile strength

Table 4: Physical properties of materials.

	density [kg.m^{-3}]	Melting point [°C]	Thermal conductivity [W/m·K]	Coefficient of thermal expansion [10^{-6}/K]	Modulus of elasticity [GPa]
DC, TL	7860	~1500	45	10.8-12.5	~210
Al	2700	555	180	24	~70

The shape and dimensions of the test specimens were designed according to EN ISO 12996 depending on the thickness of the joined materials and the diameter of the tool used, Fig. 2. The thermal drilling tool Flowdrill Long ø 5.3 mm was chosen for creating joints, Fig. 3.

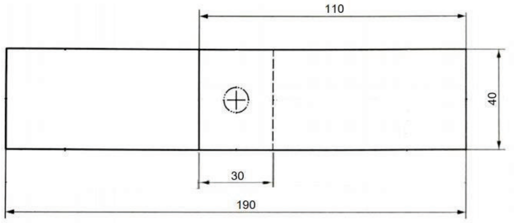


Figure 2: Shape and dimensions of joint assembly.

Figure 3: Tool Flowdrill Long ø 5.3 mm.

A clamping fixture was designed, manufactured and used for setting and clamping the materials to be joined and producing of test assemblies by thermal drilling, Fig. 4.

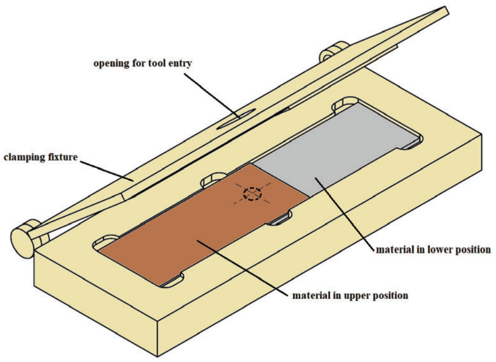


Figure 4: Clamping fixture for producing test assemblies by thermal drilling.

The joints were made in manual mode using a bench drill, where the only variable was the rotational speed of the tool. The tool feed toward the material was realized manually. During the production of joints, three values of rotation speed were tested: 1900, 2400 and 3800 rpm. Fig. 5 shows the tool in the lower dead position in the simulation program Simufact forming [18].

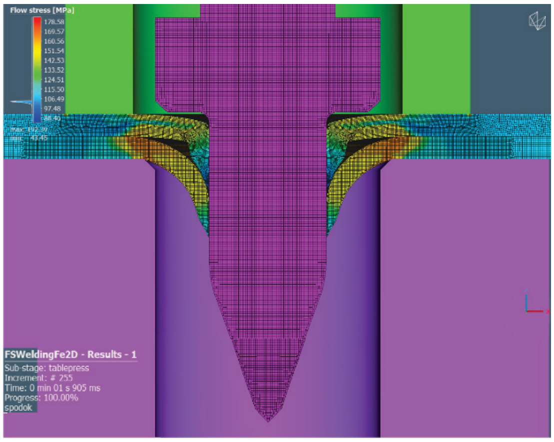


Figure 5: Tool in the lower dead position.

Thermal drilling technology has been tested on various combinations of materials used. It is necessary to realize that when joining dissimilar materials, the position of the material in the joint matters, as dissimilar materials differ both in mechanical properties, in formability, and in thermal conductivity, which are properties that significantly affect the flow of the material during joining and the shape and dimensions of the created bushings. The tested material combinations are shown in Tab. 5.

Table 5: Matrix of created joints.

Materials in upper position	Materials in lower position
DC	TL; Al
TL	DC; Al
Al	DC; TL; Al

Metallographic sections were prepared from the formed joints, on which the dimensions and shape of the resulting bushings were observed. They were also used to determine the microhardness of the base materials as well as of the deformed materials in the vicinity of the joint (rim, bushing). Hardness measurement parameters: load 100g (980.7 mN), time: 15 s. Based on these observations, material combinations suitable for joining with this technology were determined, as well as the effect of rotation speed on the shape and dimensions of the resulting bushings was established.

3. Results

Metallography of the joints

Tab. 6 to 8 show metallographic sections of all

Table 6: Metallographic cross-sections through joints – one side view (right), rotational speed 1900 rpm.

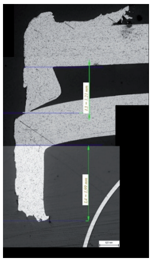
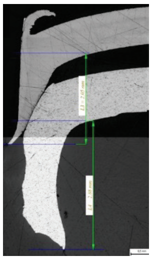
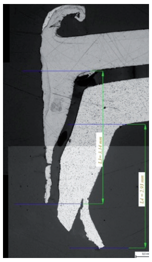
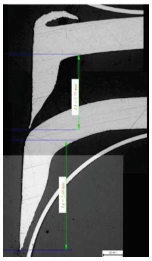
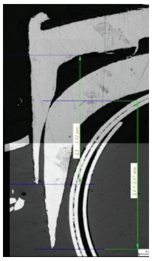
Rotation speed	Al-Al	DC-Al	TL-Al	DC-TL	TL-DC
1900 rpm					

Table 7: Metallographic cross-sections through joints – one side view (right), rotational speed 2400 rpm.

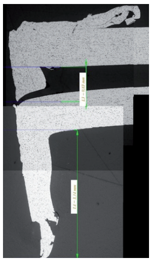
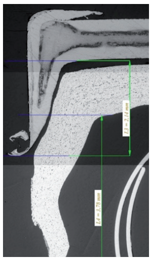
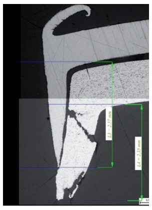
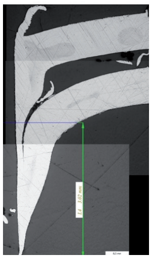
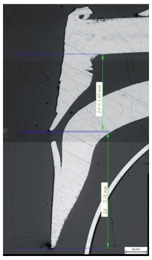
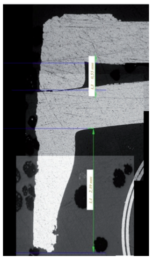
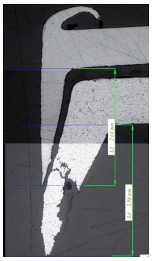
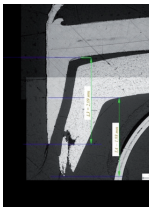
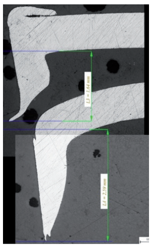
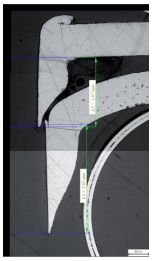
Rotation speed	Al-Al	DC-Al	TL-Al	DC-TL	TL-DC
2400 rpm					

Table 8: Metallographic cross-sections through joints – one side view (right), rotational speed 3800 rpm.

Rotation speed	Al-Al	DC-Al	TL-Al	DC-TL	TL-DC
3800 rpm					

formed joints of various material combinations. Due to the fact that the section is axisymmetric, we present only one side of the section so that all the details are clear.

From Table 6 is clear that in the material pair Al-Al no joint was formed. Although a bushing was formed on the lower plate, the material of the upper plate was concentrated in the gap between the plates, so no two nested coaxial bushings were formed. In the case of material pairs DC-Al and TL-Al, concentric bushings were formed, while the deformation of the steel primarily took place, the Al bushing was created by copying the emerging steel bushing. In the case of joints made of steels (DC-TL, TL-DC), concentric bushings were formed, but a large spring-back effect also appeared, which causes the materials to move away from each other, opening the joint and causing it to become inoperable. For all joints where the steel is in the upper position, a rim is formed on the upper surface.

The increase in tool rotation speed to 2400 min^{-1} was manifested in most joints by a slight increase in the length of the formed bushing at the expense of their thickness. The Al-Al joint did not form again; the quality of the DC-Al mechanical joint was significantly improved by increasing the tool speed. The TL-Al connection is of good quality, with a small gap between the sheets, the bushings are tight to each other, even if the thickness of the bushing of the upper material is lower compared to the previous case. In DC-TL and TL-DC joints, bushings of greater thickness are created compared to DC-AL and TL-Al, but due to the spring-back effect and greater distance between the sheets in the joint, when the joint is subjected to shear stress, the inner bushing will break in place with the smallest thickness.

When the speed was further increased to 3800 min^{-1}, the Al-Al joint was not formed again, the connection between the DC-Al, TL-Al sheets is of good quality with a small gap and tight contact of the sheets, but higher speeds caused a slight thinning of the inner bushing again. In the DC-TL and TL-DC steel joints, there was a significant shortening of the inner bushing, significant spring-back effect, deformation (bending) of the bottom plate and the formation of a large gap between the materials. There was also a breakage of the thinned part of the inner bushing. For the stated reasons, the effective form fit joint between the steels did not occur.

When analysing the results, it is necessary to focus mainly on the shape and dimensions of the inner bushing, because it is loaded by shear when the joint is stressed, and it is desirable that it be as thick as possible, that is, that the area of the inner ring, which is broken by shear, is as large as possible, Fig. 6. In addition, the length of the bushing, especially the length of their mutual contact, is also important. It is advisable that it should be as large as possible, because a larger contact area also means greater friction and resistance to the opening of the joint.

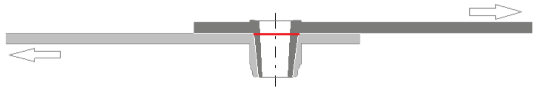


Figure 6: Expected failure of the form fit joint created by thermal drilling.

Tab. 8 shows the dimensions of the resulting bushings of individual joints.

Hardness of materials in joints

The hardness was determined as the average of three measurements taken in both base materials outside the joint, in the rim and in both bushings. The measurement locations are shown in Figure 7. Average hardness values are listed in Table 9.

The hardness of the base materials in the initial state (outside the joint) was: 106HV0.1 for DC, 131HV0.1 for TL and 119HV0.1 for Al. In the area of rim and bushing, deformation hardening of steels occurred, which resulted in an increase in hardness

Table 8: Dimensions of the resulting bushings, [mm].

Combination of material	*Rotation tool speed (min^{-1})*	*Height of the inner bushing (formed from the upper material)*	*The thickness of the inner bushing at the location of the expected failure*	*Height of the outer bushing (formed from the bottom material)*
Al-Al	1900	1.21	0.74	1.99
	2400	0.83	0.78	3.14
	3800	0.55	1.14	2.49
TL-DC	1900	Cannot be determined, broken thinned part	0.5	3.47
	2400		0.67	2.76
	3800		0.74	2.62
TL-Al	1900	3.14	0.76	2.93
	2400	2.57	0.45	2.35
	3800	2.09	0.45	1.93
DC-Al	1900	2.05	0.79	2.88
	2400	2.14	0.69	3.78
	3800	2.64	0.57	2.98
DC-TL	1900	Cannot be determined, broken thinned part	0.57	2.48
	2400		0.61	3.02
	3800		0.67	2.59

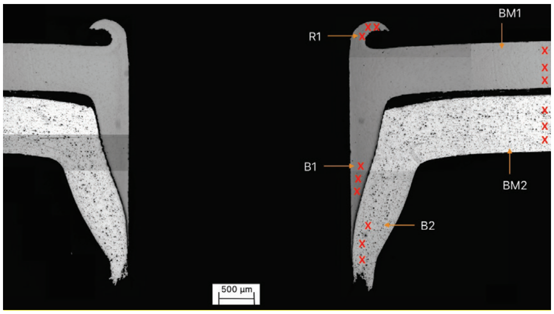


Figure 7: Location of indentations when measuring hardness: R1 - rim formed from material 1 (upper), B1-bushing formed from material 1 (upper), B2-bushing formed from material 2 (lower), BM1 – base material 1 (upper), BM2 - base material 2 (lower).

Table 9: Average hardness values in individual areas in joints.

Materials	BM1	BM2	R1	B1	B2
Al-Al	119	119	74	76	79
DC-Al	106	119	193	199	94
TL-Al	131	119	231	240	81
DC-TL	106	131	205	203	181
TL-DC	131	106	231	218	176

of 90-100 hardness units; while the aluminium alloy showed a decrease in hardness of 30-40 hardness units.

SEM analysis of contact surfaces after joint failure

It is clear from the metallographic sections that the mechanical connection of the materials occurs by their simultaneous plastic deformation, while friction occurs both between the tool and the upper material of the connected pair, and on the contact surface between the two materials. It is interesting to find out whether there is material transfer between the steel and the aluminum alloy within the friction pair during the friction processes of the joint formation. For this purpose, an EDX analysis of both sheets of the DC-Al and TL-Al joint was carried out on the contact surface after their shear failure under tensile stress. The results of analyzes from around the hole are shown in Fig. 8-11.

EDX analysis of the contact surface of the DC material in the DC-Al joint

Looking at the surface of non-galvanized deep-drawn steel DC, which was in contact with the Al alloy, a narrow band with an increased Al content (Spectrum 34) was identified around the hole, which could be transferred to the surface of the steel during thermal drilling or when the joint was sheared. The wider vicinity of the hole contains an increased amount of oxygen, which points to oxidation processes caused by friction heating during the formation of the hole.

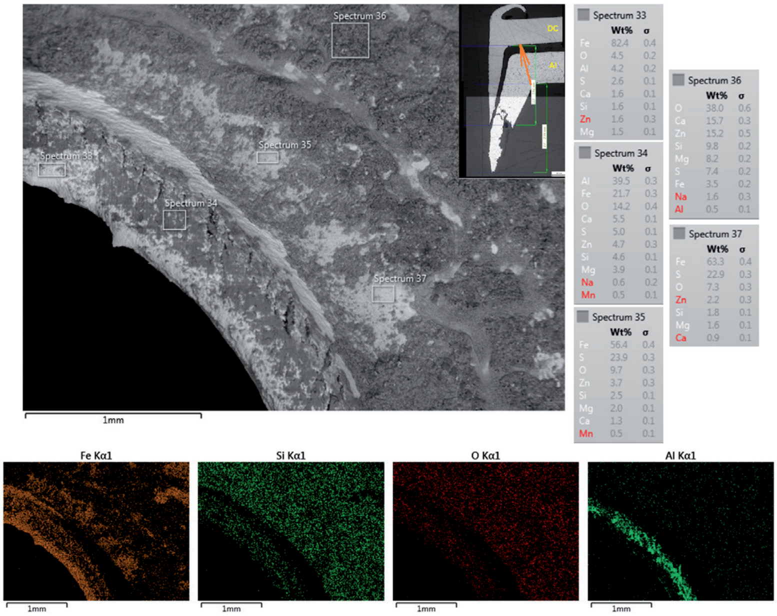


Figure 8: EDX analysis of DC surface in DC-Al joint, EDX spectra and element distribution maps in hole vicinity.

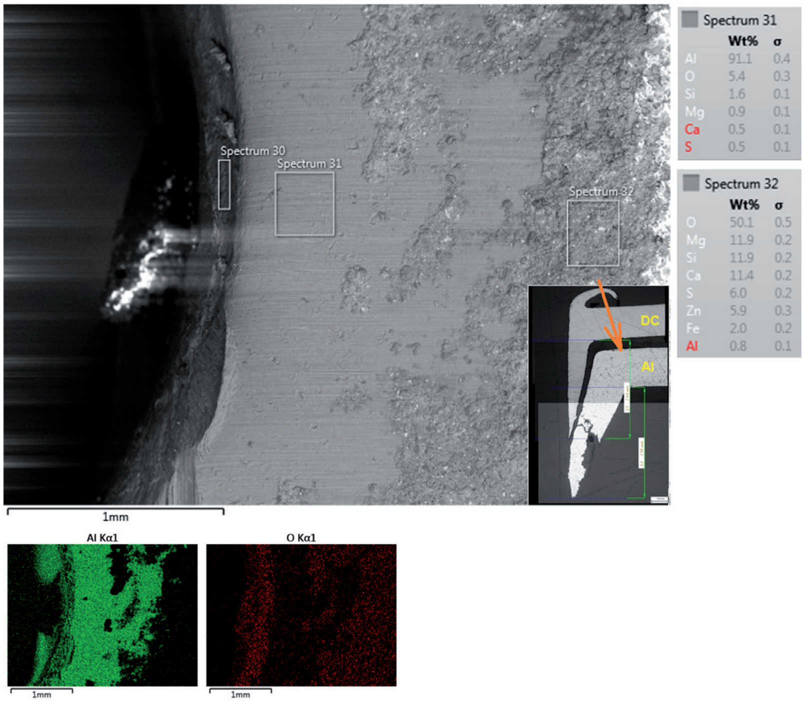


Figure 9: EDX analysis of Al surface in DC-Al joint, EDX spectra and element distribution maps in hole vicinity.

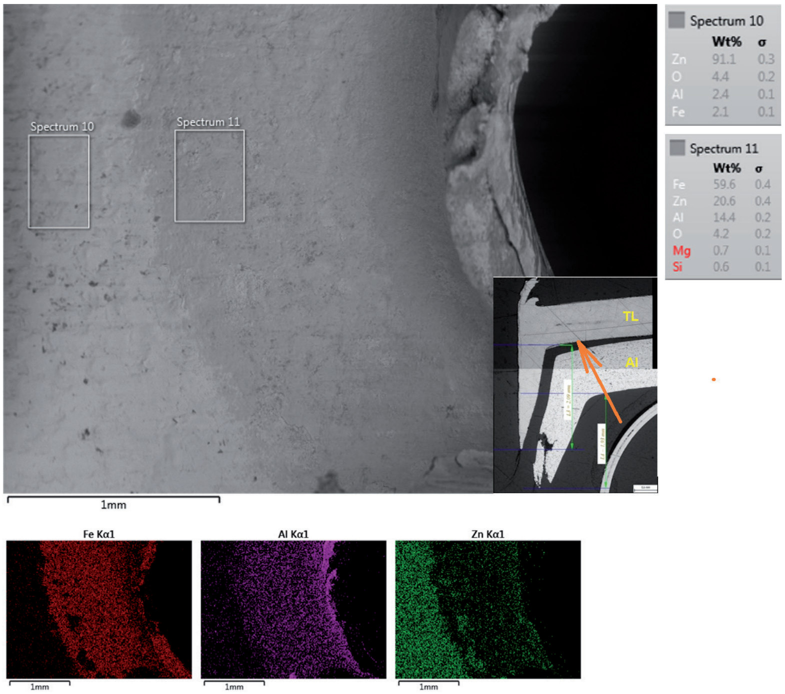


Figure 10: EDX analysis of TL surface in TL-Al joint, EDX spectra and element distribution maps in hole vicinity.

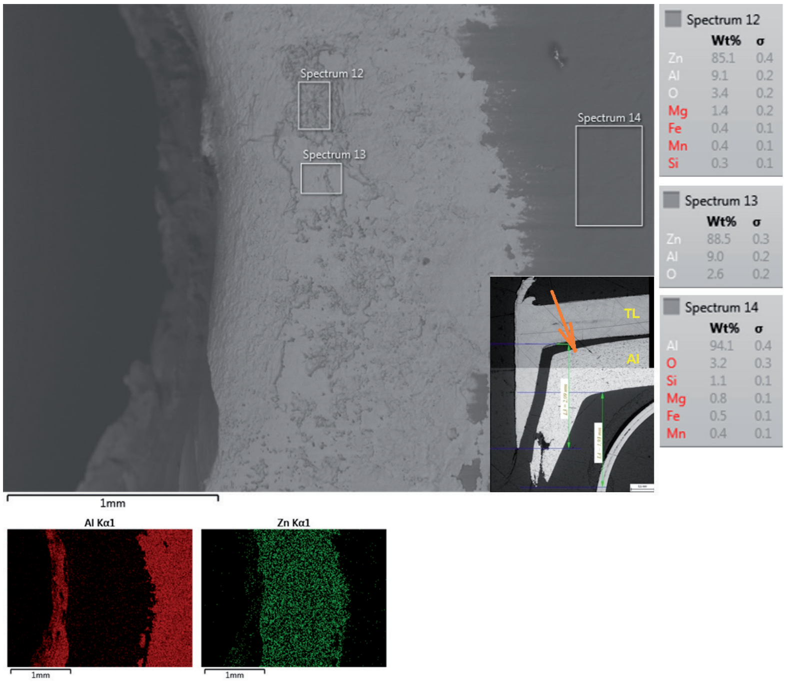


Figure 11: EDX analysis of Al surface in TL-Al joint, EDX spectra and element distribution maps in hole vicinity.

EDX analysis of the contact surface of the Al material in the DC-Al joint

When analysing the surface of an aluminum alloy after contact with DC steel, oxidation and an increased Fe content are noted further (approx. 1 mm, see Spectrum 32) from the opening. Fe is not detected in the immediate vicinity of the opening.

EDX analysis of the contact surface of the TL material in the TL-Al joint

From the EDX analyzes of the surface of the galvanized high strength low-alloyed steel TL after contact with the Al alloy, it is clear that the protective Zn layer was removed, or at least thinned, the Fe base of the steel was exposed and Al was deposited around the hole (see Spectrum 10 and 11).

EDX analysis of the contact surface of the Al material in the TL-Al joint

EDX analyzes of the surface of the Al alloy after contact with galvanized steel confirm a Zn layer stuck around the hole, which was torn off the surface of the TL steel and covers the Al-based base. The transfer of Zn to the Al base can be explained by the friction microwelds and mutual solubility of Al-Zn, which is higher than that of Al-Fe.

4. Discussion

Al-Al joints are characterized by the fact that the plates are pushed away from each other by the forming bushing of the top material, two concentric bushings are not formed, i.e. no joint is formed, regardless of the speed of rotation. When analysing the properties of the Al alloy used, the aforementioned behaviour can be explained by the fact that the mechanical properties of the Al alloy change (decrease) due to frictional heat. The Al alloy softens during drilling, and as a result, the top material moves laterally away from the axis of the hole instead of forming a bushing.

Joints made of different steel materials (DC-TL, TL-DC) also do not show suitable properties. It can be seen from the metallographic sections that the inner bushing formed from the top material thins very intensively towards the bottom material, which causes a low load-bearing capacity of the joint. The intensive thinning of the inner bushing is due to the fact that both materials have approximately the same mechanical properties, and the inner bushing is intensively thinned between the tool and the outer bushing, which forms a rigid support for the inner bushing and resists deformation. The process of thinning the inner bushing could be compared to rotational metal stamping, or deep drawing with thinning of the wall. In addition, a strong spring-back effect is evident, which will cause the materials to be separated after the tool cycle is complete. This phenomenon appears for both combinations of steels (DC-TL, TL-DC) and at all three speeds tested.

The most successful joints were formed between steel and aluminum (DC-Al, TL-Al) when the aluminum alloy is in the lower position. At the point of connection, the materials are tightly pressed against each other. The inner bushing is made of a stronger steel upper material and the aluminum alloy, softened by the frictional heat transferred from the steel, is shaped only by copying the resulting steel bushing. Although steel and Al alloy have similar mechanical properties (Re and Rm), the increased temperature at the point of contact is more clearly manifested by a change in the mechanical properties of the Al alloy, the mechanical properties of steel are not significantly changed by this heat. This is due to the different melting temperature of steels and Al alloy – 1500°C versus 555°C. If there is an increase in temperature at the drilling site, e.g. at 300°C, for steels it is, expressed relative to the melting temperature, $0.2xT_{mFe}$, while for Al alloy the same temperature represents the value of $0.54xT_{mAl}$. The softened Al alloy in the lower position thus more easily adapts to changes in the shape of the steel in the upper position, it does not offer much resistance to deformation, thus it does not act as a rigid support - a die that would cause a significant thinning of the resulting inner bushing. There appears to be no contact between Al and the tool at all. The spring-back effect is minimal. The thickness of the steel bushing lies between 0.5 - 0.7 mm, which is a good result considering the thickness of the steel plate (0.8 mm). These joints are expected to have the highest load-bearing capacity and absorption capacity, which is also an important indicator of joints, especially for the automotive industry.

The effect of rotation speed was more pronounced only in DC-Al and TL-Al joints. With DC-Al joints, the height of the steel bushing increases with rotation speed. The bushing in the DC-Al joint formed at 1900 rpm is poorly formed and can slip out of the aluminum alloy under tensile shear stress. For this reason, a minimum speed of 2400 rpm can be recommended for the DC-Al connection. In contrast, the TL-Al joint developed a steel bushing with the greatest thickness precisely at 1900 rpm. At higher speeds, the steel bushing is thinner.

From the point of view of the hardness of the formed parts of the joint, an intensive strain hardening of the steels in rim and bushing can be noted, while the alloy EN AW 6082 TL softened during friction heating and forming. The reduction in hardness of the EN AW 6082 T6 alloy at the joint can be explained by the fact that with increasing forming temperature, more precipitates are dissolved into the material matrix resulting in better dislocation movement. Additional deformation mechanisms involved with dislocations become activated at elevated temperatures. Increased dislocation mobility may also lead to increased dislocation annihilation and enhanced plastic strain [19]. At temperatures ranging from 100°C to 500°C, the alloy overages and loses its strength. Above 500°C, the second phase redissolves in the matrix, and can not be even obtained dispersion strengthening.

5. Conclusion

The following recommendations result from the metallographic analysis of the formed joints of dissimilar materials:

» *With the flowdrill technology, it is possible to produce mechanical fit form joints*

» *Flowdrill technology is suitable for joining materials with significantly different mechanical properties*

» *When joining dissimilar materials, it is advisable to place a material with higher mechanical properties, or a material that is less sensitive to changes in mechanical properties when heated to the upper position*

» *In order to ensure the correct function of the joint - load transfer - it is necessary that the joint consists of two concentric bushings*

» *The bearing capacity of the joint depends mainly on the thickness of the inner bushing in place of expected failure, as well as on the length of mutual contact between the bushings*

» *The influence of the tested tool rotational speed was especially evident in the steel - Al alloy joints*

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