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Investigation on pin caulking as a versatile joining process

David Römisch[1,a *] and Marion Merklein[1,b]

[1]Institute of Manufacturing Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstraße 13, 91058 Erlangen, Germany

[a]david.roemisch@fau.de, [b]marion.merklein@fau.de

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Abstract. Lightweight design is increasingly used to combine the specific advantages of various dissimilar materials into multi-material systems. The aim is to make production more resource-efficient and reduce emissions. However, one challenge in the adaptation of multi-material systems is the lack of versatile joining technologies capable of joining these materials. Joining with cold formed pins is a two-step process with potential in joining metal to metal and metal to fibre-reinforced plastics (FRP). These pins can be joined using two joining strategies, direct pin pressing into an unperforated joining partner and caulking of pins, which are inserted through a pre-punched joining partner. For pin pressing, several studies have already been carried out regarding joinability of steel and aluminium, but caulking offers advantages such as a reduced joining force and the fact that the pin can transmit force over the entire sheet thickness of the joining partner, which can lead to increased strength under axial load. Therefore, the caulking of pins extruded from dual-phase steel with a 6000 aluminium alloy is investigated. The focus is on a fundamental investigation of the joining process and the joint formation when caulking pins of varying heights with sheets of different thicknesses. Subsequently, a process window is derived from these findings.

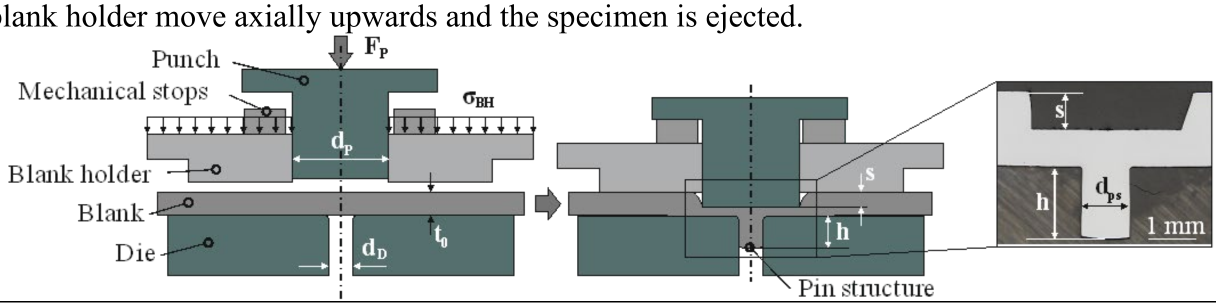
Introduction

Resource-efficient production and energy and emission savings in as many areas as possible are more relevant than ever in times of energy scarcity and climate change. This can also be seen in the transport sector, which accounts for around 26 % [1] of emissions in Europe. Here, lightweight design is increasingly being used, in which the specific advantages of different materials can be integrated into a single component. High-strength materials such as steel and aluminium as well as fibre-reinforced plastics (FRP) are often used, which are joined to form multi-material systems. However, this requires new versatile joining processes, since conventional joining processes tend to reach their process limits when joining these dissimilar materials. For this purpose, research is being conducted into various mechanical joining processes [2]. Joining with pin structures has potential in the area of joining dissimilar materials and is already being used in metal/FRP joints to increase the load-bearing capacity of bonded joints [3]. For the production of pins, processes such as additive manufacturing [4] or welding processes such as cold metal transfer [5] are used. However, there are also efforts to produce pins by forming processes, due to their good surface, strength and the possibility of integrating the process into existing process chains. Joining with cold-formed pin structures from the sheet metal plane is a new process that has already demonstrated its potential for joining steel/aluminium [6] and steel and fibre-reinforced plastics [7]. This method is a two-stage process, in which mostly cylindrical pins are first extruded from the sheet metal plane and used for joining in the next step. There are already studies on direct pin pressing, in which the pins are pressed into an unperforated joining partner after extrusion [6], causing the pin to be compressed inside the joining partner forming an undercut and thus leading to a form-fit and force-fit connection. Another joining strategy that can be used with extruded pins is caulking, in which the pin is inserted through a pre-punched joining partner and is upset at the pin head to form an undercut and a form-fit and force-fit joint. Compared with direct press-fitting, the force required for joining is reduced and, in addition, the pin can transmit force over the entire sheet thickness. At present, however, there are only a few papers dealing with joining by caulking. For this reason, caulking as a joining strategy for joining metallic pins with aluminium is investigated in this work. Different pin heights are used and caulked with the aluminium with three different sheet thicknesses. First, the joining process and then the joint formation will be investigated. Subsequently, a process window for the joining strategy is derived based on the results.

Methods and Materials

Materials. For pin extrusion, a dual phase steel HCT590X+Z (DP600), often used for structural parts in car body construction [8], with an initial sheet thickness t_0 = 1.5 mm is used. For the joint formation investigation specimens with a size of 45 x 45 mm^2 were used. The sheet material for the joining partner is a precipitation hardening aluminium silicon magnesium alloy of the 6000 series EN AW-6014-T4 with three different sheet thicknesses of 1.0 mm, 1.5 mm and 2.0 mm.

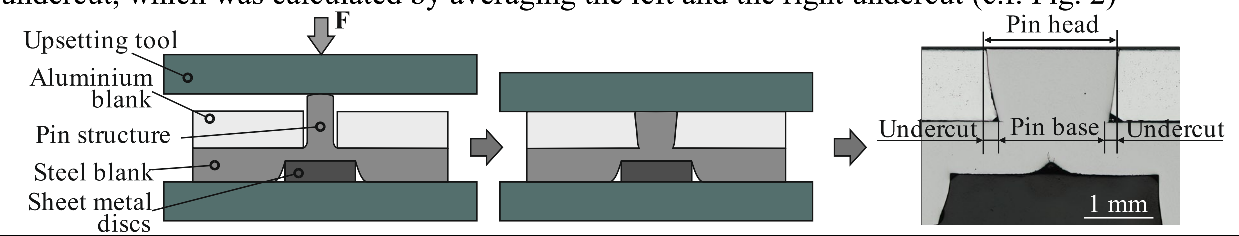
Cold forming of pin structures. The pin extrusion process is a sheet bulk metal forming process that uses a multi-acting tool design enabling a blank holder and a punch to be controlled independently. The process principle and important process parameters are shown in Fig. 1. The feasibility of the process to extrude cylindrical pins from the sheet metal plane was shown by Hirota [9] and Ghassemali [10]. The process used in this work begins with the application of the blank holder force, to prevent sheet bulging during pin extrusion and to reduce the radial flow of material into the sheet metal plane. Once the force is applied, the punch with a diameter d_P = 3 mm moves axially downwards with a constant speed of v = 5 mm/min and penetrates the sheet with a sheet thickness t_0 = 1.5 mm, whereas the forming work is carried out by a hydraulic cylinder. Due to the plastic deformation initiated by the punch, material is displaced axially downwards into the die as well as laterally outwards into the sheet plane and laterally inwards into the die with a diameter d_D = 1.5 mm. Dionol ST V 1725-2 was used for lubrication during pin extrusion. The punch penetration depth s and thus the pin height h is limited by mechanical stops with which the punch comes into contact as soon as the forming process is finished. Subsequently, the punch and blank holder move axially upwards and the specimen is ejected.



Pin extrusion - Process parameters	
Punch diameter d_P (mm)	3
Punch speed v_P (mm/min)	5
Blank holder pressure σ_{BH} (MPa)	280
Die diameter for forming d_D (mm)	1.5
Sheet thickness t_0 DP 600 (mm)	1.5

Fig. 1: Illustration of the pin extrusion process according to [6] and relevant process parameters

Joining by forming - pin caulking. For the joining of the extruded pins, caulking is investigated within the scope of this work, where a perforated joining partner is used. The hole is drilled using a 1.5 mm drill bit. The pin is subsequently positioned between two upsetting tools and the punch cavity is supported with sheet metal discs to prevent damage or a bending back of the pin during the joining process. The drilled joining partner is then positioned over the pin. In the next step, the upper upsetting tool moves axially downwards until a pre-force of 20 N is reached. As soon as the initial force is achieved, the upsetting tool moves downwards at a constant speed of 5 mm/min and upsets the pin until a maximum force threshold of 8 kN is reached. The pin is upset until it is flush with the sheet metal surface of the joining partner and the upsetting tool has full-surface contact with the joining partner. This results in a steep linear increase in force, as the joining system is elastically deformed. This increase in force thus defines the end of the joining process. An illustration of the process is shown in Fig. 2. Within this work, pins with different heights, listed in Fig. 2, were examined with regard to their suitability for joining EN AW-6014-T4 with different sheet thicknesses (1.0 mm, 1.5 mm, 2.0 mm). Here, the process requires that the pin has a greater height than the sheet thickness being joined. The configurations investigated are listed in Fig. 2. For the joint characterisation micrographs of the different joints were used and three different geometric properties were measured. The pin head diameter, the pin base diameter and the undercut, which was calculated by averaging the left and the right undercut (c.f. Fig. 2)



Pin caulking-Process parameters	
Joining speed (mm/min)	5
Sheet thickness t_0 EN AW-6014-T4 (mm)	1.0, 1.5, 2.0
Max. joining force (kN)	8
Drill diameter (mm)	1.5

Investigated configurations								
Pin height (mm)		1.50	1.75	2.00	2.25	2.50	2.75	3.00
Sheet thickness Al (mm)	1.0	x	x	x	x	x	x	x
	1.5	-	x	x	x	x	x	x
	2.0	-	-	-	x	x	x	x

Fig. 2: Schematic illustration as well as parameters of the caulking process and investigated pin height/sheet thickness configurations

Results

Pin caulking. In the following, the pin caulking joining strategy with cold extruded pins will be discussed in more detail. Similar to the alternative joining strategy of direct pin pressing [6], caulking can also be divided into 3 phases. Fig. 3a shows an example of a force-displacement curve of a pin made of DP600 with a height of 1.75 mm, which was caulked with an aluminium sheet with a thickness of 1.0 mm. Here, the 3 phases of the process have been illustrated.

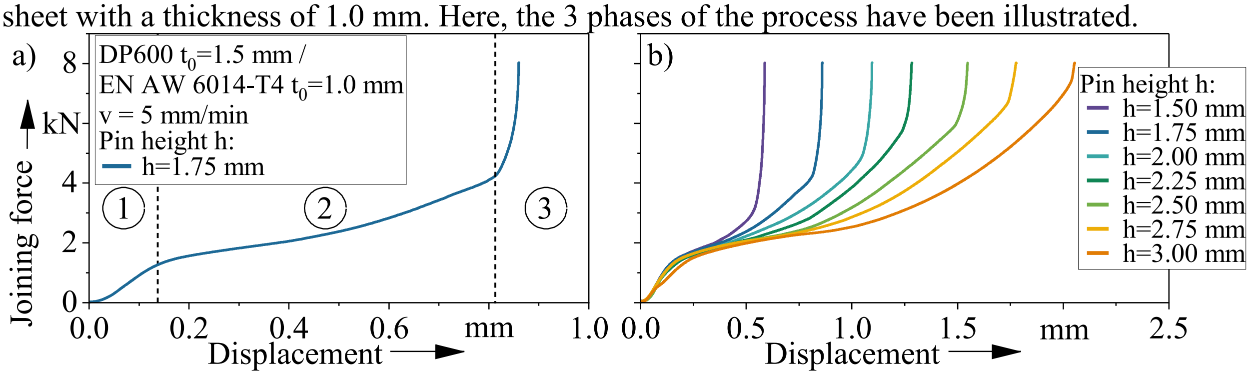


Fig. 3: Pin caulking force-displacement curves. (a) Exemplary curve with the different joining phases (b) Comparison of different pin heights joined with an EN AW 6014-T4 (t_0 = 1.0 mm)

The process begins with a setting process, which can be detected by the non-linear curve. This is caused by a curvature of the sheet due to residual stresses in the sheet caused by pin extrusion, which is flattened by the force applied by the upper upsetting tool, causing the sheet to rest fully on the surface of the lower tool. Subsequently, a linear increase in force follows due to the elastic deformation of the joining system, which consequently transitions to the elastic-plastic deformation of the pin, which initiates phase 2 of the process. This is initially characterised by the compression of the pin, which can be seen from the continuous slope of the curve. However, it cannot be ruled out that the aluminium joining partner is already deformed in this area due to the expansion of the pin and thus a superimposed deformation of the pin and the aluminium is present. From approx. 0.45 mm, however, an increase in the slope of the curve can be seen. This occurs due to the increasing plastic deformation of both joining partners and the fact that the aluminium is displaced radially and axially upwards as a result of the upsetting and the expansion of the pin. The end of phase 2 can be recognised by the strong increase in force from approx. 0.8 mm. The displacement of the upsetting tool corresponds approximately to the difference between the height of the sheet and the height of the pin, but deviates slightly from the actual value, especially due to the non-linear component at the beginning of the process. At this point, the upper upsetting tool increasingly comes into contact with the surface of the aluminium, which levels the joining zone and the material, axially pushed up by the pin at the edge of the drill hole, until there is full-surface contact. The curve then rises steeply and linearly due to the elastic deformation. The process then ends when the predetermined 8 kN are reached, which was chosen to ensure that the force is sufficient for upsetting the pin to the surface of the joining partner. In Fig. 3b, the force-displacement curves for different pin heights are plotted for the 1.0 mm aluminium sheet. Here it can be seen that with increasing pin height, the displacement travelled by the upsetting tool in phase 2 of the joining process increases to approximately the respective difference between pin and sheet thickness and the start of phase 3 begins progressively at a higher force level. This can be explained by the increasing pin height and the resulting higher required upsetting ratio of the pin. Thus, the strain hardening of the pin and the surrounding material steadily increases and more material has to be displaced radially in the sheet plane due to the larger volume of the pin. As a result, the slope of the force-displacement curve increases continuously with increasing pin height. Examining the configuration with a pin height of 3 mm in Fig. 3b it can be seen that the elastic portion of phase 1 of the process shows a discontinuity, which can be attributed to a buckling of the pin due to the high ratio of the pin height to diameter of 2.

Geometric joint characterisation. Examining the corresponding micrographs in Fig. 4 for the joints with a sheet thickness of the aluminium of 1.0 mm, the increase in the ratio of upsetting of the pins with greater height can be seen in the expanding diameter of the pin head. Due to the axial compression of the pin, the joining process results in a radial material flow in the pin caused by the resulting biaxial tensile stress state in the pin. Due to the fixed connection of the pin base with the sheet, this occurs especially in the region of the pin head, resulting in the formation of a wedge-shaped pin geometry. The diameter of the pin head increases continuously for the pin height of 1.5 mm to 3.0 mm, as shown in the micrographs in Fig. 4. However, starting at the pin height of 2.50 mm a buckling and bending of the pin can be observed, which occurs due to joining instabilities resulting from the increasing height and the high upsetting ratio of 60 % for the 2.50 mm pin. Investigating the measured mean undercut values, with an increase in pin height the undercut can be increased by 88.2 % from a value of 0.17 mm for the 1.5 mm pin to a value of 0.32 mm for a 2.25 mm pin. The undercut further increases up to a value of 0.37 mm for the 3 mm pin, however the joint cannot be characterised as “okay”, since the buckling of the pin occurred during joining.

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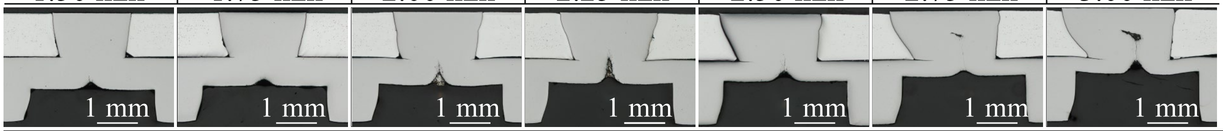
Pin height						
1.50 mm	1.75 mm	2.00 mm	2.25 mm	2.50 mm	2.75 mm	3.00 mm

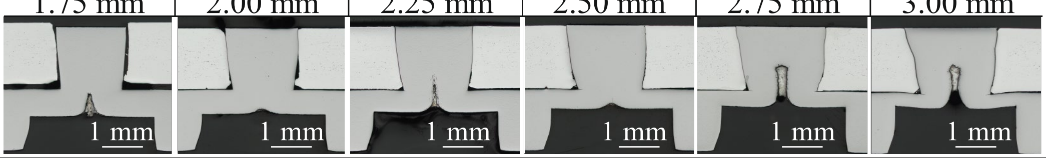


Geometric joint characteristics (t_0 = 1.0 mm)							
Pin height (mm)	1.50	1.75	2.00	2.25	2.50	2.75	3.00
Pin head diameter (mm)	1.90	2.09	2.16	2.35	2.46	2.64	2.73
Pin base diameter (mm)	1.56	1.64	1.71	1.73	1.85	1.93	1.99
Mean undercut (mm)	0.17	0.23	0.22	0.32	0.31	0.36	0.37

Fig. 4: Micrographs of the caulking joints for different pin heights with a 1.0 mm joining partner

Investigating the micrographs in Fig. 5 and the corresponding geometric characteristics of the joints caulked with the aluminium (t_0 = 1.5 mm), it first is obvious that the pin heights used compared to the 1.0 mm sheet only start at a height of 1.75 mm. This is attributed to the fact that with a pin height lower or at the sheet thickness of the joining partner, no load bearing joint can be produced. Furthermore, it can be seen that for the pin height of 1.75 mm an undercut for the pin of 0.1 mm could be measured. However, as it can be seen from the micrograph the undercut was not sufficient enough to join the two sheets adequately. One reason could be, that the drill hole got slightly larger than expected. Additionally, it is possible that the upset pin volume was too small to achieve sufficient undercutting. An increase in pin height to 2.00 mm increases the mean undercut of the joint by 50 % to a value of 0.15 mm. Further increasing the pin height leads to a continuously greater value up to a value of 0.29 mm for the 3.00 mm pin, which amounts to a 93.3 % increase compared to the 2.00 mm pin. Interestingly, for the joint with a 2.0 mm pin a lower undercut was measured compared to the 1.75 mm pin. It can be seen that the pin base diameter for the 2.0 mm pin increases by approx. 4.3 % from 1.64 mm to 1.71 mm compared to the 1.75 mm pin. A similar increase of 5.1 % can be observed for the 1.50 mm pin to the 1.75 mm pin. However, the pin head diameter increases by 10 % compared to only 3 % from the 1.75 mm pin to the 2.0 mm pin. Therefore, it can be said that the pin base increases more than the pin head, which results in a smaller wedge angle and thus also a smaller undercut.

Pin height					
1.75 mm	2.00 mm	2.25 mm	2.50 mm	2.75 mm	3.00 mm



Geometric joint characteristics (t_0 = 1.5 mm)						
Pin height (mm)	1.75	2.00	2.25	2.50	2.75	3.00
Pin head diameter (mm)	1.68	1.77	1.86	1.91	2.16	2.29
Pin base diameter (mm)	1.49	1.50	1.53	1.55	1.63	1.70
Mean undercut (mm)	0.1	0.15	0.17	0.20	0.27	0.29

Fig. 5: Micrographs of the caulking joints for different pin heights with a 1.5 mm joining partner

When examining the caulked joints with an aluminium joining partner with a sheet thickness of 2.0 mm (c.f. Fig. 6), it can be seen, similar to the sheet thickness of 1.5 mm, that the pin heights used only start from 2.25 mm and thus 0.25 mm above the initial sheet thickness. Furthermore, it can be seen that the first joint also does not indicate a sufficient undercut. As the pin height increases, the pin head diameter and the measured undercut also increase, analogous to the other sheet thicknesses. However, the values achieved for the undercuts are lower than the undercuts for

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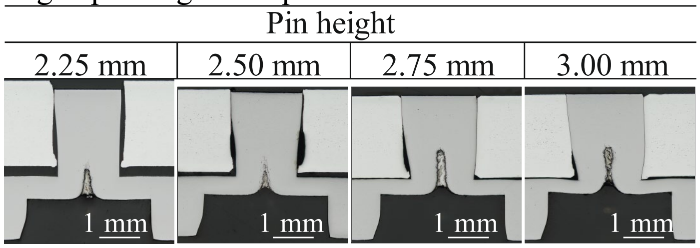
the comparable pin height/sheet thickness combinations due to the higher sheet thickness and the resulting lower percentage upsetting of the pins.



Geometric joint characteristics (t_0 = 2.0 mm)				
Pin height (mm)	2.25	2.50	2.75	3.00
Pin head diameter (mm)	1.62	1.75	1.84	1.86
Pin base diameter (mm)	1.49	1.49	1.51	1.52
Mean undercut (mm)	0.07	0.14	0.16	0.19

Fig. 6: Micrographs of the caulking joints for different pin heights with a 2.0 mm joining partner

For a comparison of the different pin height/sheet thickness configurations, the undercuts for the individual sheet thicknesses are plotted in Fig. 7. In addition, the joints are classified as "okay" and "not okay", which indicates whether the joint is load-bearing or whether there is an insufficient undercut or a joining instability such as a buckling of the pin. It can be seen that the joint with the 1.0 mm joining partner achieves a higher undercut with a comparable pin height. If we look at the respective joints with a pin height of 2.5 mm, which is present for all three sheet thicknesses, the 1.0 mm sheet thickness achieves an average undercut of 0.31 mm compared to an undercut of 0.2 mm (1.5 mm sheet) and 0.14 mm (2.0 mm sheet). This is not surprising, since the pins are significantly more compressed with a joining partner with a smaller sheet thickness than with a thicker sheet. Here the pin is compressed by 60 % for the 1.0 mm sheet compared to 40 % (1.5 mm sheet) and 20 % (2.0 mm sheet). Nevertheless, due to the fact that the compression increases with a higher pin, the measured undercuts generally tend to increase with the pin height regardless of the sheet thickness of the joining partner. It is also interesting to note that when comparing joints with different initial pin heights but the same percentage upsetting, similar undercut values can be measured. For example, an undercut of 0.17 mm was measured with a pin height of 1.5 mm (1.0 mm sheet metal), an undercut of 0.17 mm with a height of 2.25 mm (1.5 mm sheet metal) and an undercut of 0.19 mm with a pin height of 3.0 mm (2.0 mm sheet metal). Thereby, all three pin height/sheet thickness configurations showed a percentage upsetting of 33.3 %.

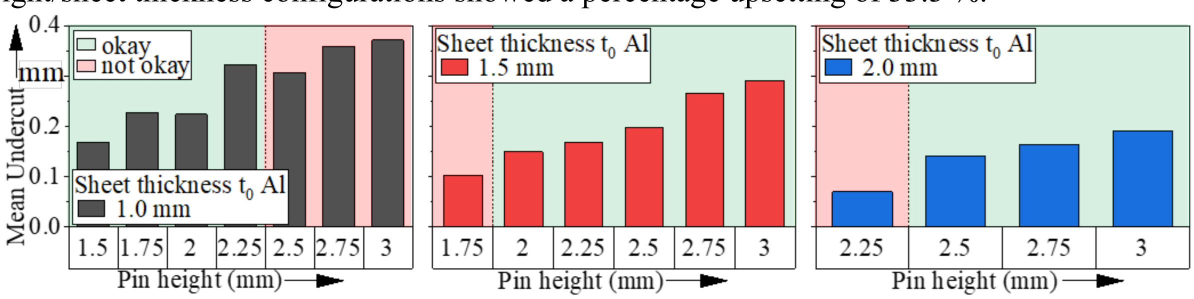


Fig. 7: Comparison of the mean undercut for the investigated joints

For this reason, the undercut was also normalised to the percentage upsetting of the pin and plotted as a dependent of the pin height in Fig. 8. It can be seen that, independent of the sheet thickness, similar dependencies of the undercut on the percentage upsetting of the pins with varying pin heights result and that these normalised values are at a similar level. Consequently, if the average value of the normalised undercuts is calculated, the average undercut per percent pin upsetting is 0.0057 ± 0.0007 mm/%, regardless of the pin height or the used sheet thickness of the joining partner. Therefore, it can be concluded that the pin height/sheet thickness ratio or the resulting ratio of pin upsetting can be used to influence the joint formation and to adjust the undercut.

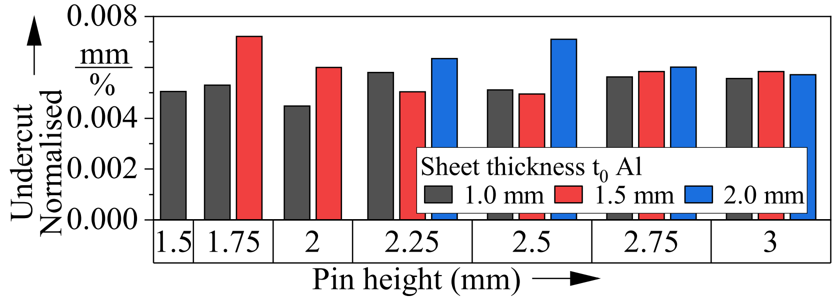


Fig. 8: Comparison of the undercut values for the different pin height/sheet thickness configurations normalised to the percentage upsetting of the respective pin

Based on the results presented, a process window can accordingly be derived that provides information about the joinability of the different sheet thicknesses investigated with different pin heights (c.f. Fig. 9). It can be seen that there are overlapping areas between the sheets in terms of joinability with the same pin heights, but that no pin height is able to join all three sheets. However, one advantage of pin joining is the posibility to react to varying boundary conditions by adjusting the pin height. This is also the case with pin caulking. Considering the areas where the joints turned out to be "not okay" in the investigations, it can be seen that in the case of caulking, the lower limit is initially determined by the sheet thickness of the joining partner, and an additional pin height of at least 0.25 mm is necessary to achieve a load-bearing joint. However, it can be assumed that with increasing pin height and correspondingly a larger undercut, a higher load-bearing capacity can be achieved. In addition, as explained above, with a joining partner sheet thickness of 1.0 mm, a pin compression of 60 % or more, which corresponds to a 2.5 mm pin, leads to joining instabilities that cause the pin to buckle laterally. This upsetting is not reached with the examined pin heights for the other sheet thicknesses, which is why no upper limit can be determined for the sheet thicknesses of 1.5 mm and 2.0 mm. However, it can be seen from the micrographs that with increasing pin height, the sheet thinning below the pin increases. This can lead to premature failure of the joints under load. For this reason, further investigations should be carried out to analyse whether and to what extent the sheet thinning has an effect on the joint strength.

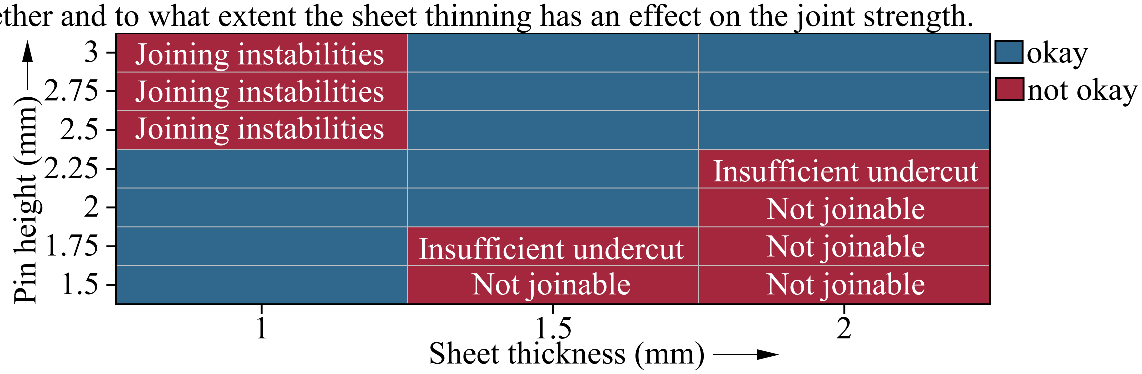


Fig. 9: Illustration of the determined process window for the three different sheet thicknesses

Summary and outlook

In this contribution, caulking, which has the potential for joining metal/metal and metal/FRP to reduce the component weight and therefore energy consumption, was fundamentally investigated as an alternative joining strategy to direct pin pressing. The influence of different pin heights/sheet thickness combinations on the joint formation and the resulting geometric joint properties was analysed. Thereby, an understanding of the joining process could be established. Additionally, it was shown that as the pin height increases, an improvement in the undercut occurs, which can be influenced by the percentage upsetting of the pin. Furthermore, with a joining partner sheet thickness of 1.0 mm, joining instabilities in the form of buckling pins occurred at a pin compression of 60 % or more, which led to joints that had to be classified as not okay. Moreover, with the 1.5 mm and 2.0 mm joining partner an additional minimum pin height of 0.25 mm above the sheet thickness is necessary to create load-bearing joints. In addition, the large pin heights, which are particularly necessary for joining greater sheet thicknesses, show that there is severe sheet thinning during pin extrusion, which can have a negative impact on the load-bearing capacity of the joint.

Future investigations should mechanically characterise the presented joints based on the results shown here, in order to determine corresponding load-bearing capacities with regard to the undercut values measured. Both the shear and axial load capacities should be investigated in order to analyse a possible influence of the sheet thinning.

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