Experimental analysis of the influence of the embossing and upsetting process on joint strength in resistance element welding with upset auxiliary joining elements

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Abstract. The use of conventional resistance spot welding in the car body shop for joining an aluminium part to a steel part is possible with the process-invention of the resistance element welding (REW) with upset auxiliary joining elements. Within this process, the challenges arise from the novel approach of combining forming process steps in the insertion of the auxiliary joining elements. Thus, the process understanding is to be compiled to the combination of the individual process steps. For this reason, the study deals with the influence of the forming process steps on joint strength of REW with upset auxiliary joining elements. The focus is set to the improvement of the positive locking and force fit considering the results of previous strength analysis. As the key result, the initial relative position of the carrier sheet and the auxiliary joining element is highlighted as the most significant factor on joint strength. The material flow, illustrated in metallographic microsections, is used to explain this effect. Based on the elaborated cause-and-effect-chains, a geometrical model is derived and validated to produce high-quality joints with high joint strength.

1. Introduction and state of the art
Volatile markets, international trade barriers and an increasing regionalisation are current major trends which induce dynamic changes in the economic environment of the automotive industry. Consequently, the production system requires high flexibility [1]. In contrast, the stricter regulations of emissions are an essential trigger for the electrification of individual mobility [2]. The associated range challenge, combined with the increasing size of the battery packs, the main driver for the increase in vehicle mass, is countered by mass savings in the car body [3]. In car body design multi-material construction is a promising approach [4] that has been accelerated in recent years [5]

The development of resistance element welding (REW) can be defined as a countermeasure to join multi-material-compounds in the production lines with the same joining technology as with conventional steel parts. With this joining technology, it is possible to realise joining of dissimilar materials by conventional resistance spot welding (RSW). In principle, the REW involves the use of an auxiliary joining element which is integrated into the aluminium carrier sheet in different ways. Subsequently, the conventional RSW can be used to join the new compound of aluminium carrier sheet and integrated auxiliary joining element to another steel part by welding on the element.

Several different procedures of REW have already been examined. The process principle of REW was published by MESCUT ET AL. [6]. In this process, a rivet-like element is inserted into the pre-
punched aluminium carrier sheet [7]. Subsequently, the carrier sheet can be joint by RSW to another steel part [8]. The insertion of the joining element can be done with an extra tool or with the welding tongs [6]. The positioning step can be saved by the latter [6]. Concerning this joining method MESCHUT ET AL. analysed the achievable shear strengths and compared them to similar joining methods, such as friction element welding [6]. Furthermore, applicable welding parameters were identified and the loading behaviour under corrosion load was investigated [9]. MEYER investigated a similar process alternative, where the joining element possesses countersunk-heads [10]. Based on this, WIESE pursued the goal of industrializing the elements with countersunk heads [11]. The approach proposes to combine the punching process with a warm embossing process operated by the welding gun [11]. Comparable element geometries are known from the work of POTTHAST ET AL., where the elements were called “SWOP elements” [12]. The load level under shear stress has been also investigated for this purpose and the joint has been examined under corrosion stress [12]. A comparable joining process is the RSW on self-piercing elements published by HOU ET AL. [13] and further described in [14]. In this process, the welding lens is formed at the lower end of the rivet element [13]. In contrast, an alternative process with the weld spot being formed at the upper side of the rivet element, which is punched in the aluminium sheet, is first published in [15]. Concerning this process, KOTSCHOTE analysed the process parameters, especially the welding heat, in consideration of their influence on joint strength [16].

A clearly distinguishable process alternative, considered in this study, is resistance element welding with upset auxiliary joining elements [17]. Figure 1 gives a schematic overview of the procedural principle.

![Figure 1. Process scheme of resistance element welding with upset auxiliary joining elements.](image)

The joining procedure has to be divided into two forming operations and a subsequent thermal joining process step. First, the aluminium carrier sheet is embossed with a special blank holder geometry and pre-punched by shear cutting in the same stroke. Afterwards, auxiliary joining elements produced by shear cutting are inserted into the pre-punched aluminium carrier sheet and are upset by cold upsetting respectively cold forging. After this process step a positive locking and a force fit results between the joining element and the aluminium carrier sheet. Finally, the weld spot can be set on the joining element to the steel part. Subsequently, a metallic bonding occurs between the element and the steel part. Within former investigations the load-bearing behaviour under shear load [17] and additionally with the peeling test [18] were analysed. In both load-cases the compound failed by unbuttoning of the auxiliary joining element. A failure of the weld spot did not occur in the tests carried out [17]. Concluding from these results, an improvement in positive locking and force fit may lead to an increase in maximum joint strength. Another study pursued the evaluation of the impact of the cut surface, which occurs by shear cutting of the auxiliary joining elements, on joint strength [19]. It turned out that a higher smooth cut proportion results in a higher joint strength [19].
In principle, the targeted use of the forming process steps makes the difference between the considered process from the process alternatives. This is, on one hand, the embossing of the chamfers during the pre-punching of the aluminium carrier sheet and on the other hand the totally upsetting of the joining elements to achieve a positive locking in both directions [17]. In the comparable processes, however, no intentional forming of the joining elements is used to create a joint between the carrier sheet and the element. Due to the novel combination of the forming process steps for pressing in the auxiliary elements by upsetting, there is still no systematic process understanding of the influencing factors on joint strength. Based on this, this study focuses on the forming processes of REW with upset auxiliary joining elements.

2. Objectives and methods

2.1. Objectives
The overall objective of this study is the experimental analysis of the influence of the upsetting process of resistance element welding with upset auxiliary joining elements on the joint strength and its controllability. The study is completed by the derivation of an impact factor model which comprises the relevant influencing factors on joint strength. Thus, an improvement of the process understanding of REW with upset auxiliary joining elements is achieved.

The methodology approach is based on the hypothesis that both, the positive locking and the force fit can be influenced significantly by the forming operation of the procedure. Thereby, the approach is threefold. Firstly, the initial state of the semi-finished products and the upsetting process is analysed. Afterwards, the cause-and-effect-chains are elaborated using a material flow study. Thirdly, the influencing factors are clustered and form the basis of the derived model.

2.2. Experimental materials
In the context of this study aluminium carrier sheets made of Al6-Out – designation after VDA 239-200 [20] – with a sheet thickness of 1 mm were used. This selection was based on various possible applications of the considered joining process in current car bodies. The auxiliary joining elements were made of CR3 steel with a sheet thickness of 2.2 mm – designation after VDA 239-100 [21]. This steel is classified as suitable for deep drawing. It was selected due to its formability, which is important for the upsetting process, and the weldability, necessary for the RSW process. For validation, on the other hand, the micro-alloyed steel CR240La with a sheet thickness of 2.2 mm is used – designation after VDA 239-100 [21].

2.3. Experimental method for characterising the joint strength
In order to determine the joint strength of carrier sheet and auxiliary joining element after the upsetting process and before the welding process step, push out tests were carried out according to DVS/EFB MERKBLATT 3480-1 [22]. Both load directions were analysed in the push out tests. The specimen dimensions are 80 mm x 80 mm. The sample size is n = 7 for top to down and n = 3 for down to top.

3. Analysing the forming process steps of resistance element welding
The upsetting process of the auxiliary joining elements leads to the shaping of the pre-punched aluminium carrier sheet by the formed joining elements. The shear-cut auxiliary joining elements and the pre-punched aluminium carrier sheet form the initial state of this upsetting process. The influence of the cutting surface parameters on the joint strength of REW is already known from the study [19]. For this reason, the pre-punched carrier sheet is analysed at the beginning.

As shown in Figure 1, a pre-hole is produced, which possesses a chamfer embossed on both sides at the edge of the hole. Technically, this embossing process is solved by a blank holder and a die, which have an embossing geometry. This integrated embossing process results in the fact that only smooth-cut proportion is formed inside the hole. This is due to the reduced deformability due to the strain hardening, on the one hand. On the other hand, the embossing geometry of the die prevents the development of an oblique fracture zone. Furthermore, the implementation of the embossing process
by the blank holder leads to a warping of the carrier sheet and a border-close thickening. This is because during the embossing of the two chamfers the carrier sheet is not held down, and thus reacts to the centric impression of the embossing geometry by a warping. The warping and the smooth cut proportion are shown in the following figure 2.

Figure 2. Aluminium carrier sheet with focus on warping and cut surfaces.

Based on the now known initial state of the auxiliary joining element and the carrier sheet, the analysis of the relative position of the two semi-finished products in the upsetting process can be continued. Therefore, the adjustment value of the actuators, which lift the carrier sheets, is called $z_{spring}$ in the following. The actuator is a screw element with a spring-mounted ball. Due to the high upsetting forces, no influence of the used spring stiffness on the process is to be expected. The starting point of the study is an average $z_{spring}$ of 0.6 mm, which results from the averaging of the two semi-finished product thicknesses in the initial state. Around this value, the $z$-position was variated in the reasonable technical range from 0.45 mm to 0.75 mm with an increment of 0.1 mm. Afterwards, the joint strength was determined through push out tests. The achieved joint strengths are plotted in figure 3.

Figure 3. Push out joint strength with different adjustment value $z_{spring}$.

Figure 3 shows that a higher joint strength is achieved with a decreasing $z_{spring}$. The higher $z_{spring}$, the smaller the push out joint strength in top-down direction. A $z_{spring}$ of 0.45 mm led to a joint strength of about 2350 N. With $z_{spring}$ between 0.55 mm to 0.65 mm joint strengths of about 2250 N were reached. The standard deviation was on a low level of about 50 N. Beginning with a $z_{spring}$ of 0.75 mm a higher standard variation occurred (250 N) and the mean value of joint strength was about 1800 N. All in all, a reduction of $z_{spring}$ (40 %) leads to a strong increase of joint strength (30 %) although using the same joining elements. This correlation has to be justified by the material flow of the elements during upsetting. The higher the forming volume of auxiliary joining element above the centre plane of the carrier sheet gets, the higher becomes the portion of undercut of the auxiliary joining elements in push-out direction. This aspect can be seen in the microsections shown in figure 4. The graphic shows the decreasing undercut portion by an increasing $z_{spring}$ marked with green lines in the microsections. It can be seen in figure 4 that a lower $z_{spring}$ leads to a larger undercut portion, which has an advantageous effect against the loading direction top-down. This effective undercut portion shifts downwards due to the $z_{spring}$ increase. With a $z_{spring}$ of 0.75 mm, the effective undercut portion on the
top is significantly lower than with a z-position of 0.45 mm, which leads to the significantly reduced strength.

![Material flow during upsetting process.](image)

**Figure 4.** Microsections of the compound produced with different adjustment value $z_{spring}$.

### 4. Overall discussion and model derivation

Based on these results, it can be concluded that joint strength is decisively influenced by the relative position of the carrier sheet and the auxiliary joining element. The basic cause-and-effect relationship is to be explained by the material flow of the auxiliary joining element and the carrier sheet during the upsetting process. To clarify this context the following figure 5 shows the material flow in different upsetting process states with a $z_{spring}$ for symmetrical shaping.

![Material flow during upsetting process.](image)

**Figure 5.** Material flow during upsetting process.

As in figure 5 can be seen, the upsetting leads to a material flow of the element in the radial direction. The joining element begins to bulge radial by an increasing upsetting and non-ideal friction conditions in the contact zones to the upper and bottom die. Then, the material flow is obstructed in the zone where the first contact between element and carrier sheet occurs. In this process step the pre-punched aluminium carrier sheet forms the resistance to the bulging of the element. In contrast, free material flow can be maintained in the zones of the embossed chamfers until the cavity is filled. But also, the carrier sheet deforms, and a material flow arises in the outer zones. Changing the initial z-position the material flow of the upset auxiliary joining element will be changed. Depending on the relative position of the carrier sheet, the resistance to the bulging works in different height of the auxiliary joining element. Consequently, both the shaping of the undercut proportion and the filling of the carrier sheet cavity will be influenced. With the finished stroke, the final shape of the element with the undercut is reached. In this way, the undercut portion is distributed differently and can be exploited in a targeted manner to achieve specifically required strengths with the same semi-finished products. Thus, it is possible to optimize the joint for the present main load of the application so that, for instance, a targeted failure can be adjusted in the event of a crash. This flexibility advantage of the process is to be emphasized compared to the other resistance element welding processes.

Regarding the joint strength, the shaping of the macroscopic positive locking should be mentioned as the most significant effect. The decisive factor to influence this locking type is the relative position
of the two semi-finished products to each other in the initial state of upsetting. To describe this relationship for process control, it is necessary to summarize the various impact factors on the material flow in one model below. In this way, the essential factors are brought into a context to predict and obtain a desired compound shape. To obtain a symmetrical mould filling, the proportion of the element volume above and below the centre plane of the carrier sheet must therefore be positioned in equal parts relative to the middle plane of the carrier sheet. In the modelling of this cause-effect relationship, in addition to the semi-finished thicknesses, the outer contour of the auxiliary joining elements (cutting surface parameters) as well as the warping of the carrier sheet (compare figure 2) must be taken into account. The cutting surface of the carrier sheet can be neglected or assumed as a vertically running cutting surface due to the 100% proportion of the smooth cutting zone. This model approach considers all relevant geometry characteristics that have the main impact on joint strength. These relevant influencing factors are summarized in the impact model shown in figure 6.

For this approach it is assumed in the modelling that the flow behaviour of the different cut surface zones is identical. To this end, the outer contour is idealized, as shown in figure 6. To estimate the volume proportions, the three cut surface zones are divided into three characteristic volume proportions (edge draw-in zone, smooth cut zone & fracture zone). The burr is neglected because of the low burr height (about 0.05% of the element thickness, see figure 6). The edge draw-in is assumed to be a 90° circle sector for modelling. The warping of the carrier sheet must be added, too. Considering this parameter set, it is possible to describe the significant geometric input variables for the material flow. The determination of these parameters is a basic prerequisite for controlling the material flow, whereby the joint strength can be decisively adjusted. In addition, the model forms the framework for further parameter analyses to quantify the impact on material flow. For this purpose, the model maps the geometric parameters to be considered when creating a numerical model for finite element analysis.

The validity of the cause-and-effect relationship is qualified in the following on a second material pairing. For this purpose, auxiliary joining elements from the micro-alloyed steel CR240La are upset at different z-positions. Subsequently, the push out strength of both load directions is determined. The results are summarized in figure 7.

**Figure 6.** Model of relevant influencing factors on joint strength.

**Figure 7.** Push out force related to z-position with second material pairing.
This material pairing also shows the context described above and summarized in the model. With decreasing $z$-position, an increased joint strength can be achieved (red mean values). The highest joint strength is at a higher level with a $z$-position of 0.45 mm with an average of 3550 N than with the CR3 elements. This is due to the higher material strength of the auxiliary joining element. A 40% reduction in the $z$-position leads to a 35% increase in strength. Considering a mean standard deviation of 100 N, the percentage strength increase is comparable to the first material pairing. The same correlation can also be identified in the microsections. The larger the undercut portion that acts against the expression, the greater the joint strength. The same relation can be identified in the opposite direction of the push out load (blue mean values). If the undercut portion on the underside is increased, the strength in the opposite push out direction increases proportionally. This once again highlights the crucial importance of the macroscopic positive locking component. The formation of the positive locking is again to be explored by the material flow, wherein the $z$-position is the most significant influencing factor. In addition, for a holistic view, it is necessary to consider the expression of the cutting surface characteristics and the carrier sheet warping, as shown in the model.

5. Summary and Outlook
Multi-material-design is a key strategy to reduce mass in car body design and reduce fuel consumption. Though, challenges for joining technology occur since dissimilar materials have to be joined. Resistance element welding (REW) with upset auxiliary joining elements is one possibility for joining dissimilar materials by conventional resistance spot welding.

The objective of the investigation is to determine the significant influence factors of the forming process steps on joint strength of the considered REW process alternative. Previous results showed that the positive locking and force fit are the two fitting types which have to be improved of REW joints. This defined the focus on the impact investigations of the forming process steps. The analysis of the factors led to the fact that the $z$-position, which is the decisive variable of the relative position, is the main influencing factor on joint strength. The analyses revealed that the form closure is primarily determined by the relative position of the auxiliary joining element and the aluminium carrier sheet. This is because the material flow during the upsetting process can be controlled in this way and thus the positive locking can be influenced. Furthermore, the cut surfaces of the joining elements and the warping of the carrier sheet influence the material flow. The factors were summed up in a geometrical $z$-position model regarding, on the other hand, the thickness and cut surfaces of the joining elements and on the other hand the thickness and warping of the aluminium carrier sheets. The correlation was confirmed by a second material pairing by means of push out tests and analyses of the microsections. Based on these results, the effect of the significant factors on joint strength under the conventional loads will be quantified in future works. Moreover, a numerical model based on the derived model was developed which is used in further investigations on geometry variations and their influence on joint strength. Finally, the investigation of the combination with an adhesive and under corrosion load are in progress.

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