Effects of increased tool velocity on mechanical joining of steel and aluminum sheet metals

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Abstract

The paper shows possibilities for improving the joining process of self-pierce riveting with solid rivets (SPR-SR) by increasing tool velocity. The focus is put on the joining process of high-strength steel sheets with aluminum sheets. Proper and reliable joining of these material combinations is a major challenge for mechanical joining techniques. In the conventional joining process, with common tool velocities well below 1 m/s, different problems during the joining process caused by the high strength of the steel sheets can occur. These problems can be reduced significantly by increasing tool velocity.

1. Introduction

The project aims to enhance the process limits of self-pierce riveting with solid rivets of high-strength steel sheets with aluminum sheets by using high speed joining and showing its potential for elementary and hybrid joining.

For several years, research in various fields for usable effects by increasing the tool velocity has been done by different research facilities. Main subjects of the investigations are the plastic strain rate and temperature-dependent material properties in the joining process [1,2] as well as the inertial effects in the global structure [3,4]. In the literature, the term “high speed joining” is mainly used to describe processes with a tool velocity range of about 5 m/s to 100 m/s. In the following investigations, elevated tool velocities of about 5 to 10 m/s are applied, while tool velocities in conventional joining applications in mechanical joining are well below 1 m/s.

2. Process conditions and test setup

2.1. Joining with self-piercing solid rivets

Through joining with self-piercing solid rivets permanent connections of sheet metal parts without pre-manufactured holes can be produced [5]. The piercing process is performed by a cylindrical solid rivet, and a two-sided accessibility to the workpieces is required. With this process two or more workpieces can be joined. The piercing capability of the material and a deformability of the die-side material are important. Because of the combination of interlock and force closure, SPR connections have a significantly higher service life than thermal joined connections particularly at oscillating load [6].

In the beginning of the process, the workpieces are fixed between die and blank holder (Fig. 1, I.). Afterwards, resulting from the movement of the punch, the rivet pierces a hole into the components and is subsequently pressed into the workpieces until the countersunk head of the rivet is installed flush with the surface of the upper piece of the sheet metal (Fig. 1, II.). In the third step of the riveting process,
workpieces and rivet are jointly pressed against the die at a high level of force to indent the die into the lower sheet metal. This presses the material volume of the die-side sheet metal into the shaft groove of the rivet, which then creates interlocking (Fig. 1, III.).

A high level of ductility and a low level of material strength are beneficial for forming the die-side sheet metal into the rivet shaft groove. Hence, the aluminum sheets are preferably arranged on the die-side in case of steel-aluminum joints. The setting velocity is well below 1 m/s with the conventional SPR-SR process.

2.2. Limitations in joining of high-strength steels with aluminum sheets

In the first step of the process, the sheets to be connected are pierced by the rivet as described, whereby the rivet functions as a punch. The necessary cutting force is transmitted on the projection of the die on the lower piece of sheet metal. This is the reason why there might be an indentation of the elevation on the die in the die-side sheet metal even before piercing the holes in the components, if there is a high level of piercing force caused by a high level of material strength in the steel sheet. Consequently, there is no possibility in the third process step to press a sufficiently large material volume into the rivet groove. This might be the cause for poor quality of the joint as there is insufficient interlock between rivet and die-side sheet.

Furthermore, small circular blanks, so called slugs, are separated from the workpieces in the piercing process. These slugs are discharged through the hole in the die. Sometimes, the upper slug has a larger diameter than the hole in the die, due to an improper piercing process of the high-strength steel sheets (Fig. 2, I). The projecting burr is then sheared off on the cutting edge of the die while discharging these parts (Fig. 2, II) and is formed into the area of the rivet shaft groove in the further process routine (Fig. 2, III).

2.3. Test setup for piercing and joining experiments

The results presented in this article were produced with a high speed joining machine using a pneumatic actuator (Fig. 3). The structure of the machine is based on a four-column frame. The drive consists of an impact cylinder and an impact weight, which is mounted on the piston rod of the cylinder. The impact weight impacts on the guided punch, which pierces the rivet into the sheets.

This joining machine reaches impact speeds between the impact weight and the punch up to 15 m/s. However, the impact speed can be regulated by a precision pressure regulator system. The upper part of the machine can be lifted and lowered for inserting the joining elements or workpieces and for the replacement of the punches by pneumatic cylinders.
(Fig. 1, II) at different tool velocities in detail, piercing tests were carried out. In order to ensure the comparability to the joining experiments for most parts the same tools respectively tool dimensions where used for the piercing process. In contrast to the joining investigations, the forming ring of the die and the conically formed part of the rivet head was removed (Fig. 4, left) to prevent further plastic deformation of the parts as shown in Fig. 1, III.

3. Results

3.1. SPR-SR process at elevated velocity

As tests on various connections indicate, it is possible to counter early die indentation into the die-side sheet metal as well as the occurrence of an undesired burr by increasing the tool velocity at SPR-SR. In Fig. 5, the cross sections of a connection of two sheets are presented, to show the influence of elevated tool velocity on the connection quality. Due to the suboptimal piercing process during conventional joining, parts of the steel slugs are not discharged through the die and prevent the correct forming of the aluminum sheet into the shaft groove of the rivet (Fig. 5, left). In contrast to the conventional process, SPR-SR at elevated tool velocity offers an advantageous piercing quality, whereby the steel slugs are entirely discharged through the die and the shaft groove of the rivet can be filled completely with aluminum (Fig. 5, right).

3.2. Piercing at elevated velocity

The results of the piercing investigations are shown in Fig. 6. The dimensions (largest and smallest diameter of the pierced hole in both sheets) shown in the cross sections are average values from 7 measured samples per tool velocity.

The dimensions of the holes, pierced at conventional velocity, clearly indicate a conical tearing of the slugs from the steel sheets. This confirms the problem of burr formation of the conventional joining shown in Fig. 5, left. In contrast to the sheets, pierced at conventional tool velocity, the hole, pierced at elevated tool velocity, has much more cylindrical shape. This result underlines the significantly better joint quality at elevated tool velocity (Fig. 5, right).

Moreover, the punch-side sheet (22MnB5, t = 2.0 mm), pierced at different tool velocities, was analyzed using a scanning electron microscope (SEM). The SEM images are shown in Fig. 7.

At both sheets, pierced with different tool velocity, the cross section can be divided in a smooth cutting zone and a fracture zone. However, due to the different tool velocities, significant differences in the dimensions of these areas can be
determined. The smooth cutting zone of the sheet, pierced at conventional tool velocity, has approximately double the height of the smooth cutting zone of the sheet pierced at elevated tool velocity. Differences are also visible in the structure of the fracture zone of the holes pierced with different tool velocities.

3.3. Strengths of the manufactured joints

In Fig. 8, the connection strength of the joints, manufactured with different tool velocities, is compared. The quasi-static shear load test was carried out for elementary joints and for the combination of mechanical joining with adhesive (hybrid joining).

![Fig. 8. Comparison of the joint strength (quasi-static shear load test) of the joints manufactured with different tool velocities.](image)

Despite the obvious differences in the joint quality (burr formation, shaft groove filling), when comparing the elementary joints, manufactured with different tool velocities, the difference of the maximum shear load force is relatively small. Reason for this is the type of sample failure when testing these material combinations. Due to the high strength of the steel sheet and the rivet material, the rivet simply is pulled through the aluminum sheet during the shear load test. When comparing the strength of the hybrid joints, the absolute value and scattering of the shear strength of the joints, manufactured with elevated tool velocity, is clearly better compared to the conventional process. Reason for these differences can be seen in the failure images of the hybrid joints (Fig. 9).

![Fig. 9. Failure images of the hybrid joints manufactured with different tool velocity after quasi-static shear load test.](image)

The strength of the hybrid joints depends mostly on the adhesive bonding or the adhesive surface. Through the conventional punch riveting process a certain amount of adhesive is squeezed out of the joint (Fig. 9, left). This reduces the effective adhesive surface and therefore the joint strength [7]. As can be seen in Fig. 9 (right), the effective adhesive surface is much higher using elevated tool velocity when joining these materials with self-piercing solid rivets in combination with adhesives.

4. Discussion of the results

The experimental results show a considerable impact of the tool velocity on the quality and the strength of the joint. It seems reasonable to suppose that changing material properties under the elevated setting velocity are causal for the observed effects. On the basis of FE-simulations of the piercing process the occurring strain rates and temperatures will be assessed.

In Fig. 10 and Fig. 11 the results of numerical investigations are shown. In this example, piercing of sheet metal (steel; thickness: 2 mm; diameter of punch: 5 mm) with two different tool velocities is considered.

In consequence of higher tool velocity, the piercing process is done with higher strain rates (Fig. 10), which can cause a higher flow stress and a reduced ductility of the steel material. Furthermore, the temperature is rising in the cutting zone. Thermal conduction occurs while piercing the sheet metal with conventional tool velocity, so that there is only an insignificant increase in the workpiece temperature in the cutting zone. With increasing tool velocity, less heat is transported because of the time-dependency of thermal conduction. The result is a very small volume with high temperature, up to the melting point of the metallic material [8,9].

![Fig. 10. Strain rate in the workpiece at two punch velocities (FEM).](image)

The temperature dependence in the cutting zone at two punch velocities using FE-simulation is shown in Fig. 11. The boundary conditions are defined as follows: no heat exchange between sheet metal and tools occur and 95% of the forming work is transformed into heat. When piercing the material with a velocity of 0.002 m/s, heat is transported by thermal conduction almost completely so that there is a maximum temperature of only 33 °C in the cutting zone. Considering
higher tool velocities of 5 m/s and 10 m/s, a temperature of 570 °C respectively 610 °C can be observed.

These two effects, strain rate-dependent hardening and temperature-dependent softening, influence each other contrarily and depend on the material that is pierced. When piercing the material, only a very small volume is affected, the so called shear band. Piercing ductile material with a high tool velocity causes a fine-grained fracture surface, comparable with a brittle fracture zone [9]. The results show that the high strain rates as well as local temperatures in the material are the main causes for the different results of joining with increased velocities. Detailed characterization of the damage behavior of high-strength steel sheet for joining at different tool velocities is currently carried out.

5. Conclusions

The experimental results on mechanical joining at increased tool velocities presented in this paper indicate a great potential for joining high-strength steel. For the SPR-SR process it was shown that the undesired effects of early die indentation into the die-side sheet metal and burr formation can be avoided by increased tool velocity. The changing material behavior improves the quality of the manufactured joints. Additionally, the elevated tool velocity leads to better results when the riveting process is combined with adhesives. The reason is a more consistent adhesive layer after the SPR-SR process at elevated tool velocity compared to conventional process.

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Fig. 11. Temperature in the workpiece at two punch velocities (FEM).

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