Influence of the Boundary Layer in Magnetic Pulse Sheet Welds of Aluminium to Steel

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Abstract

In this paper, influential factors on the bonding strength of magnetic pulse welds between Aluminium (A1050) and Steel (S235JR) sheets are shown. First, a process window defined by varying charging energy and standoff distance for the welds. These welds will be characterised by the means of weld length and shear strength. Sound parameters are worked out at a standoff of 1.5 mm and a charging energy of 9 kJ. Nevertheless, no direct correlation between archived weld length and weld strength can be seen for the specific parameter set with a glass blasted, nearly polished surface. The achievable shear strength for this parameter set varies in the magnitude of 30 %.

The chosen parameters are used to investigate the effect of surface preparation on the weld. Surface preparation has an acceptable impact on the achievable weld length in the interface and on the maximum shear strength. Furthermore, a controlled surface appearance reduces the statistic deviation of the weld length. It is shown that machining, which cuts grooves perpendicular to the collision direction, enhances the joint performance as well as the achievable weld characteristics.

Furthermore, an acceptable impact of the rolling direction of the steel on the appearance of the joint interface will be shown. A rolling direction which lies perpendicular to the collision direction enhances the bulging of the steel into the aluminium.

Keywords

Welding, Aluminium, Surface

1 Introduction

1.1 Motivation

Lightweight design has been a permanent trend in various industrial areas in the last few years. Specifically for transportation applications it has gained an outstanding importance, due to its potential to reduce fuel consumptions and thus CO_2 emission. One of the main driving forces of light weight designs is the mixed material approach. Apart from the occasional use of other alloys, the materials that are used mostly for lightweight designs are aluminium and steel. [11]

For this purpose, a joining operation for steel and aluminium alloys is necessary [11]. However, because of their properties, joining operations for the joining of aluminium to steel are limited. Basically, there are three approaches to this operation. The first is adhesive bonding, it ensures advantages in stiffness for the car body. Nevertheless, a sound surface preparation is needed to provide the aimed properties. Furthermore, an additional joining operation for the car body has to be considered until the curing of the adhesive is finished. The second approach to joining aluminium to steel are form fit joints, e.g. clinching. These joints have a good quality but are not suitable for crash relevant structures, because their behaviour is anisotropic and their strength is not as the results gained in other operations. The third approach is the welding of aluminium to steel through low heat input welding sources. In detail, this welding method equals the soldering of the aluminium to the steel partner; hence the wetting of the aluminium to the steel is dependent on the surface preparation. Furthermore, plenty of heat is generated and intermetallic phases are likely to be formed and have a disadvantageous impact on the joint performance.

A recent approach to joining aluminium to steel is the so called magnetic pulse welding technology (MPW). It is a promising process, which is also likely to solve various problems of other joining operations and enlarges the possibilities of multi-material designs with aluminium and steel. This paper aims to show the potential of this process for sheet metal welding and will discuss the impact factors of the boundary layer on the weld formation process.

1.2 State of the Art

The basic principle of magnetic pulse sheet welding is displayed in Figure 1. According to [1], an increasing coil current, which flows through the coil, induces eddy currents into the aluminium sheet. These eddy currents have the opposite direction to the current of the coil. Hence, a force between both currents occurs, which causes the aluminium to be deformed in certain positions. In order to form a bond between both materials, the aluminium impacts onto the steel parent mainly under an oblique collision angle and with a certain collision speed.

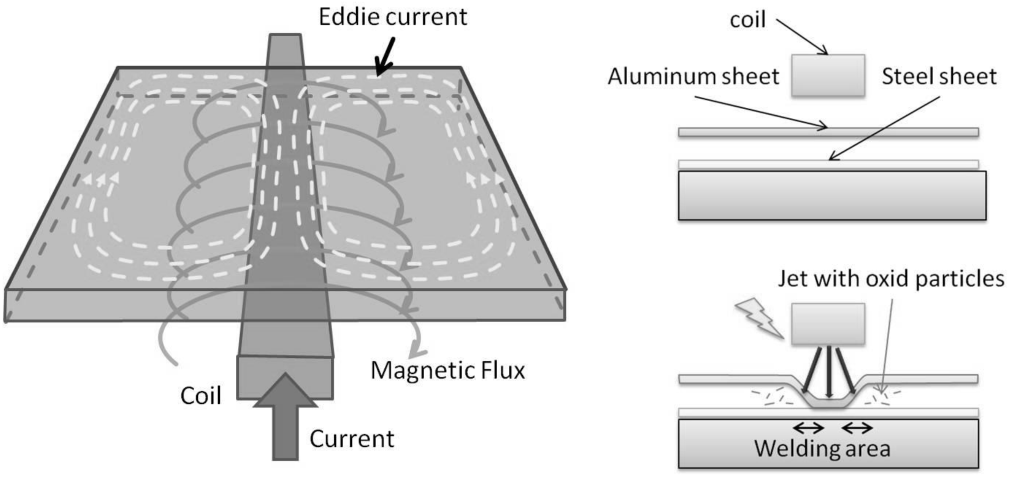


Figure 1: *Sheet metal welding, left according to Watanabe [1]*

All the papers, which are known to the authors and which deal with aluminium steel welds, are based on a small amount of specimens welded with the same parameters. They describe the weld formation phenomena in a qualitative way. *Lee* investigated the interfacial microstructure of aluminium A6111 to SPCC steel weld [2]. With the help of optical micrographs, he showed that the aluminium seems to suffer a lot more deformation than the steel parent. Furthermore, the hardness distribution shows that a work hardening of the material near to the interface takes place and he assumes that the "work-hardened layer around the intermediate layer is considered to be the origin of high interfacial bonding strength" [2].

The characteristics of a magnetic pulse weld of aluminium to steel are also discussed for tube welding by *Marya, et al.* in [3] and [4], [3] shows that the intermediate layer of an aluminium steel weld contains intermetallic phases which are likely to be formed due to non-equilibrium conditions. Furthermore, the work hardening is proved. The impact of the intermetallic layer on the tensile shear strength is investigated in [4]. The paper shows the impact of the minimum thickness of the interface layer on the tensile shear strength and states that a thickness of 5 µm delivers sound joints. However, only three different specimens were tested within the testing series for that paper.

A good sample for a process window research is [5], in which sheet metal welding of aluminium to stainless steel is described. A rather big amount of different process parameters were tested and plotted. The main focus of the investigation lay on the influence of different coil cross sections on the tensile shear strength. Hereby, the adjustable parameters charging energy and stand-off were varied, showing that a tapered cross section produces advantageous welds. The joined materials had a small thickness (steel: 0.25 mm; Al: 1 mm) and both joining partners were accelerated, hence the results are not directly transferable to a lot of applications, e.g. car body manufacturing. Overall, *Kore* achieved sound welds, but gave no information about the impact of the surface preparation on the weld formation as well as on the weld formation itself.

2 Aim of the Work

This paper aims to clarify the reliability of the MPW process for the welding of aluminium to steel. Research results from the University of Kassel, Germany, in [6], [7] and [8], as well as the results from [9], show that for the MPW of aluminium to steel a big variance in weld strength can be expected. Hence, this aspect will be examined for certain conditions during welding.

In context to past tests performed by the Department for Cutting and Joining Manufacturing Process at the University of Kassel, the hypothesis that weld length and tensile strength correlate was formed. This paper wants to show that the results of MPW can be treated as a Gaussian distribution and, in addition, shows the impact of the surface roughness on the process.

3 Experimental Setup

3.1 Specimen Material and Preparation

The specimen materials were AA 1050 as a flyer material with a thickness of 1.5 mm and a S235 JR as parent material with a thickness of 2 mm, Table 1.

	e-module [MPa]	$R_{p0,2}$ [N/mm²]	$R_{eH/eL}$ [N/mm²]	R_m [N/mm²]	H_V0,1	density [kg/cm²]
AA 1050	70	101,8		107,2	42	2,7
S235 JR	210		337,2/331,9	378,1	68	7,85

***Table 1:** Mechanical properties of the flyer and base material*

For the evaluation of the reliability and the calculation of whether the process can be treated as a process under Gaussian distribution conditions, 50 specimens were glass blasted by a mikromat eco 50 machine, manufactured by joke Technology GmbH. The average size of the glass pearls was 110 µm – 70 µm.
To examine different surface preparations for the steel parent, a brown aluminium oxide (NKF 70) blasting with an average grain size of 180 µm – 250 µm was processed in the same machine. Furthermore, a grinding process with a band grinder, with corning number 80 and Al_2O_3 as corn material, was used for the surface preparation. Two directions of grinding were applied to the specimens, one parallel and one perpendicular to the collision velocity vector.
Finally, a cleaned laser system was used to form the surface with the help of the laser ablation technique. The laser was a Q-switch laser with a wavelength of 1064 nm and a maximum power of 50 W. The obstacles were machined perpendicularly to the welding velocity vector. All surfaces were documented, using a white-light interferometer, MicroProf manufactured by the company Fries Research & Technology GmbH. Before welding, the elements were cleaned by using ethanol and a paper towel. The aluminium flyer was simply cleaned with ethanol and a paper towel, because it will be deformed heavily and with regard to [10], no large impact of further surface preparations can be expected.

3.2 Testing

For testing, the specimens were machined using a wire eroding process with a Fanuc Robocut a-0 to keep the heat input and the mechanical load as low as possible. The preparation is shown in Figure 2. The round edges of the weld seam were cut out to ensure that only fully formed weld seams were tested. Hence, the weld seams have a uniform appearance. The micro section that was cut out is located nearer to the middle of the specimen. This ensures that the micro sections lie in the area of uniform welding parameters for the weld process.

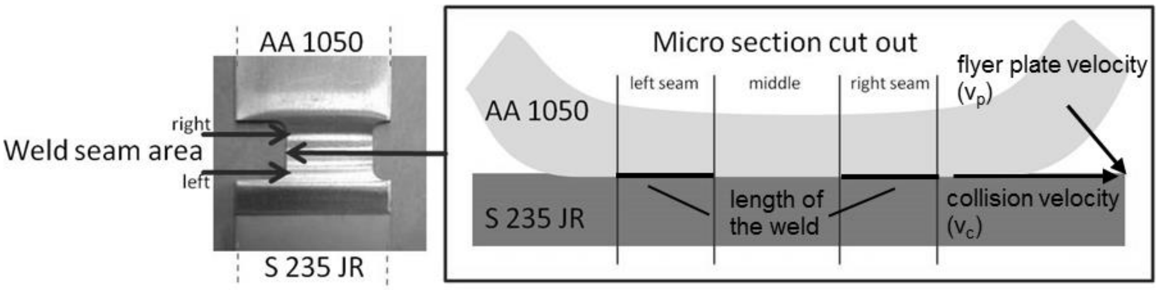


Figure 2: *Specimens' preparation and weld seam denomination*

Tensile tests of the specimens were carried out with a Zwick/Roell Z100 tensile testing machine. The micro sections were ground and polished to a 1 µm finish. Afterwards, a picture of the micro sections was taken with a microscope from Leitz and a CCD camera.

3.3 Magnetic Pulse Welding Process

For the welding process, a PS 48-16 magnetic pulse machine, manufactured by the company pstproducts GmbH, was used. The overall maximum charging energy is 52 kJ with a charging voltage of 16 kV as well as the coil has a web thickness of 5 mm.

The welding parameters were investigated by means of laser-polished surfaces. The charging energy of the machine was varied from 5 to 12 kJ as well as the standoff between flayer and target in 0.5 mm steps from 1.5 mm to 2.5 mm for specimens. The process window was defined by comparison of the reached tensile strength and charging energy.

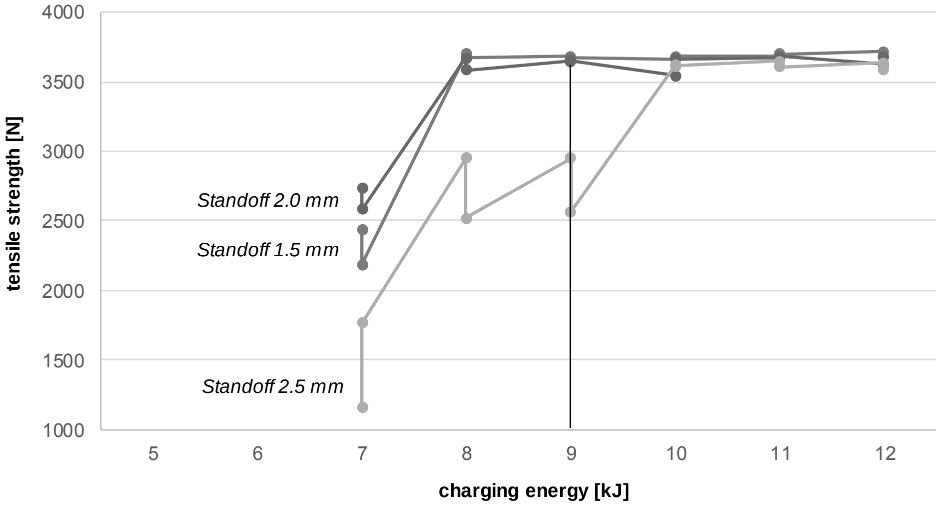


Figure 3: *Magnetic pulse welding process window*

Figure 3 shows the welding process window, which shows that an increasing standoff requires a higher charging energy. The lower standoff was taken, whereby low charging energy could be used for the process. This leads to low impact velocities and thus to small energy inputs into the base material. The charging energy of 9 kJ was selected to ensure welding within and not on the limit of the process window. In sum, the charging voltage was 6,642 kV and the overall circuit frequency of the process was 19.8 kHz. The standoff between flyer and target was 1.5 mm and the charging energy 9 kJ.

4 Experimental Work

4.1 Test of the Weld Properties for a Standard Deviation

First the reliability and reproducibility of the MPW process was investigated. Therefore, 50 specimens with a glass blasted and cleaned surface were welded. The results in Figure 4 show that no reproducible tensile strength and weld length for a carefully glass blasted and cleaned surface can be accomplished. The weld failure stands in no relation to the weld length, hence not only the weld length can be a criteria for the tensile shear strength of MPW bond.

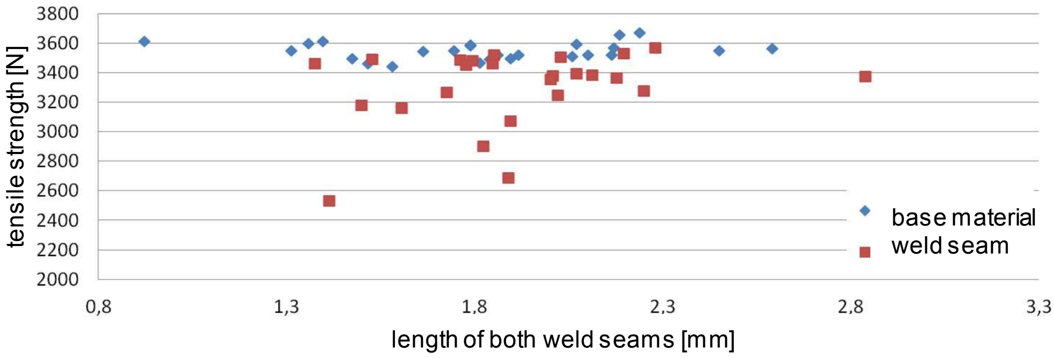


Figure 4: *Relationship between tensile strength, weld length and failure mode*

A Shapiro-Wilk-Test was carried out to test the weld properties for the hypothesis regarding the standard deviation using SPSS-Software by IBM [12]. First, a graphical evaluation of the specimens with histogram, boxplot and Q-Q-Plot was performed, Figure 5.

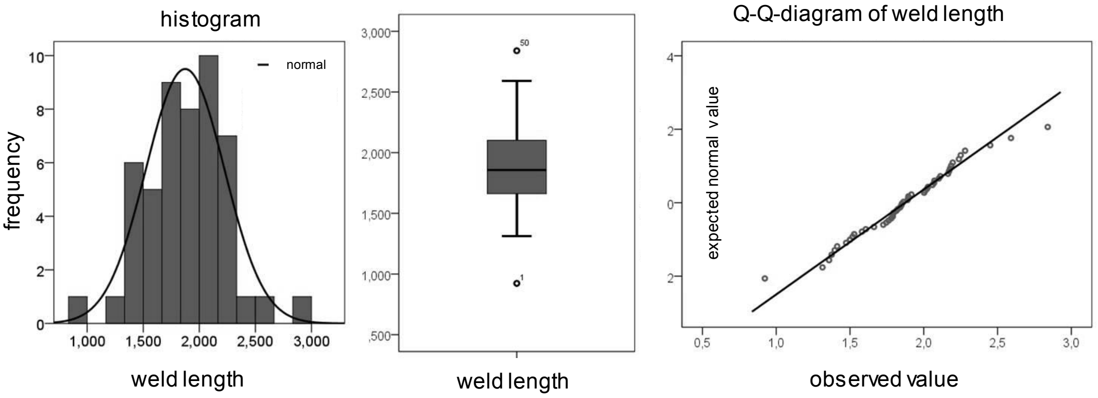


Figure 5: *Histogram, Boxplot and Q-Q-Plot of weld length*

The evaluation showed no signs for a deviation from a standard distribution. Therefore, the characteristics of the distribution can be compared with the characteristics of the standard distribution, Table 2. The comparison of the determined results displayed no significant deviation.

Parameter	Series of Measurements	Standard Deviation
(average value – median) / s	0,05	0
Quartile gap / s	1,30	1,34
Specimens in 1s interval	68 %	68 %
Specimens in 2s interval	96 %	95 %
Specimens in 3s interval	100 %	99,73 %

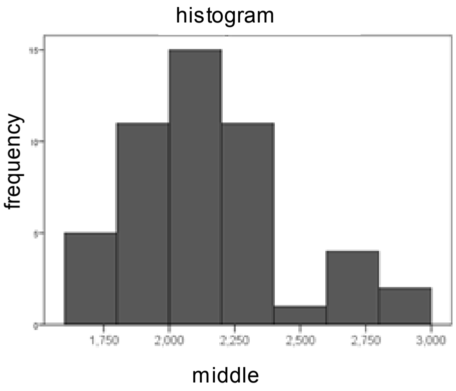
Table 2: *Analysis of weld length and standard distribution*

Based on the observed data, a null hypothesis is given as a result. Hence, the distribution of the weld length corresponds to that of the standard distribution. The significance of the standard distribution was determined with a high quality (low β-error) on the basics of tests for standard distribution and was compared with α-error, Table 3. As an option, a Kolmogorov-Smirnov-Test can be used additionally to the Shapiro-Wilk-Test. However, the Shapiro-Wilk-Test provides better quality for low sample sizes. Therefore the conclusions are based on results from this test. The assumed α-error is set at 5%, as the hypothesis is not true.

Testing procedure	Statistical significance value (α = 0,05)
Shapiro-Wilk	0,738
Kolmogorov-Smirnov	0,93

Table 3: *Tests for standard distribution*

The results of the statistical significance tests show that the values are clearly exceeded. Thus, the null hypothesis cannot be rejected. Furthermore, we can assume that the distribution of the lengths of the weld is a standard distribution and that statistical methods for the evaluation of the weld length can be used. The graphical analysis for standard distribution was also performed for the mid-width. Here, a standard distribution could not be demonstrated. The depiction of the distribution shows a right-skewed distribution, Figure 6.



Statistic

middle

N	valid	49
	lacking	1
Average value		2,14693
Median		2,1222
Skewness		0,825
Standard error of skewness		0,34

Figure 6: *Graphic analysis for normal distribution of the middle width*

This distribution property is equally characterized for the whole length (right weld, middle and left weld). Therefore, median will be used for the evaluation of the middle and the whole length as a benchmark. The figure suggests that there is no linear dependence between weld length and tensile strength. This assumption is confirmed by a correlation calculation. Based on these results, we can assume that the length of weld is always normally distributed.

4.2 Influence of Different Roughness Characteristics

In addition, different surface preparations were applied to the steel parent and in each case 50 specimens were welded, as this was also the aim of the paper. The general appearance of the surface can be seen in Figure 7. The *glass blasted* specimens have the smallest value of average roughness of about 2 µm. The average roughness of both the grinded and *Al_2O_3 (NKF)* blasted profiles are quite similar as they are close to 3 µm. The laser machined surface has the highest average roughness of close to 5 µm.

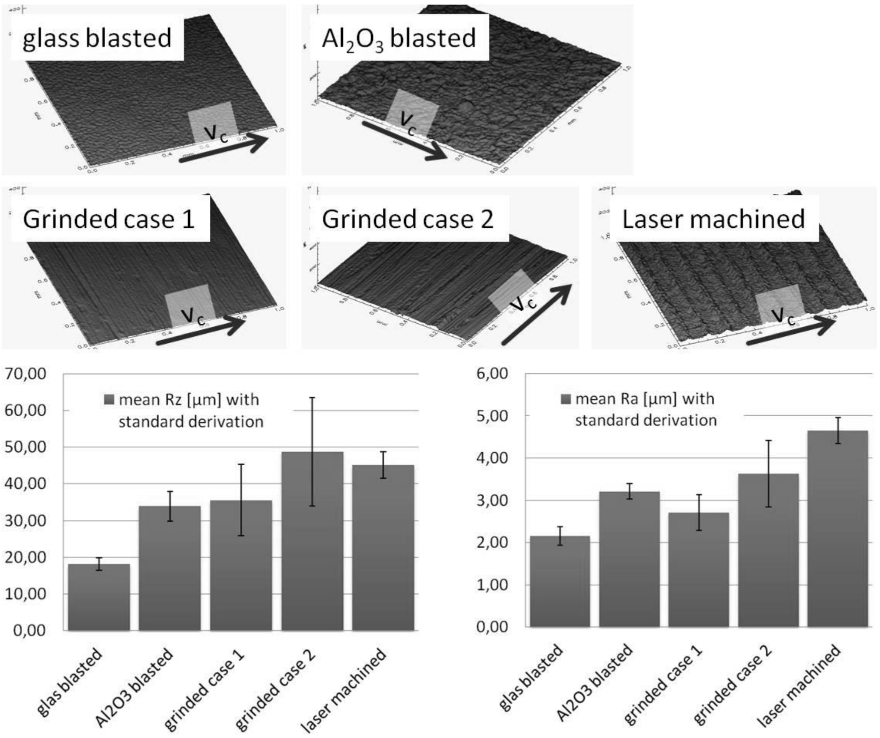
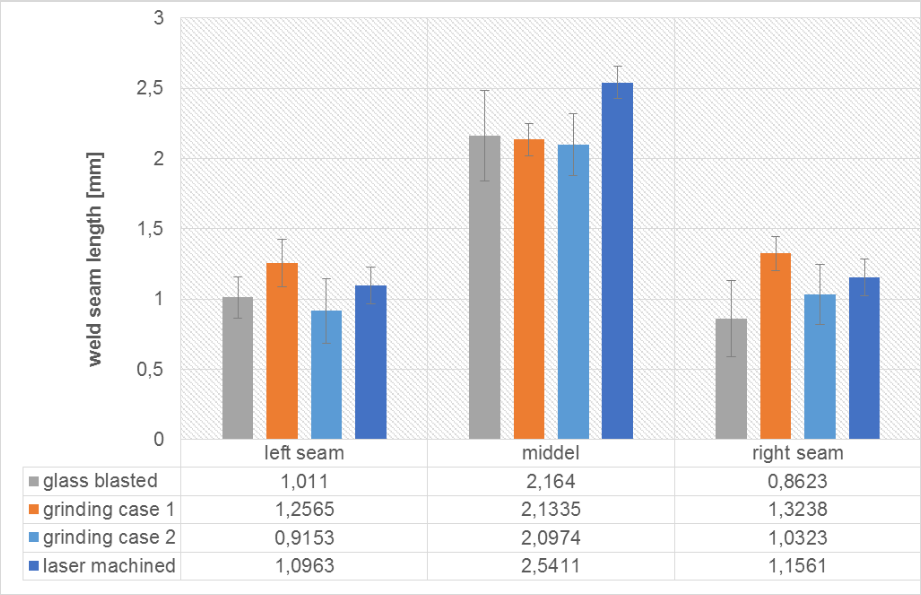


Figure 7: *Surface preparations*

A weld could be accomplished with all specimen preparations, except with the *Al_2O_3 (NKF) blasted* specimen. It was not possible to obtain a weld with this kind of surface. Hence, no metallurgical examination could be done for this specimen.
All other specimens were subjected to a metallurgical examination. The results of the measured weld length can be seen in Figure 8. For glass blasting and *grinding case 2,* the average weld length and the length of the middle section are nearly the same. For *grinding case 1,* the average weld length is approximately 30 % longer. For the laser machined specimen, the weld length is comparable to that of the glass blasted specimen but has a significantly wider middle section.



	left seam	middel	right seam
■ glass blasted	1,011	2,164	0,8623
■ grinding case 1	1,2565	2,1335	1,3238
■ grinding case 2	0,9153	2,0974	1,0323
■ laser machined	1,0963	2,5411	1,1561

Figure 8: *Interface weld length at different surface preparations*

The micro sections give a deeper understanding of the process behavior. When looking closely at the interface, intermetallic phases that occur after obstacles can be detected, especially in the *grinded case 1* and *laser machined* specimen, Figure 9. Furthermore, a wavy appearance, due to the preparation, occurs and hence a mechanical interlocking can be observed. The intermetallic phases are mainly located behind obstacles which were caused by the surface preparation.

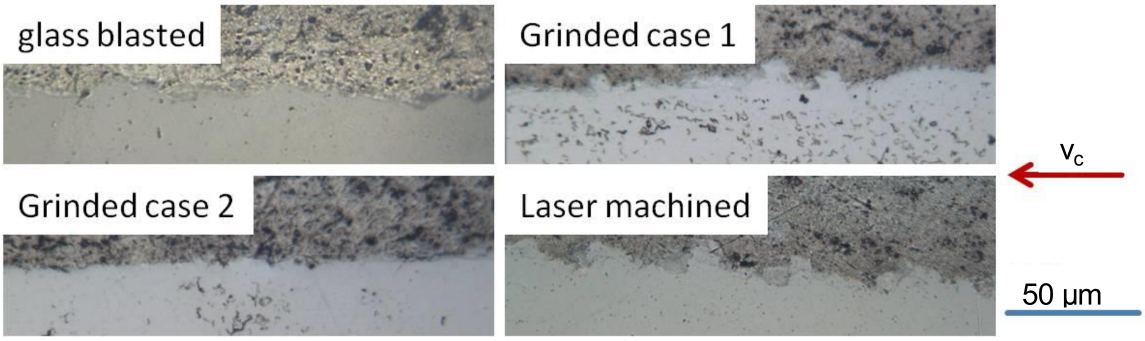


Figure 9: *Micro sections of the weld area for different surface preparations*

In terms of achieved tensile shear strength, both the *grinded case 1* and the *laser machined* surface preparation delivered sound welds with a failure only in the base material. Hence, the results have been very reliable. The glass blasted surface results

were shown previously in Figure 4. The same pattern was achieved for *grinded case 2* surfaces.
As regards the distribution, the macroscopic evaluation of the weld length shows no significant deviation from the theoretical basic value. Thus, we can assume that the average length of the welds in both directions is equal. However, the test showed one difference concerning the equality of variances.

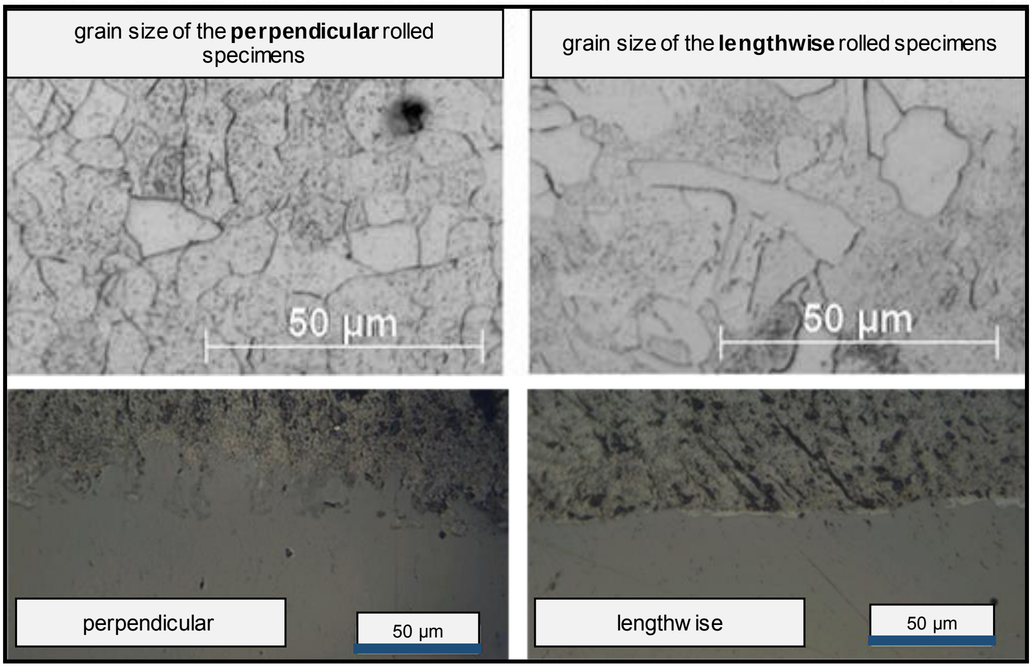


Figure 10: *Joint interface and grain size with perpendicular and lengthwise rolled steel*

The specimens with a perpendicular rolling direction to the collision vector showed a statistically significant lower variance. Thus, the formation of the weld with this specimens´ preparation is reproducible. Despite the equal length of the welds, the perpendicular rolled specimens have a significantly different interface than the lengthwise rolled specimens. For a comparison, two interface micrographs were taken 300 mm from the weld start. The two interfaces are displayed together with the receiving position in Figure 10.

5 Conclusion

As part of the investigation, the process window was defined by varying the parameters. The charging energy of the machine was set at 9 kJ for all specimens. This resulted in a charging voltage of 6.642 kV. The overall circuit frequency of the process was 19.8 kHz. The standoff between flyer and target material was 1.5 mm. In summary, we can state that no linear dependence between weld length and tensile strength is given.
In general, we could show that the surface treatment which is applied before welding with magnetic pulses influences the welding process of aluminium and steel significantly. In regard to the different surface preparations, we could demonstrate that a preparation, which forms uniform obstacles perpendicular to the weld seam, delivers sound welds with a reliable joint quality. The joint quality of these welds is produced by an interlocking of the boundary layer and a significantly longer weld length (up to 30% compared to other preparations, e.g. glass blasting, Figure 8, p.8) of the weld seams.

For the future the main questions that need to be answered are:

- Why do specimens that are prepared perpendicularly to the collision velocity vector have an advantageous behaviour?
- Why is the reliability of those specimens higher?
- Why is the middle sector for the laser machined surfaces bigger in comparison to the other preparation methods and why is this specimen still reliable?

To answer these questions we need to take a closer look at the formation of the weld, with regards to the time dependent behavior of the process.

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