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Influence of Surface Roughness in Electron Beam Welding

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Abstract. The requirements of welded components are rising continuously through increasing demands in engineering. But in engineering not only the quality of welds is important also an economic and timesaving production is crucial. Especially in welding of large cross sections economization potential is existing and significant. Beside the welding technique itself the joint preparation is a major part of work. Electron beam welding has some major advantages in this area. Due the high energy density a very short welding time as well as a small heat affected zone can be achieved. Furthermore the joint preparation can be held simple. Nevertheless, a careful machining and cleaning of the joint surfaces is recommended in literature. In addition to geometric tolerances a specific surface roughness should be kept. These statements are quite general and unspecific. In this contribution a systematic investigation on the influence of joint preparation on the joint properties is presented. By performing several welding experiments with different surface roughness this study provides empirical conclusions. Beside the microscopic investigation of different cross sections and mechanical tests of the welded samples also the process stability during welding was reviewed.

1. Introduction

In many industrial fields, welding is a major part of manufacturing. Welded joints not only have to offer a consistent high quality but they also have to be economic in production. When it comes to large cross sections this fact is becoming even more crucial. Here, welding effort and especially joint preparation can become a major part of production time and cost.

Electron beam welding (EBW) has some mature advantages in welding of large cross section and in joint preparation. Welding is done with a single pass and the joint preparation is, independent of the wall thickness, a simple butt preparation. Hence the surface roughness of the welding faces has to be well considered in view of weld quality and joint preparation time. So far little attention has been paid on to the influence of the SR on the final weld and on the welding process. In literature the statements according the surface texture of the welding surface are quite general or differ widely. Often the surface texture is not even mentioned [1], [2] or the recommendations differ widely. In literature surface preparing suggestions differ from the need of a smooth machined surface [3] up to the statement that a too smooth surface may hinder degassing of the weld [4].

The aim of this paper is to analyse the influence of the surface roughness on the welding process and the final weld quality. For two different wall thicknesses, welding specimens with four different surface roughness values were prepared and welded. The welding process was monitored and microscopic investigations, as well as tensile tests were carried out to examine the welds.

1.1. Electron Beam Welding
Electron beam welding is a fusion welding process where the kinetic energy of electrons is used as heat source. Electrons are accelerated and impact on a work piece with high velocity; when hitting the metal surface, the electrons are decelerated in the material. Thereby the incoming electrons transfer their kinetic energy to the lattice atoms in the workpiece which increases the local temperature immediately [3], [5].

By focusing the EB the energy density of the beam spot can be controlled. At a power density above 10^5W/cm², the deep welding effect occurs. Conduction of heat now is secondary; locally the material evaporates instantly and a steam capillary (keyhole), surrounded by molten metal is established [4], leading to a very small heat affected zone (HAZ).

By applying relative movement between the workpiece and the electron beam the weld seam is formed. EBW offers a very high seam depth to width ratio, which is advantageous especially in thick walled welding [6]. Compared to laser beam welding the EB remains almost uninfluenced by metal vapour or plasma, [7].

However an interaction with the metal vapour, especially when metals with high vapour pressure are welded can happen in the EB gun. This so called arcing is a spark discharging in the electron gun. If too much metal vapour reaches the EB gun a flashover between the anode and cathode can occur. The susceptibility to arcing is given especially at high acceleration voltages and thicker walls. Arcing is also forced when gas pores and impurities in the metal, or dirt on the welding faces lead to small explosions. These explosions send a higher amount of metal vapour to the EB gun.

Depending on the stability of the established arcs, flashovers are distinguished in soft- and hard flashovers. Hard flashovers are characterized by the formation of a non-self-extinguishing arc between parts at high voltage potential and ground. Hard flashovers lead, by activation the overcurrent protection, to an immediate interruption of the welding process, and therefore mostly irreparable welding defects. Soft flashovers have a self-erasing arc and have less intensity. They are mostly established between the beam source and the Wehnelt (bias) cylinder. They cause a short term current change in the electron beam and may cause welding defects [3], [8], [9]. The higher the acceleration voltage, and the more pores and contaminations are in the material and at the welding faces, the more likely flashovers can happen.

1.2. Surface roughness
Surface roughness is a component of surface texture. It is quantified by the deviations in the direction normal of a surface from its ideal form. Surface roughness is a sort of shape deviation and according to DIN 4760 the macroscopic surface roughness can be subdivided to 3rd order roughness and 4th order roughness.

Roughness can be measured as a surface profile with a profilometer. For the detection and classification of the surface roughness various parameters are available. For technical usage typically the mean roughness index Ra, expressed in microns, is used. Ra is the mean deviation of the roughness profile and is defined as "the arithmetic average of the absolute values (y_i) of the profile height deviations from the mean line, recorded within the evaluation length" [11].The Ra index is represent the combined 3rd and 4th order surface deviation.

$$Ra = \int_0^1 |y|_i \times d_x \qquad (1)$$

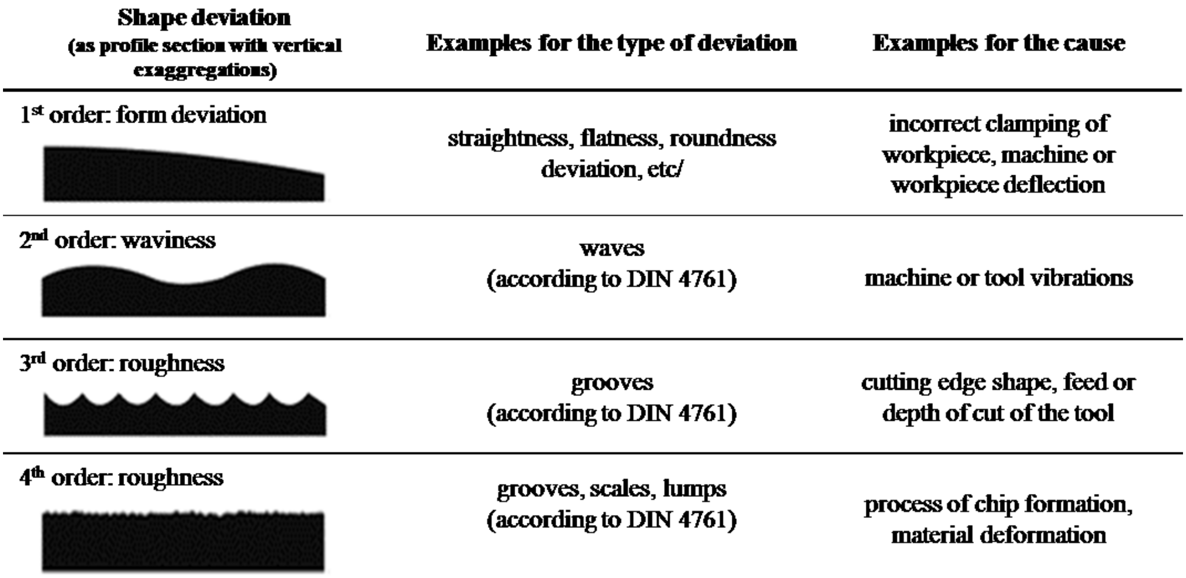

Figure 1. Classification of shape deviation (DIN 4760) [10]

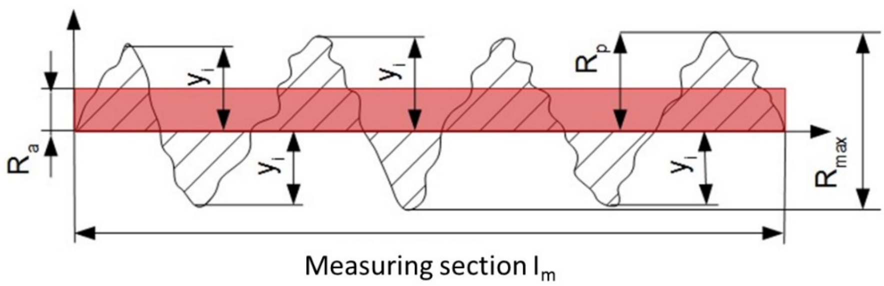

Figure 2. Geometrical illustration of Ra [11]

Every machining operation leaves a characteristic surface texture depending on the machining process, the type and shape of the cutting tool and the chip formation. In the following table the surface roughness values are connected to the milling processes. A milling operation with a higher cutting efficiency usually produces a higher surface roughness.

Table 1. Surface roughness values of different milling processes

Ra (µm)	Milling operation
12.5	Pre roughing
6.3	Roughing
1.6	Finishing
0.8	Superfinishing

2. Experiments

In the following subchapters the used material, welding equipment, specimen setup and investigation methods are described.

2.1. Material
For the experiments a stainless soft martensitic steel X3CrNiMo13-4 (1.4313) was used. Its application is wide spread in hydraulic engines, turbines and naval engineering. The chemical composition is given in Table 2. The tensile strength in tempered conditions (tempering temperature 550 – 600°C) is between 780 and 980 MPa [12].

Table 2. Composition X3CrNiMo13-4

C	Si	Mn	Cr	Mo	Ni	N
< 0.029	0.40	0.85	13.00	0.55	4.20	0.04

2.2. Welding setup
For investigation, weld samples with a plate thickness of 20mm and 100mm were used. The samples were prepared as butt welds and welded in PA position (1G flat position, according to ISO 6947) without preheating. For welding the 100mm samples a metal backing was used to prevent the weld pool of fall trough. Welding was carried out with a probeam universal chamber machine, equipped with a 45kW EB-gun. Optimal welding parameters were determined in prior experiments. The welding surfaces of the specimen were face milled to the defined surface roughness. For every mean roughness index and plate thickness three samples were welded. The experimental matrix is shown in Table 3. Before welding the welding surfaces were brushed with a stainless steel brush and subsequently cleaned with an isopropanol soaked industrial wiping paper.

Table 3. Experiment Matrix

Plate thickness (mm)	Surface Roughness Ra (µm)
20mm	12.5 / 6.3 / 1.6 / 0.8
100mm	12.5 / 6.3 / 1.6 / 0.8

2.3. Investigation Methods
The welding process was recorded with an inbuilt CCD camera to determine the process stability.
Several micro sections were taken and investigated by means of light microscopy to check the weld on defects. The micro sections taken can be seen in Figure 3. The arrows mark the examination surface. Additionally for every thickness and surface roughness, one longitudinal section of the whole weld was produced. Therefore the welded samples were cut alongside the weld and the longitudinal section was grinded till the weld centreline. Cross tensile test where carried out for basic characterisation. Tensile test were performed according to DIN50125, specimen geometry B with 8mm diameter. The specimen removal positions are marked in Figure 3.

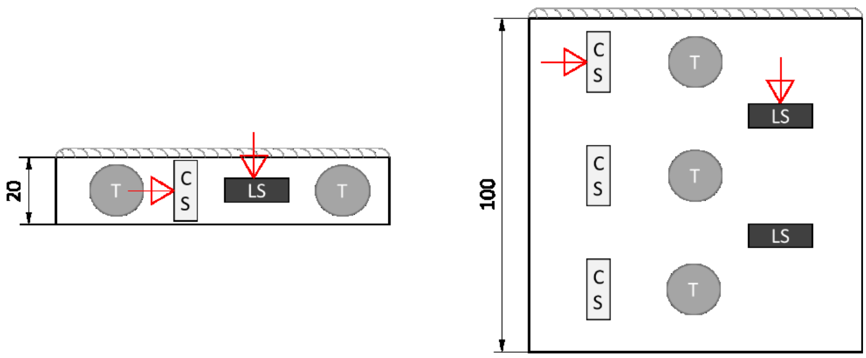

Figure 3. Position and amount of micro sections an tensile specimen; T- tensile specimen, CS-cross section, LS- longitudinal section

3. Results

This chapter is sub divided in macroscopic and microscopic investigation of the weld seam. Followed by the subchapter presenting the results of the tensile test and the observations of the welding process.

3.1. Macroscopic Pictures

For every surface roughness and thickness a longitudinal and two cross sections were made (Figure 4 to Figure 7). No macroscopic visible defects were found at any specimen. The microstructure in the weld centre line shows dendrites in front view with no irregularities. The cracks which can be seen at the end in the 100mm specimen (Figure 5) occurred due to a too short slope out procedure. The cross-sections offer no macroscopic defects, when an arcing free process was carried out.

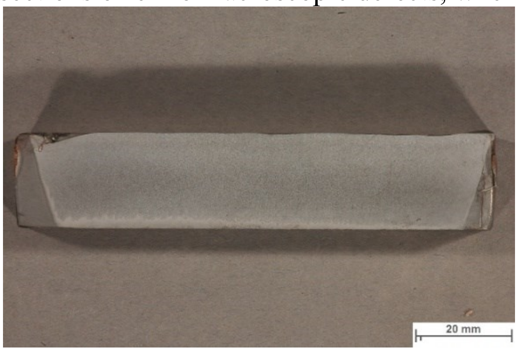

Figure 4. Longitudinal-section 20mm

Figure 5. Longitudinal-section 100mm

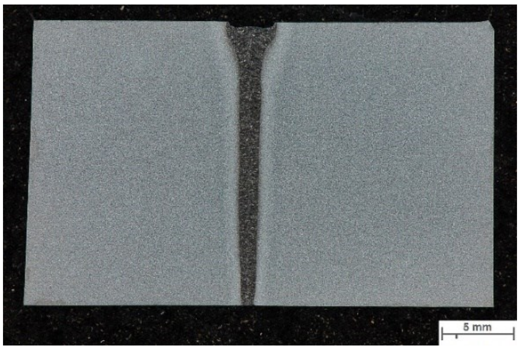

Figure 6. Cross-section 20mm

Figure 7. Cross-section 100mm

The 20mm weld was made without backing, so a root formation was necessary. The specimens with a surface roughness of Ra 12.5 show a distinctive undercut at the weld face. Figure 8 shows two half cross sections to compare the undercut of the Ra12.5 to the other SR values, represented by Ra1.6. The SR values Ra6.3 and Ra0.8 provide the same shape as the Ra 1.6 (right side in Figure 8).

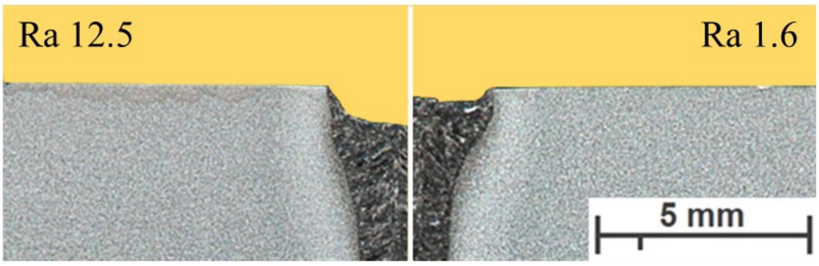

Figure 8. Undercut for different SR values

3.2. Microscopic Pictures

28 microscopic sections were investigated by means of light microscopy. For no specimen a remarkable increased porosity was found. Some welds showed pores whereas other welds did not. A correlation of porosity to surface roughness could not be discovered. The following two figures show an example for a seam with pores (Figure 9) and a seam without pores (Figure 10). Pores found in the weld seams did not exceed a size of 20µm.

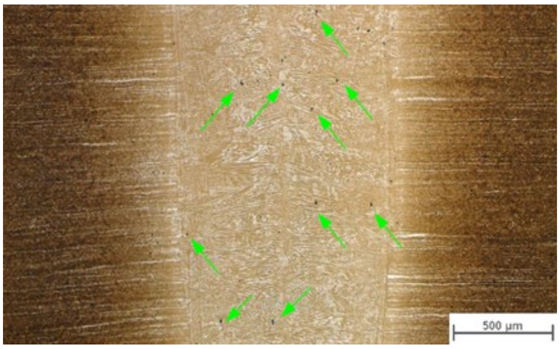

Figure 9. 20mm weld, Ra0.8, pores visible

Figure 10. 20mm weld, Ra6.3, no pores visible

3.3. Tensile Test

All tensile specimen ruptured in the base material. The tensile strength is conform the material data sheet and identical for all surface roughness values with the same wall thickness. No distinctive variation in tensile strength for the 100mm top, middle and bottom tensile specimen occurred. The 20mm specimen have an approximately 30MPa higher tensile strength compared to the 100mm specimens. The two Ra12.5 20mm specimen have about 2mm less nominal strain. In Figure 11 and Figure 12 the stress-strain diagrams are shown.

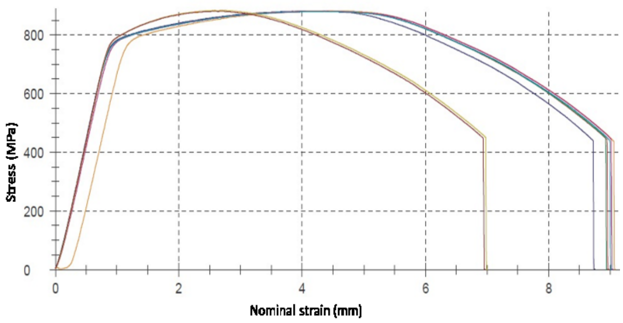

Figure 11. Stress strain curves 20mm specimen

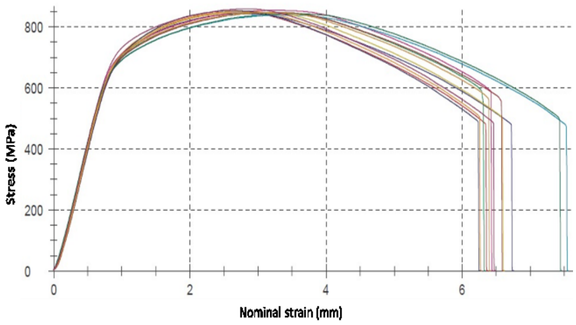

Figure 12. Stress strain curves 100mm specimen

3.4. Welding Process

The welding process, when welding the 20mm samples, was stable. No influenced by the different surface roughness values was given. When welding the 100mm thick parts the process become more prone to arcing due to the higher amount of metal vapour. Welding the 100mm specimen with Ra0.8, and Ra1.6 surface roughness, no flashovers occur. While welding the Ra6.3 specimen, one soft flashover occurred but no welding defect was found in the weld. For the Ra12.5 specimens several soft flashovers happened during the welding procedure. One high intense flashover forced a small explosion in the keyhole and led to a major ejection of liquid material. In Figure 13 the stable keyhole can be seen just before the spark over. Figure 14 shows a short term beam breakdown, caused by this high intense flashover, and the resulting spattering. This specimen, revealed a cavity in the weld centre at the position of this flashover (Figure 15). No hard flashovers occurred at any specimen.

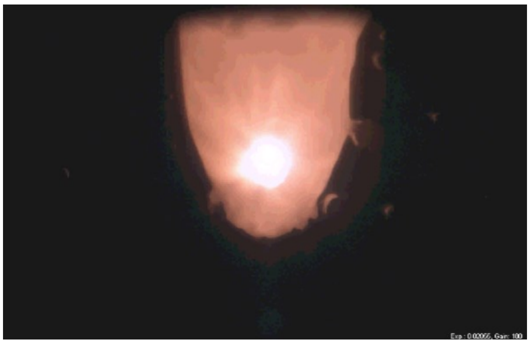

Figure 13. Stable Keyhole

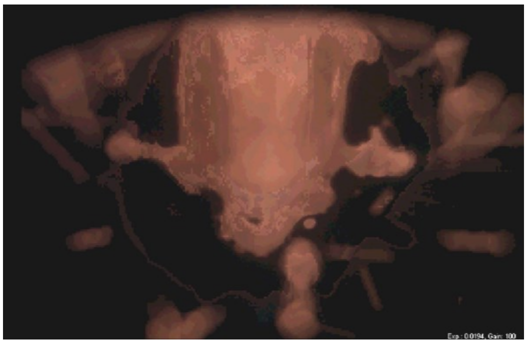

Figure 14. Flashover, with broken down keyhole and spatter formation

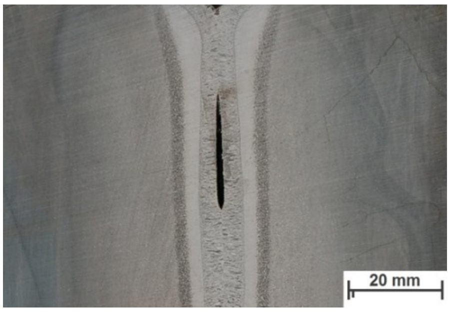

Figure 15. Welding defect based on the soft flashover shown in Figure 14.

4. Summary and Conclusion

The influence of roughness on the joint quality for 20 and 100mm electron beam welds of steel 1.4313 was systematically investigated.

It was observed, that the surface roughness directly has only a minor influence on the weld seam quality of electron beam welds. A direct influence was just observed for welded 20mm plates. For this wall thickness a distinctive undercut at the weld face was observed. This may happen due to the wider gap (missing volume), which exists when surfaces with high roughness are placed together. A difference in porosity or in tensile strength could not be observed. However, a major influence, is that surfaces with a higher roughness are harder to clean accurately and a not properly cleaned surface may lead to arcing during the process. This is especially the case for welding thick walled parts.

The results of this work may be summarised as follows:

- Surface roughness has no effect on the tensile strength of the weld
- For the investigated surface roughness values, no difference in the porosity of the weld was recognised
- When welding 20mm plates in full penetration technique, a higher surface roughness caused a distinctive undercut
- A higher surface roughness lead to arcing during welding the 100mm specimens. No arcing occurred during welding the 20mm specimen

The following conclusions can be drawn from this investigation

- Cleaning of the welding surface is a crucial point. Surfaces with a rougher surface texture are harder to clean. Due to an insufficient cleaning a contaminated surfaces can cause arcing.
- Producing an “easy to clean” surface is more important than the roughness itself.

- A suitable milling surface roughness for electron beam welding is between Ra1.8 and Ra6.3. For a wall thickness where full penetration welding is carried out a low surface roughness (Ra1.8) is recommended to avoid severe undercut.

5. Outlook
This paper provides a recommendation for the surface preparation for electron beam welding. However, some question remain unanswered and will be investigated in ongoing work.
It has to be considered that these investigations are limited to face milled surfaces, future research will be done on surfaces produced with different processes (grinding, sawing). Additional research will be required to cover the influence of the 1st and 2nd order shape deviation. To analyse the influence on toughness, Charpy V-notch tests should be carried out.
Concerning the process, the acceleration voltage will be added as a subject of investigation. By using a lower accelerating voltage arcing may be reduced for specimens with high surface roughness.

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