Influence of Mandrel's Surface on the Mechanical Properties of Joints Produced by Electromagnetic Compression*

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Abstract

Electromagnetic compression of tubular profiles with high electrical conductivity is an innovative joining process for the manufacturing of lightweight structures. Taking conventional interference fits into account, the contact area's influence on the joint's quality seems to be of significance, as e.g. the contact area and the friction coefficient between the joining partners determine an allowed axial load or torsional momentum proportionally. Therefore, different contact area surfaces were prepared by shot peening and different machining operations and strategies. The mandrel's surfaces were prepared by shot peening with glass beads and Al_2O_3 particles. Alternatively, preparation was done using simultaneous five axis milling, because potential joining partners in lightweight frame structures within the Transregional Collaborative Research Centre SFB/TR10 would be manufactured similarly. After that, the manufactured surfaces were characterized by measuring the surface roughness and using confocal whitelight microscopy. After joining by electromagnetic compression, the influence of different mandrel's surface conditions on the joint's mechanical properties were analyzed by tensile tests. Finally, conclusions and design rules for the manufacturing of joints by electromagnetic compression are given.

Keywords

Electromagnetic compression, Joining, Shot peening, Milling

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1 Introduction

One major objective of the Collaborative Research Center SFB/TR10 is the flexible and competitive production of frame structures, which fulfill the condition of lightweight constructions as structural parts, cabins or chassis frames. To achieve this common aim, the application of innovative joining technologies as well as joining strategies are necessary. Joining by electromagnetic forming (EMF) as a cold joining process is an attractive alternative solution compared to conventional welding or riveting processes [1]. Targeting the introduction of joining by electromagnetic compression into a manufacturing process chain, the joining process, pre-stages, and post-stages of production have to be taken into account. For example, previously raw or semifinished parts can be used after manufacturing as connecting elements (nodes) in order to assemble tubes to frame structures. They are mandatorily machined before joining by e.g. milling processes. As the shape of the nodes is usually very complex, the machining procedures may be done by simultaneous five-axis milling. The milling of lightweight aluminum nodes and the preparation of areas for joining described require adequate milling strategies in order to be efficient and to manufacture a high quality product. Moreover, the quality of the surface layer results from the chosen milling strategy and its parameters, taking e.g. cutting tools, cutting rate and feed rate into account. In turn, the resulting surface characteristics influence the mechanical properties of the joint as known from manufacturing conventional interference fits. Consequently, the influences of the surface on the mechanical properties of joints manufactured by electromagnetic compression were investigated, characterizing the surface by the average surface roughness and by scanning electron microscope (SEM).

2 Joining by Electromagnetic Compression

As the energy density of a pulsed magnetic field is used for the contact-less forming of a workpiece, the resulting deformation is closely related to the electromagnetic properties. The process model (Figure 2) can be described as an oscillating circuit which includes the capacitor *C*, the resistance *R*, and the inductance *L* of the pulse generator as well as the consumer load consisting of tool coil (solenoid) and workpiece (tube). After the capacitor bank has been charged it is suddenly discharged by the closing of a high current switch. As a result, a damped oscillating current flows through the coil, generating a corresponding magnetic field. According to Lenz's law, a current in the workpiece is induced flowing in the opposite direction to its cause. Due to the skin effect, the current and the magnetic field penetrate the workpiece wall in the course of the process progresses. The resulting pressure pulse acts orthogonally on both the field strength and the induced current, i.e. in a radial direction on tube and tool coil, as shown in Figure 2 [2].

In contrast to quasi-static forming procedures the pressure pulse in EMF causes high strain rate effects in the formed material [4]. The resulting magnetic pressure $p(t,r,z)$ is determined by the energy density of the magnetic field outside H_a and inside H_i of the workpiece and can be calculated on the basis of the measured coil current as described in detail in [2].

$$p(t,r,z) = \frac{1}{2} \cdot \mu_0 \cdot \left(H_a^2(t,r,z) - H_i^2(t,r,z) \right) \tag{1}$$

If the yield strength of the tube is exceeded, a permanent reduction of diameter occurs.

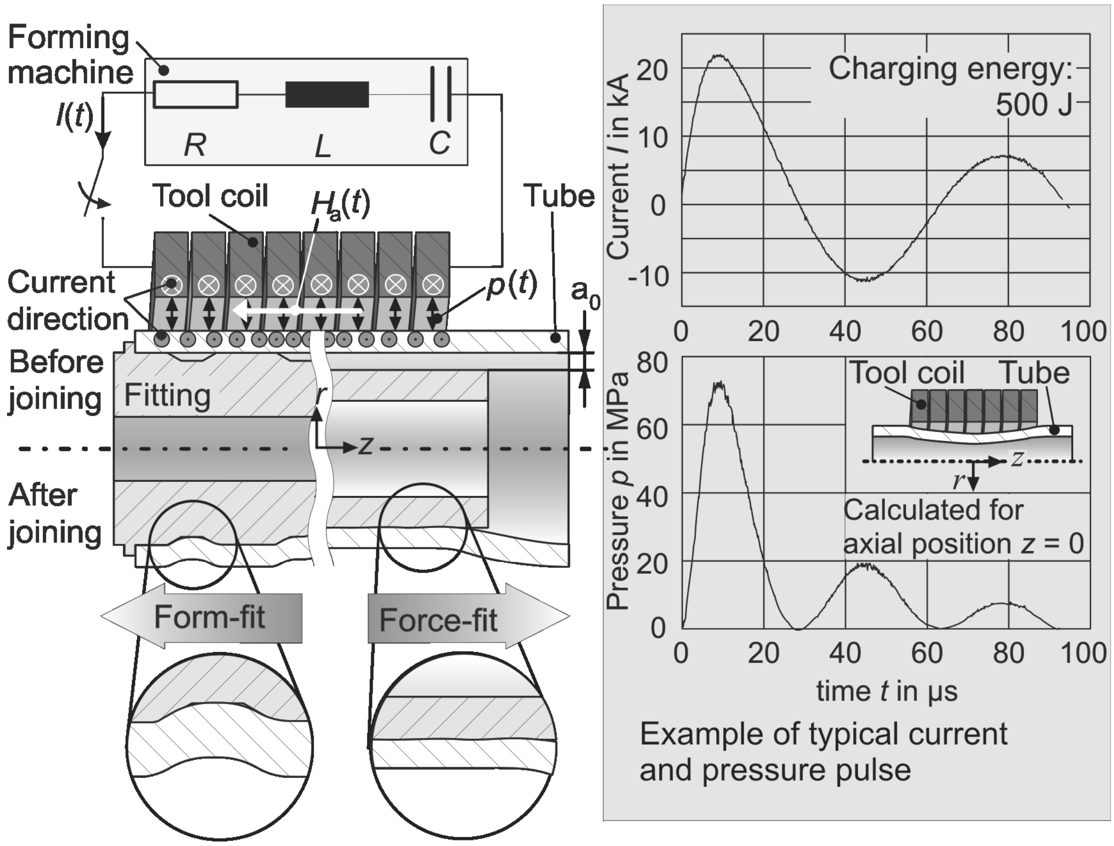


***Figure 1**: Process principle of joining by electromagnetic compression with a directly acting tool coil*

At the same time as electromagnetic compression can be used for forming, joining operations are feasible as well. In general, joints produced by electromagnetic tube compression can transmit forces by dominating force-fit or dominating form-fit. Moreover, if a very high specific energy is supplied a so called magnetic pulse welded connection can be produced as well [4,5].

As described in detail in [6], the constriction velocity of a tube being compressed as well as its mass determines the kinetic energy at the moment of impact and therefore the force which acts on the mandrel. Assuming a massive mandrel, during this deformation process the tube is deformed plastically and the mandrel's deformation remains purely elastic. During the decrease of the forces, a corresponding elastic relaxation of mandrel and tube occurs. If a full relaxation of the mandrel is prevented by the tube, a permanent pressure in the joining area (in the radial direction) is established [7]. This pressure is a balanced condition on the one hand of the mandrel's stress relief, and on the other hand the resulting interference fit (caused by the elastic recovery of the mandrel) in the tube. The strength of interference fits manufactured so far strongly depends on the area of the contact zone, the friction coefficient, and the remaining residual stresses in the contact zone. The last depend on material parameters like yield point and Young's modulus [8] as well as on the geometrical stiffness of the parts to be joined [9]. In Figure 4, the influence of the compression velocity (determined by the charging energy) on the strength of the joints is presented.

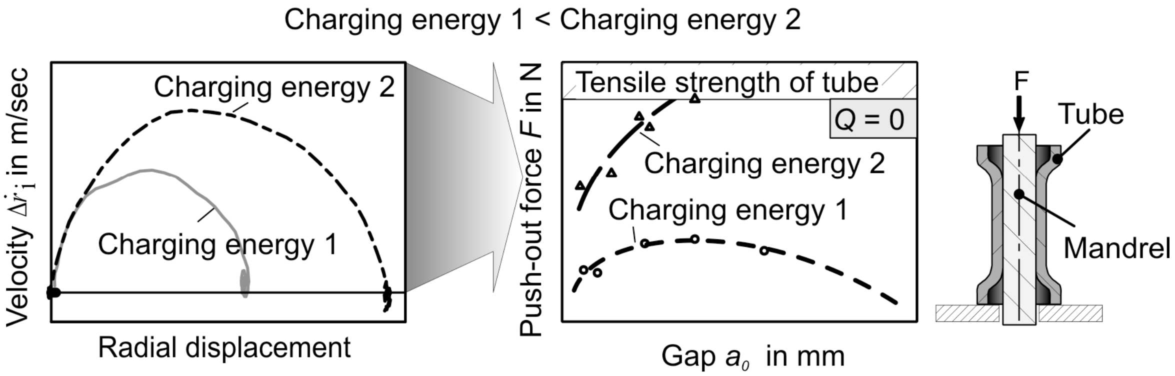


***Figure 2**: Principle of joining by electromagnetic compression*

3 Manufacturing and Testing of Joints

3.1 Preparation of Joining Partners

The material of both tube and mandrel was made of AA6060. The outer diameter of the tube was 20 mm with a wall thickness of 1 mm. The gap between tube and mandrel was 1.2 mm. Since the influence of the mandrel's surface on the mechanical properties of joints was intended to be analyzed, the mandrel's topography was first modified by shot peening or by milling. Then, the specimens were joined with tubes by electromagnetic compression.

The preparation of surfaces for electromagnetic forming was done by five-axis CNC machining on a Deckel-Maho milling machine (DMU 50 Evolution). This multi-axis machining set-up was chosen to provide a flexible possibility for an efficient process of manufacturing lightweight components and to fulfill the requirements of geometric accuracy and a high surface quality. The main importance was to create a reproducible roughness in a flexible finishing process. The NC-data were generated by a common CAM-system as used for the manufacturing of complex parts like dies and moulds. During these surface finishing processes, high process forces as they occur in the machining of hard and hardened materials [10] were not expected, so that a deformation of the specimen could be excluded. Although the mandrels could have been turned, milling finishing strategies were chosen because they are necessary to be integrated within the manufacturing process chain of a node with several extends for adapting. Figure 3 shows the principle of milling a surface. There are two different basic ways of structuring a surface of a joining zone. The macro-structure allows the profile to fit into the structured areas of a mandrel or a node, to increase the strength of the connection. The micro-structure/surface roughness is important for a grouting between the inner and the outer part. Although the transition between both types of surface characteristics is smooth, a measurable surface roughness (e.g. smaller than 50 µm) and a structure which can have the form of a groove or a pocket and a visible depth (e.g. greater than 0.05 mm), can be distinguished. Both factors have a particular influence on the strength of an electromagnetically joined connection. While the microstructure, according to the influence on the friction and the transferable tangential stress between both joining partners, leads to a more force-fit based connection, macrostructured elements offer a high potential to increase the form-fit. To reduce the complexity of the workpieces for basic research, the relevant joining part of the node is substituted by a simple mandrel. The use of standard tools is inevitable for a later adaption of a flexible and efficient manufacturing of a complete node. Ball end mills with a diameter of 6 mm with a coating that reduces the adhesive behavior of the ductile aluminum alloy were used to cover a wide range of micro- and macro-structures with process-safe strategies. The main difficulties in a simultaneous machining of the mandrels segment are similar to those in the machining of cavities in dies and moulds [11]. Collisions between the tool or the tool holder and the workpiece need to be avoided and, therefore, the range of angles of inclinations which also depend on the length of the tool and the geometry of the tool holder has to be chosen carefully. Oscillations that can occur due to the length and thinness of the mandrels and the appearing process forces during milling were reduced to a minimum within an area that was not used for the joining process by choosing a minimum length when clamping the mandrel.

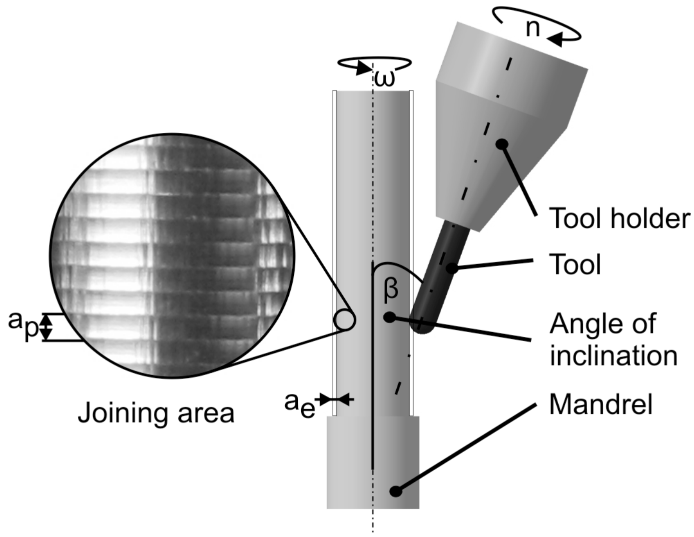


Figure 3*: Principle of milling the mandrels*

For the alternatively used shot peening process, a micro peening device (IEPCO Peenmatic 770), an Al_2O_3 shot with a mean diameter of 20 - 30 µm (EKR 320 A), and glass beads with a mean diameter of 20 – 30 µm (MS 550 B) were applied. In addition, the shot pressure was varied from 0.5 up to 1.5 bar. A 10 mm distance to the surface as well as a feed of 0.5 mm/s were kept constant [12].

3.2 Joining by Electromagnetic Compression

The forming machine SMU1500 with a maximum charging energy of 1.5 kJ was used for joining by electromagnetic compression. At first, joining was done preliminarily with charging energies of 0.9 kJ, 1.1 kJ and 1.5 kJ, to determine adequate process parameters for force-fit joining. The measured current and the calculated magnetic pressure for the mentioned charging energies are indicated in Figure 4.

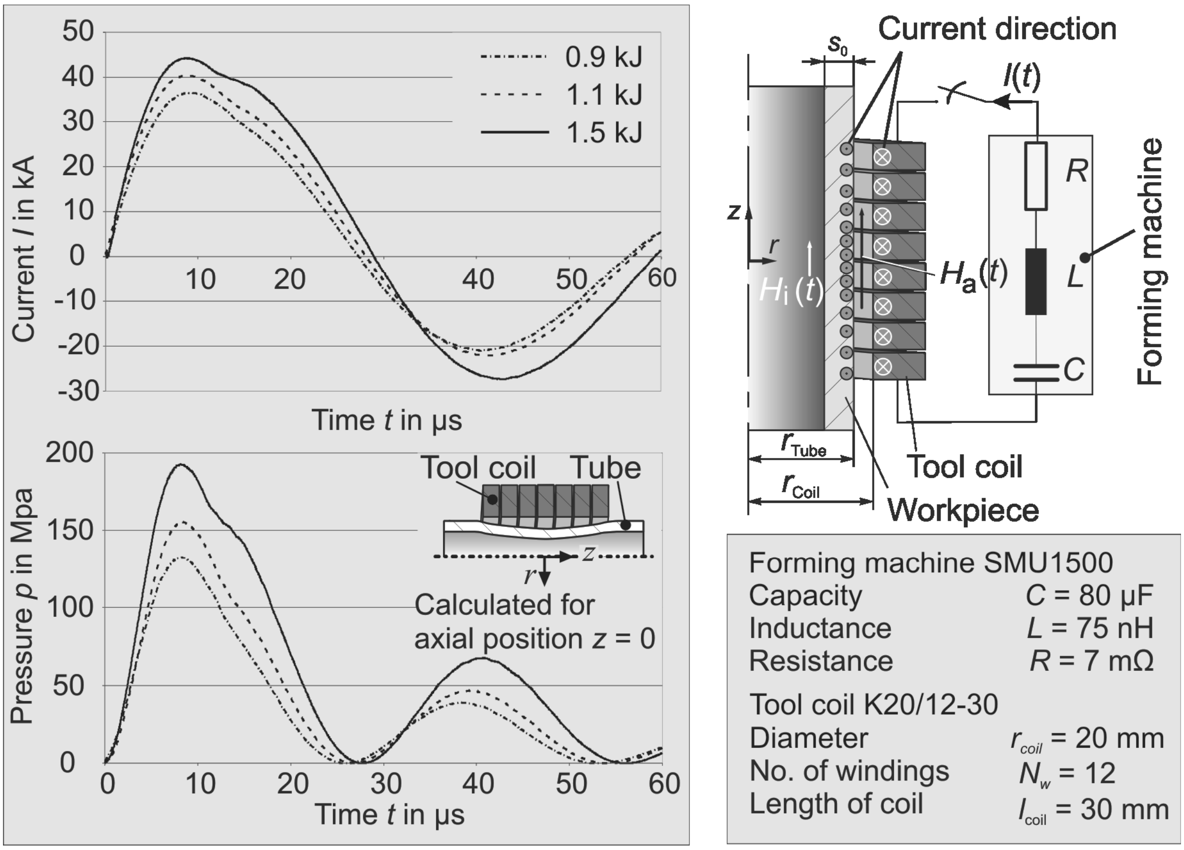


***Figure 4**: Experimental set-up for joining by electromagnetic compression*

The experimental setup for joining was built up of a tool coil and a guiding device with an expandable mandrel for clamping the tube at a top crossbar and a mounting with a corresponding standard fit to the joining partner (mandrel) at a bottom crossbar. The alignment of toolcoil to the specimens is provided by gimbal-mounting the guiding device to the machine.

3.3 Characterization of Joining Partners and Joint

In order to analyze the influence of the mandrel's surface on the mechanical properties of the joint, the initially turned surface was altered by shot peening or milling. The strength of the joints was determined by tensile tests using a universal tensile testing machine Zwick 1478 with a maximum force of 100 kN. The crosshead velocity during tensile testing was adjusted to 2 mm/min. The quantities measured were force and strain, in both axial and tangential direction in the joining area, using strain gauges. In addition, light optical microscope and scanning electron microscope (SEM) investigations were done to characterize the interface between tubes and mandrels after shot peening or milling and before joining.

4 Experimental Results

4.1 Surface Characterization before Joining

Fig. 5 shows the average surface roughness as a function of the shot pressure for both shot media. The mandrel's roughness is strongly increased by peening at small shot pressure already. Beyond 0.5 bar the influence of shot pressure on the surface roughness is rather small. This behavior can be observed for both shot media.

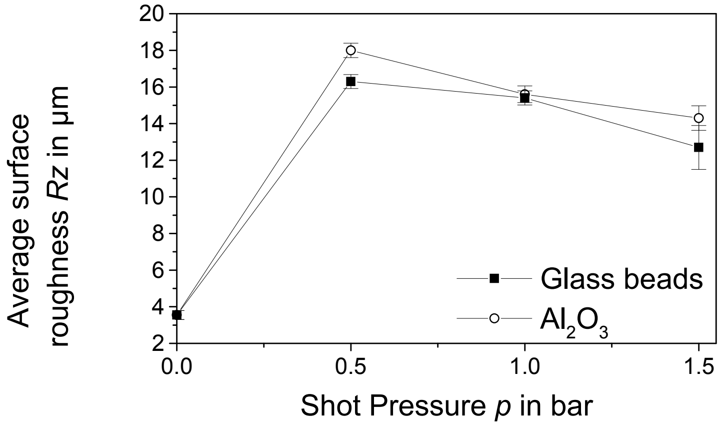
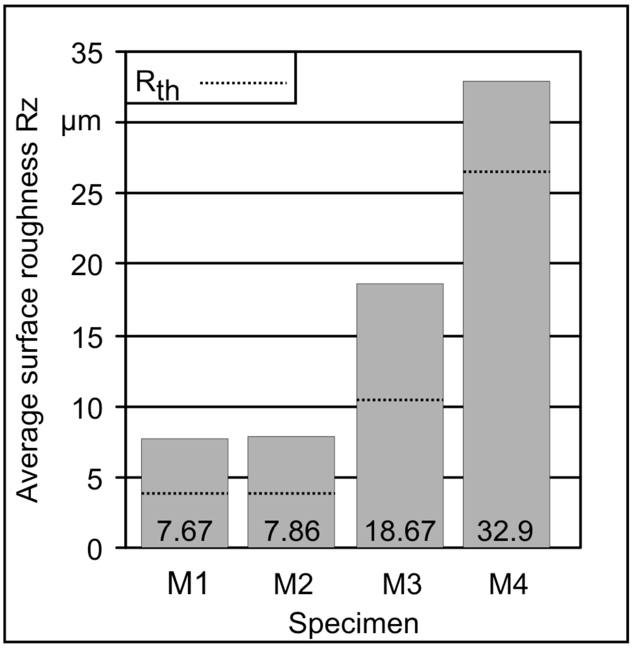


***Figure 5**: Average surface roughness depending on shot peening pressure and media*

The milling process parameters were chosen according to the findings of several experiments about manufacturing surfaces for products made of AA6060. A helical tool path along the mandrel was chosen in order to avoid marks that appear in strategies that work with a constant z-level movement of the tool. Moreover, this strategy is more time efficient and guarantees a more constant surface quality, because infeed movements and toolpaths without cutting are reduced to a minimum. The milling process was done without any lubrication, which is more ecological, but increases the risk of adhesive aluminum being stuck within the small chip flutes of the tool. Figure 6 shows four sets of milling parameters exemplarily chosen and the resulting average surface roughnesses in comparison to the theoretically feasible values. The determining factor for the theoretical surface roughness is the line width or axial depth of cut (a_p) of the process. The theoretical roughness can easily be calculated with the knowledge of this line width (b_r) and the diameter of the tool (D_k).

$$R_{th} = \frac{D_k}{2} - \sqrt{\frac{D_k^2 - b_r^2}{4}} \qquad (2)$$

The real measurements differ due to the varying engagement conditions along the cutting edge. Therefore, the following parameters prevent an exact allocation of the single influencing factors: change of cutting speed from center of the ball end mill to the shaft of the tool, the different initial oversizes before the finishing process allowing the variation of the radial depth of cut a_e, and the different radii of the cutting edge which especially have a high influence at minor axial depths of cut [13]. This leads to the conclusion that for the provision of a reproducable roughness for joining areas within a narrow range, the really occurring average surface roughnesses have to be measured. Even for greater line widths, when the theoretical surface roughness approaches the real measured values, the calculated factors cannot be used as a basis for a prediction.



Material:	EN-AW 6060 (AlMgSi0,5)
Tool:	Ball-end mill, D = 6 mm
Coating:	TiAlN
Strategy:	Simultaneous 5-axis finishing

M1	
Cutting speed:	v_c = 300 m/min
Feed rate:	f_z = 0.1 mm
Angle of inclination:	β = 15°
Axial depth of cut:	a_p = 0.3 mm
Rad. depth of cut:	a_e = 0.1 mm
M2	
Cutting speed:	v_c = 300 m/min
Feed rate:	f_z = 0.05 mm
Angle of inclination:	β = 15°
Axial depth of cut:	a_p = 0.3 mm
Rad. depth of cut:	a_e = 0.3 mm
M3	
Cutting speed:	v_c = 300 m/min
Feed rate:	f_z = 0.05 mm
Angle of inclination:	β = 15°
Axial depth of cut:	a_p = 0.5 mm
Rad. depth of cut:	a_e = 0.1 mm
M4	
Cutting speed:	v_c = 300 m/min
Feed rate:	f_z = 0.05 mm
Angle of inclination:	β = 30°
Axial depth of cut:	a_p = 0.8 mm
Rad. depth of cut:	a_e = 0.2 mm

***Figure 6**: Average surface roughness depending on milling parameters*

It can be seen that the differing oversizes between the mandrels of the first series (M1) and the mandrels of the second series (M2) have no influence on the resulting average surface roughness. The measured data above represent the roughnesses of different mandrels manufactured in each case with the same parameters and within the same clamping as those used for joining. The difference of 0.19 µm is within the variation of different measurings of the tactile roughness measuring system that was used (Mahr Perthometer) and is insignificant. While the specimen of the series M3 represents a medium roughness, M4 expresses, on the one hand, the maximum roughness that can be manufactured with the chosen tools and process parameters and, on the other hand, a smooth transition to a macrostructured surface and, therefore, the upper end of a microstructured joining area. After manufacturing, the mandrels were electromagnetically joined with the tubes and the properties during tensile loading were tested.

4.2 Analysis of the Mechanical Properties of the Joints

Taking preliminary joining into account, two typical characteristics occurred during tensile testing, as shown in Figure 7 a + c. In Figure 7 a, the force increases and then suddenly drops. After that, the tube starts to slip off the mandrel showing a typical seize effect. Consequently, the pull-out force increases again until the tube is pulled off the mandrel [14]. The mandrel's surface of force-fit joints showing seizing in tensile tests is shown in Figure 7 b. In Figure 7 c, the force shows a straight increase until plastic deformation of the tube occurs, which finally leads to an abrupt fracture of the tube in the area next to the joining area as shown in Figure 7 d.

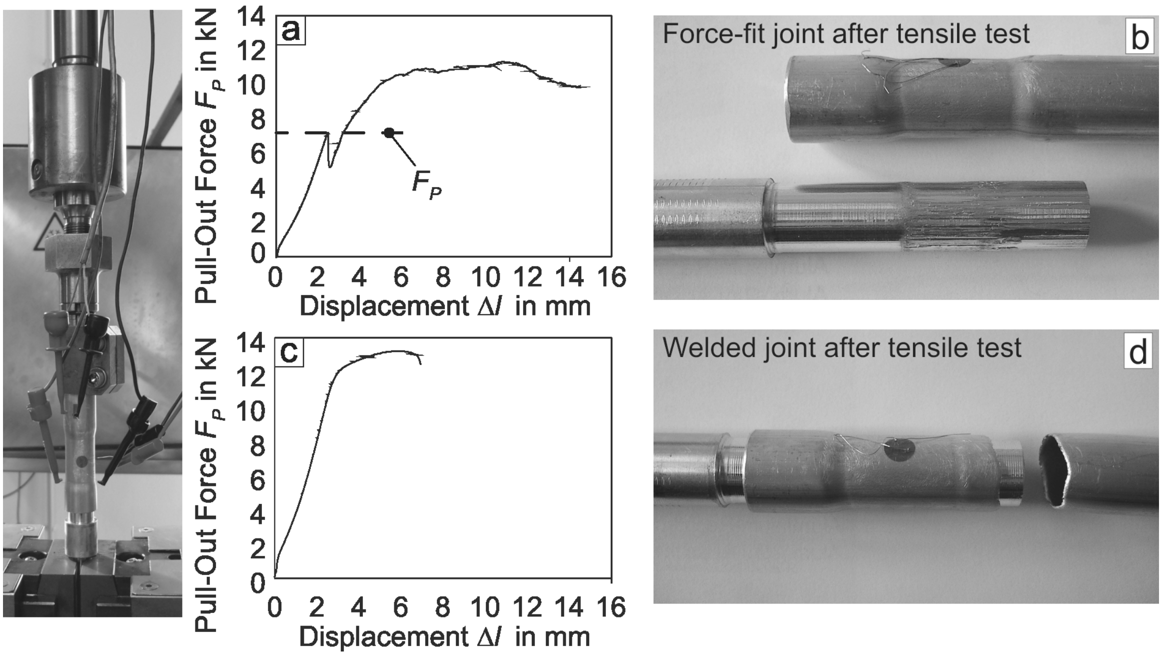


***Figure 7**: Typical characteristics of force against displacement in tensile tests of force-fit joints (a) and impulse-welded joints (c)*

Concerning the joints manufactured with a charging energy of 1.5 kJ, the impact velocity [4] leads to an impulse-magnetic welding of tube and mandrel as shown in Figure 8. The force-vs.-displacement characteristic given in Figure 7 c occurs inevitably and independent of the joint's surface characteristic.

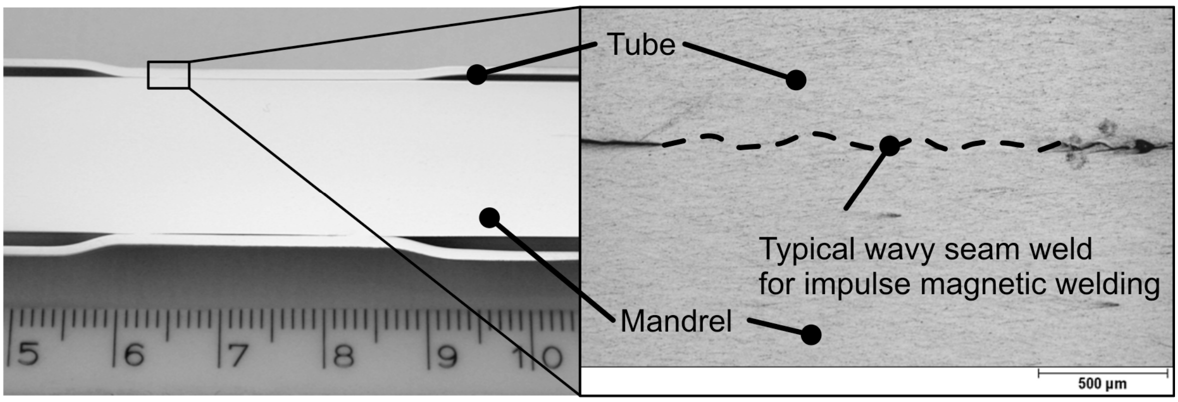


***Figure 8**: Joining area cut in axial direction (left), micrograph of welded area (right)*

Therefore, a charging energy of 1.5 kJ was inapplicable for determining the surface's influence on force-fit joints. Joints manufactured with a charging energy of 0.9 kJ and the according gap width a_0 generally result in rather low pull-out forces. Therefore, joining was done with a charging energy of 1.1 kJ.The pull-out force versus the used shot pressure for the shot peening of the mandrels for Al_2O_3 and glass beads as shot media is shown in Figure 9. The effect achieved with the glass beads is much lesser than with Al_2O_3 particles. While the specimens shot peened with glass beads merely reach a maximum pull-out force of less than 2.5 kN, the pull-out force can be increased up to 4 kN by shot peening with Al_2O_3 particles.

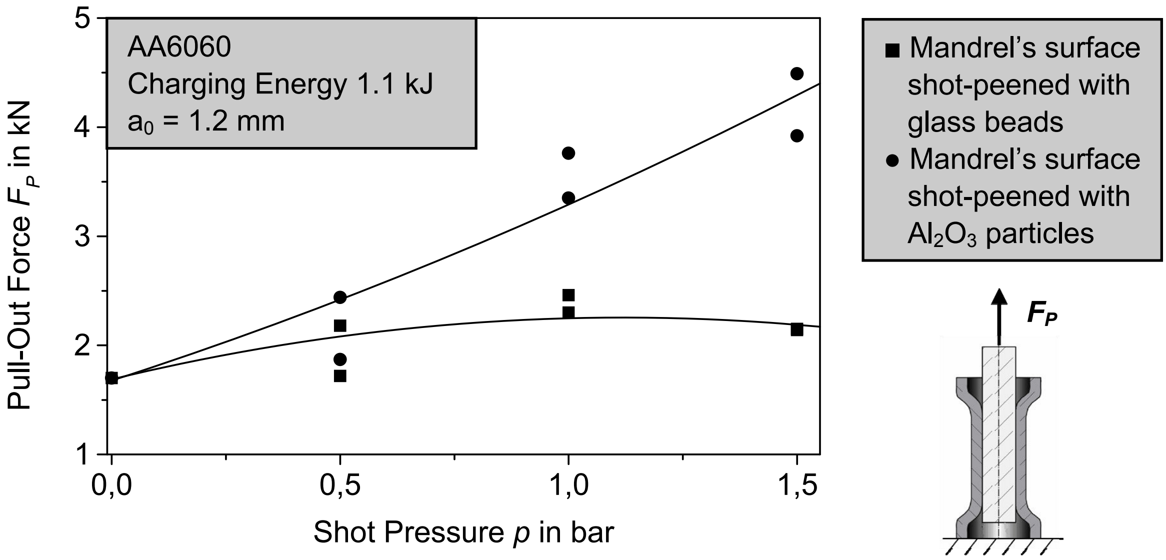


***Figure 9**: Pull-out-forces as a function of the shot pressure after shot peening*

The increase of the pull-out force by shot peening with Al_2O_3 is based on micro form fit in the contact area between tube and mandrel because the surface morphology is very different as shown in Figure 10 [14].

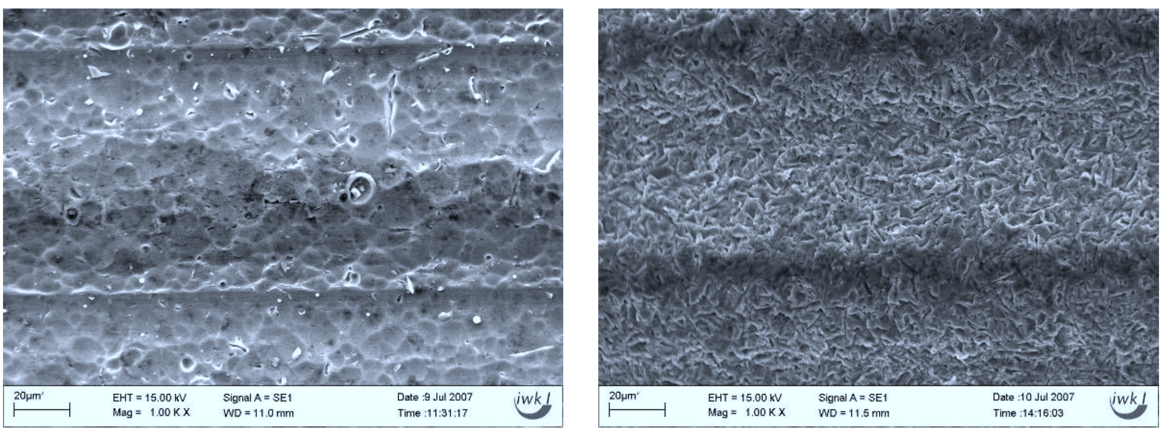


***Figure 10**: Surface of shot-peened mandrels (air pressure 0.5 bar). Left: glass beads, 20 - 30 µm. Right: Al_2O_3, 20 - 30 µm*

Figure 11 shows the correlation between pull-out forces and the average surface roughness Rz of the mandrel's surface induced by milling. The pull-out forces of the milled mandrels increase with the roughness to a maximum force of app. 8 kN. This is a result of the roughness itself and the resulting micro form-fit (squares). An additional effect can be seen on the mandrel's surfaces after the milling process M2 (circles), which leads to an increased work hardening compared to the other processes. Furthermore, this leads to a higher interference fit in the contact area and a significantly higher pull-out force. A further explanation could be the different percentage contact area which is not considered by measuring the average surface roughness. These assumptions need to be proved in further research work which will be focusing on larger roughness values.

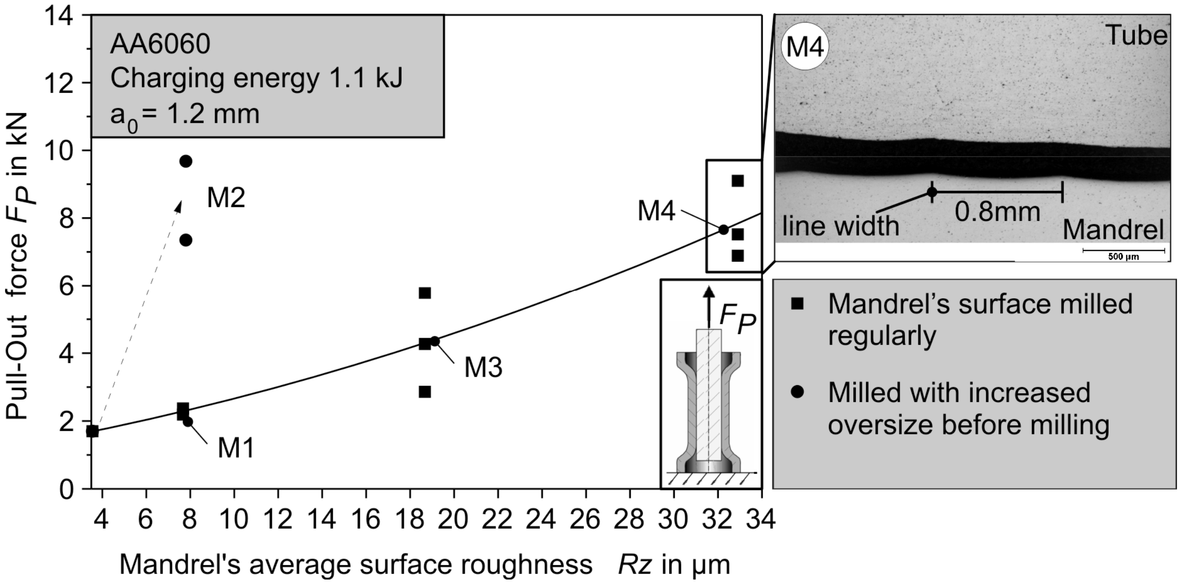


***Figure 11**: Pull-out-forces as a function of the mandrel's roughness after milling and micrograph of the joint area in axial direction*

In addition, micrographs in axial direction were investigated to evaluate the contact's characteristic of the joining zone. Consequently, the penetration of the mandrel's surface layer to the tube's surface was analyzed. As displayed in Figure 11, the roughness of the M4 surface left an impression in the tube's surface. This effect could not be observed with the other surfaces. The gap between mandrel and tube is caused by cutting for metallographical preparation leading to tangential elastic relaxation.

5 Summary

To improve the transmission of forces between mandrels and tubes in force fit joints manufactured by EMF, two surface treatments were investigated. At first, shot peening of the mandrels with high-shot pressure and square-cut shot media leads to a maximum pull-out force of 4 kN. The pull-out force can be increased up to 8 kN by structuring the mandrel's surface through milling, introducing significant roughness to the surface. This is done, on the one hand, by increasing the roughness or, on the other hand, by increasing work hardening in the surface layer of the mandrel caused by a higher remaining oversize before the finishing milling process of M2. Further investigations will be done to determine the oversize's influence on the strength of a connection. In future, with the knowledge from these investigations, it will be possible to precisely set up the strength of a connection up to its pull-out force, according to the characteristics of the mandrel and its joining area. Furthermore, this knowledge allows to transfer desired surfaces to the manufacturing of lightweight nodes within an economic and flexible process chain.

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