Simulative and experimental investigations on single-sided resistance spot brazing of sheet metal tube connections as an alternative to single-sided resistance spot welding

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Abstract. In order to reduce the deficits in single-sided resistance welding (SSSW), single-sided resistance brazing is a promising alternative. The reason for this is a process-related reduced thermal and mechanical component impact compared to SSSW. In the underlying article, the single-sided resistance brazing process will therefore be presented. In addition to the process architecture, the process advantage is presented and the joining characteristics are clarified. Finally, the presumed process advantage is confirmed by means of a practical example.

1 Introduction

In order to achieve lightweight construction and thus ensure a reduction in CO2-emission, hollow sections made of high-strength steel are used in many industrial sectors, including the automotive sector. In contrast to individual sheet metal bodies, which are produced using cost-intensive forming processes and then being joined together to form closed structures, steel sections can be manufactured using simple and cost-effective production methods such as roll forming. In addition to car body construction, there is another application in the area of the powertrain. Here, thin-walled tubes are used to transmit torque (e.g. propshaft). A major challenge is the limited possibility of joining these profiles with sheet metal. Therefore, the so-called single-sided spot welding (short: SSSW), i.e. resistance welding with one-sided accessibility, was developed for the production of such sheet metal hollow section joints [1], [2]. Figure 1 a) and Figure 1 b) show the process structure schematically.

![Figure 1](image-url)

Figure 1. Schematic illustration of single-sided resistance spot welding a) sheet metal - tube, b) sheet metal - hollow section, c) characteristic welding nugget, d) crack in tube after dynamic torsional stress; [2], [3].
However, if one considers the previous investigations and findings presented in the state of research and development, the deficits of the so-called SSSW become clear: Due to the lack of accessibility and thus supporting effect of the electrode, considerable mechanically and thermally activated plastic deformation occurs during the process (local and global deformation) [2], [4], [5], [6], [7], [8]. When, for example, comparing the electrical current process window in conventional resistance welding (RP = 2 - 3 kA) with the one of single-sided resistance welding (SSSW = 1 - 2 kA), the difference becomes obvious. [1], [9] In case of too low contact pressure, splashing also occurs in the process [1], [5], [6], [9] whereby the splash limit is sometimes below the lower quality limit [2]. If one further compares the microsections of a conventional resistance weld with a one-sided joint, a curved solidification line is visible due to a change in heat conduction [3]. The characteristic deformation processes in the SSSW also leads to an increased tendency to blowholes in the welding nugget [4] and to the formation of a so-called ring nugget [2], [3], [5], [6]. In addition, the hollow profile stiffness significantly limits the process window. With a profile wall thickness t < 1.25 mm, for example, no satisfactory results could be obtained due to very limited welding parameter ranges with splashes and strong deformation. This is due to the limited stiffness of the hollow profile, which is why only low electrode forces could be selected. [6] Finally, the high heat input during welding reduces the fatigue strength of the joined components. The reason for this is the formation of a sharp-shaped hardening zone together with the characteristic local deformation in the welding area. [7], [8] A welding nugget with the characteristic deficits is shown in Figure 1 c).

A practical example from the field of propshaft production will illustrate the problem. Here, sheets with a defined weight (so-called balancing sheets) are applied to the outer diameter of the shaft to compensate imbalances. Due to the limited accessibility, caused by the tube cross section, the single-sided resistance welding is used as application method. The process-related thermal and mechanical damage mechanisms already described lead to a loss of strength in the propshaft. Under dynamic loading, tube failure occurs in the area of the balancing sheet weld (Figure 1 d)). To counteract this cause of failure, the tubes used are currently oversized. This limits a possible reduction in the cross-section or wall thickness of the tube and consequently the achievement of lightweight construction goals through the joining process. For this reason, the development is being pushed ahead in order to develop thermally minimally invasive alternative processes for the application of balancing sheets.

A promising alternative to resistance welding is resistance brazing. In [10], [11], [12], [13] investigations into resistance spot brazing of thin sheets have already been described. In comparison to conventionally resistance welded sheet metal-sheet metal joints, an increased fatigue strength (150 %) could be proven by the reduction of thermally and mechanically caused stress [13]. In [8] a brazing process for the application of sheet metal to tubes is described. However, investigations on single-sided resistance brazing are not known. From the described findings, the conclusion is obvious to use the listed advantages of resistance brazing to minimize the deficits of SSSW. The aim is therefore to develop a process that causes a lower thermal and mechanical load on the joining partners compared to single-sided resistance welding. In the underlying contribution, therefore, the single-sided resistance brazing with mechanically introduced solder is to be investigated more closely. In addition to the process architecture, the advantage of single-sided resistance brazing is presented and confirmed with the aid of a practical example.

2 Process- and simulation setup
As in single-sided resistance welding, single-sided resistance brazing involves joining a sheet to a hollow profile or tube. Figure 2 a) schematically shows the process arrangement for single-sided resistance brazing. However, as this is a brazing process, the solder application and the choice of a suitable solder material are decisive. Based on [10], [11], [12] a copper solder was chosen, which is mechanically inserted into a 1.5 mm thick DC01 plate. Due to the mechanical insert of the solder, the sheet metal to be joined is deformed, so that a hump is formed. Care has been taken to ensure that a gap is created between the solder and the tube in the initial contact state to allow indirect heating of the solder depot (Figure 2 b)). The sheet metal used has a radius of 30 mm. The outer diameter of the tube
is 55 mm with a wall thickness of 1.5 mm. The tube material selected is 26MnB5. In [14] a simulation model was built and validated with the software SORPAS 2D in order to effectively design the process development and to gain an understanding of the process (Figure 2 c)). The simulation model is also used in the underlying investigations.

![Simulation Model](image)

**Figure 2.** a) schematic process arrangement for single-sided resistance brazing; b) detailed representation of the solder depot with gap s between solder and tube; c) representation of the simulation model [14].

### 3 Numerical and experimental investigations on single-sided resistance brazing

#### 3.1 Numerical comparison of the process flow for single-sided resistance brazing with single-sided resistance welding

In order to be able to make a process comparison between brazing and welding, a simulation model for single-sided resistance welding was also built using the SORPAS 2D software. If the simulation results are compared with experimental results, it becomes clear that the simulation achieves valid results. If, for example, the nugget diameter is considered, the simulation deviates by only 3.80 % from the metallographically determined nugget diameter. Based on the two simulation models, the process flow of single-sided resistance welding was compared with the process of single-sided resistance brazing. In order to obtain the best possible analogy, the geometrical and material parameters were chosen to be as identical as possible. However, the electrode shape of the working electrode differs due to the process characteristics. Here, a conical electrode shape was used for welding. In each case, a parameter set was selected in which an acceptable joint was produced in experimental tests. The heating process was derived from the calculated temperature distributions. Figure 3 shows the heating mechanism of both processes. In single-sided resistance welding, generally higher current intensities and shorter process times must be selected. The initial heating takes place in the interface between the sheet metal and the tube. The heat propagation is further multidirectional (Figure 3 a)). If one considers the corresponding peak temperatures of the joining partners, the described process becomes clear again (Figure 3 b)). Both the tube and the sheet are heated equally strongly after the squeeze phase (here 100 ms).
In comparison, the heating process in single-sided resistance brazing differs significantly. Here the initial heating takes place in the interface between electrode and sheet metal. The heat propagation is in the direction of the tube and the solder (Figure 3 c)). The calculated temperature curve reflects the process again (Figure 3 d)). After the squeeze phase (100 ms) there is a sudden increase in the sheet metal temperature due to the initial heat development in the sheet metal hump area. The heat propagation causes the solder to heat up continuously. Due to the gap s between solder and tube, the tube remains almost unaffected by heat in the first process section (approx. 200 °C). After approx. 230 ms a sudden rise in tube temperature is visible. From this point on, the initial gap s is completely closed so that contact can be established between the strongly heated solder (approx. 949 °C) and the tube. This results in a heating of the tube in the contact area between solder and tube. In the further course, the tube temperature follows the maximum solder temperature. As soon as the solder has reached the melting temperature ($T_{\text{solder}} = 1080 ^\circ\text{C}$), a solid connection can be assumed. If one ultimately compares the thermal influence on the joining partners of both processes, the difference becomes clear. In resistance welding, the peak temperature of the tube is 1635 °C. In comparison, a maximum tube temperature of 1240 °C was determined for resistance brazing. The sheet metal is also heated less ($T_{\text{max, sheet metal, welding}} = 1662 ^\circ\text{C}; T_{\text{max, sheet metal, brazing}} = 1496 ^\circ\text{C}$). In order to clarify the heating process described for single-sided resistance brazing, experimental process flow tests were carried out. Looking at the microsections, it can be seen that the simulated process sequence corresponds to the real process (Figure 4). With increasing process time, the expansion of the heat-affected zone (dotted line) reflects the heating process.

It was shown that the single-sided resistance brazing process represents a thermally minimal process alternative to single-sided resistance welding. Due to the lower temperatures, the thermally activated plastic tube deformation can be avoided, especially with smaller tube wall thicknesses.
3.2 Characterization of the connection for single-sided resistance brazing

If one further compares the resulting joining zone of a resistance-welded specimen with a resistance-brazed specimen, a clear difference can be seen. Table 1 shows possible criteria for differentiating between the two joining methods. In the case of resistance welding, the joint formation is realized by the formation of a welding nugget. In order to be able to make an evaluation, the minimum nugget diameter is generally determined in the microsection. As a further quality criterion, the plug diameter can be measured after a peel test accompanying series production (Figure 5 a)). The characteristic heating process described above results in a high thermal influence on the sheet metal and the tube. An increased risk of thermally activated local deformation is the result.

| Table 1. Criteria of a resistance brazed and a resistance welded joint. |
|---------------------------------------------------------------|
| **Single-sided resistance welding** | **Single-sided resistance brazing** |
| microsection | connection |
| | forming of weld nugget |
| | metallographic evaluation |
| | destructive evaluation during series production by peel test |
| | initial heating |
| | thermal influence sheet metal |
| | thermal influence tube |
| | risk of local deformation |
| | minimum nugget diameter |
| | measurement of plug diameter |
| | interface sheet metal - tube |
| | melting of solder |
| | contact lenght solder-tube |
| | evaluation of fracture type |
| | measurement of fracture diameter |
| | interface electrode - sheet metal |
| | evaluation during series production by peel test |
| | measurement of fracture diameter |
| | low |
| | medium |
| | high |
| | high |

In comparison, the connection in resistance brazing is mainly achieved by melting the solder. Due to the heating process a lower thermal influence on the joining partners can be achieved. The danger of thermally activated local deformation is reduced. Since no welding nugget is produced during resistance brazing, the contact length between the solder and the tube can be used as a comparative value in the context of metallographic evaluation. However, further investigations are necessary to determine a minimum length depending on the load case. For the following investigations, a minimum contact length $d_{\text{contact}} \geq 3.5 \times \sqrt{t_{\text{sheet}}}$ is determined based on [15]. A further difference becomes clear when looking at the evaluation accompanying series production by means of the peel test. Because there is no plug after the test, alternative criteria must also be selected here. Depending on the process parameters, characteristic fracture surfaces occur during resistance brazing. Figure 5 b)) shows the development of the fracture surface with increasing process time.

**Figure 5.** Result of the peel test: a) plug evaluation during resistance welding b) development of the fracture surface on the tube during resistance brazing.
If the energy input is too low (Figure 5 b), example 1) a purely adhesive failure occurs between the solder and the tube without a clear copper-colored solder imprint being visible on the tube. As time and/or current increases, the size of the visible solder imprint increases (Figure 5 b), example 2 - 8). If the energy input is large enough, a cohesive fracture is also visible (Figure 5 b), example 9). A further increase of the energy results in a purely cohesive fracture (Figure 5 b), example 10). In addition to the different fracture types, the size of the fracture surface visible on the tube also increases. Due to the lack of guidelines, further investigations must be carried out in order to enable a uniform evaluation of the resistance brazed joint. The aim of the following investigations is to produce an adhesive-cohesive or purely cohesive fracture (Figure 5 b), examples 9 - 10).

In order to get an impression of the joint strength in relation to the fracture surfaces, shear tests were carried out. The test setup and the results are shown in Figure 6. The joined sheet metal-tube connection was axially loaded to failure by means of a tube with an inner diameter of 55 mm. The maximum force at the time of failure was measured three times and the average was determined. Furthermore, the resulting fracture type and the size of the fracture surface were analyzed (Figure 6 b). Adhesive failure was found in the test specimen group 1. As no clear copper-colored solder imprint was available, the fracture surface was not measured after the shear test. An average force of 0.87 kN was determined. In comparison, the process time was increased for test specimen group 2. Due to the increased energy input, an increase in shear strength to 4.0 kN was determined. The fracture has a pronounced adhesive character. An average fracture surface of 5.5 mm was measured. Only when the process time was increased again, a purely cohesive fracture with an average area of 6.3 mm was detected. A renewed increase in shear strength to 5.5 kN was determined. It is thus clear that the type of fracture and the fracture area can be used as an evaluation parameter for single-sided resistance brazing. However, more detailed investigations are necessary to establish precise guidelines.

3.3 Presentation of the process advantage using a practical example
As already mentioned at the beginning, the welding of balance sheets in propshaft production leads to a significant loss of strength under dynamic loads. This is caused by a failure of the tube in the area of the heat-affected zone of the weld (Figure 1 d)). In order to verify the process advantage of the single-sided resistance brazing process in practice, 30 test shafts with identical geometry and material data were set up. The necessary sheets were brazed onto 15 of each of these shafts and welded onto the remaining 15 shafts. This test setup reflects the balancing process necessary for propshaft production. Care was taken to ensure that the parameter set used for each process corresponds to an acceptable joining result. Subsequently, the test shafts were subjected to a dynamic torsion test under alternating loads until failure. Three identical load horizons were tested for each application method, so that five test shafts...
were tested per load horizon and application process. Subsequently, a process-specific weohler curve was determined in each case. The test setup and the test results are shown in Figure 7.

![Figure 7. Comparison of brazed shafts with welded shafts: a) presentation of the test setup; b) test results of the dynamic torsion test](image)

If the results of the individual load levels are compared more precisely, the most significant difference was found in the lowest load case. Here an average number of load cycles of 263841 was determined for the welded version. By brazing as a minimally invasive process alternative, the time to failure could be increased by 503%. The average load cycle here was 1326377. At higher load amplitudes only smaller increases become visible. In the intermediate load case the percentage improvement by brazing is still 170%. At the highest load case almost identical results are visible. The reason for the reduction of the improvement effect at higher load amplitudes is the characteristic failure cause of the shaft. At low loads and the associated high number of load cycles, a crack of the tube as a result of the sheet metal application was consistently detected in the welded version. The higher the load amplitude, the higher the probability that other causes of failure (e.g. plastic deformation of the tube, fracture of the friction weld) will occur. Thus, the sheet metal application process mainly influences the lowest load horizon. An increase in performance under dynamic loading has been demonstrated. This is due to a process-related reduced thermal and mechanical influence on the components.

4 Summary
In order to minimize the deficits in single-sided resistance welding, single-sided resistance brazing was examined more closely. In addition to the process architecture, a simulation model was also presented in order to build up an understanding of the process. In a comparison between single-sided resistance welding and single-sided resistance brazing, the advantage of the new process becomes clear. While the initial heating in the SSSW takes place in the contact area of the sheet metal tube and then spreads multidirectional, in resistance brazing the tube is only subjected to very low thermal stress in the initial stage of the process. This is due to the specific indirect heating process of the solder. As soon as the constructive gap between solder and tube is closed, the tube is also heated for a short time. Comparing the maximum temperatures in the tube, a difference of 400 °C was found. In the following, the differences between a welded and a brazed tube-sheet metal joint were shown and the joint created by resistance brazing was characterized. Due to the dissimilar connection mechanisms, alternative evaluation criteria have to be chosen for the brazing process. In addition to the contact length between solder and tube which can be measured in the metallographic analysis, the fracture surface provides information about the joint quality. However, in order to determine more precise quality parameters, further detailed investigations are necessary. Finally, the process advantage was demonstrated. Using the example of propshaft production, test shafts were equipped with a sheet metal. In addition to the SSSW, the sheet metal was also applied using single-sided resistance brazing. In the following dynamic torsion test it was shown that the fatigue strength of the component increases significantly. The reason for this is the reduced thermal and mechanical component influence of the brazing process. It was thus proven that single-sided resistance brazing has high potential as an alternative to single-sided resistance welding.
5References

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