SIMULATION BASED DETERMINATION OF THE ELECTRICAL CONTACT RESISTANCE DURING RESISTANCE SPOT WELDING

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ABSTRACT

The primary goal of this research paper was to use numerical techniques to validate a new approach for measuring the electrical contact resistance during resistance spot welding. In this approach, short term welding experiments using 1 period AC inputs on single uncoated HTC 600 X steel sheets were performed. The welding current values were varied in order to generate different temperatures at the electrode/sheet contact interface. The total resistance between the electrodes was measured from the first few milliseconds of each welding experiment and correlated to the maximum value of the applied current and indirectly to the temperature at the contact interfaces. The finite element modelling software SYSWELD was used on the basis of generated contact resistance data to simulate the temperature fields and to test the accuracy of this approach. The bulk resistance data was numerically isolated from the measured total resistance to differentiate the contribution of each part to the measured contact resistance data in both simulation and experiment. The calculated temperatures were verified by investigation of the heat affected zone in the cross sections of the sheet. It was determined that the shape of the total resistance curve in the lower maximum current range corresponded to the electrode contact resistance the electrode/sheet interface.

INTRODUCTION

Resistance spot welding is still the primary method for joining in the automobile industry. In fact, every car has approximately 5000 resistance spot welds [1]. The heat production Q[J] in the resistance spot welding process comes from Joule heating:

$$Q = \int_0^t I^2(t) * R_i(t,...)\,dt \qquad (1)$$

where I[A] is the welding current and R_i[Ω] is the total resistance of the contributing resistance values, specifically the summation in series of the bulk material resistances of the electrodes and the sheets, and the electrical contact resistance (RCE) at the electrode/sheet (E/S) and sheet/sheet (S/S) interfaces [2]. The RCE is measured in the units Ohm m^2 and provides a large contribution to spot weld formation. Both RCE values vary greatly with temperature, interfacial pressure, and area of contact. In addition, the RCE vs. temperature curves are very important input parameter for all resistance spot welding simulations, yet the shape of this curve has remained one of the most widely discussed and investigated topics in the resistance spot welding community for over 50 years. The reason for this is the many complicating factors influencing the RCE of metals, the inconsistency in experimental measuring techniques outside on the welding process, and the inability to separate the bulk material resistance data from contact resistance. In order to ensure the accuracy of a resistance spot welding simulation, a detailed understanding of the thermoelectric interactions at the contact interfaces must be known, and the values of the measured curves must of course match those of reality.

Many researchers have attempted to find the RCE as a function of temperature and interfacial pressure using experimental techniques [3-8]. One technique is to apply different contact forces at room temperature, pass a low current through the materials, and measure the voltage drop across the interface. In order to see the influence of temperature, researchers placed a measuring device in a furnace and slowly heated to required temperatures. The disadvantage of this technique is the low current applied across the interface and the slow interface heating rate compared to real welding condition. With these methods, the shape of the RCE curve for uncoated steels was measured to be an exponential decrease with increasing temperature and mainly linear decrease with increasing force. These trends are due to deformation of contacting asperities at the contact interface, which are defined as the tiny effective surfaces that are in contact when two materials are together. Thus, as the area of contacting asperities increases due to softening, the RCE will decrease.

A GLEEBLE machine [8] was also used to measure the RCE, the advantage being more realistic interfacial heating rates and currents. The results for uncoated steels showed an initial rapid decrease and then a local ridge in the contact resistance curve, which was related to either a growth in surface oxide layer or an increase in constriction resistance from the bulk contribution at the surface. Constriction resistance, which was first defined by Holm [9], describes the heating of small areas of the contact surface due to a constriction in the current flow from asperity contact leading to a high current density. Babu [10] proposed a model to predict the shape of the contact resistance curve using experimentally measured pressure dependence contact resistance values and temperature dependent bulk material resistivity and yield strength. A peak in the contact resistance curve for uncoated steel/steel and uncoated steel/copper contact was proposed, which resulted from the competition of bulk material resistance and contact resistance in different temperature ranges.

This present work proposes a new method to measure during welding the RCE value at the E/S interface. Short time welding experiments on single sheets with varying welding current were used to cover the range of increasing interfacial temperatures. Until now there has been no accurate measurement technique due to the inability to isolate the bulk material resistance contribution from the RCE measurement. The aim of this work is to use the finite element modelling software SYSWELD to verify and discuss the accuracy and validity of the approach.

DEFINITION OF NEW APPROACH

This new approach attempts to measure the RCE at the E/S interface during real time welding experiments. Essential to this approach is the modification of the practical resistance spot welding process.

Only one sheet was used in this approach instead of the normal welding with two sheets. The reason for performing an experiment with one sheet was to eliminate the RCE at the S/S interface in order to focus on the RCE at the E/S interface. A schematic diagram of the new approach with the contributing resistances is shown in Fig. 1. It can be seen that the bulk resistance of one sheet as well as the RCE at the two E/S interfaces are present. The bulk resistance of the electrode is small and will not be discussed in the context of this paper.

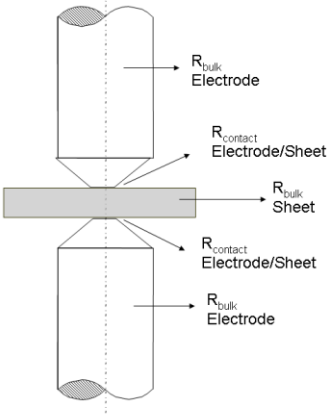

Fig. 1: Overview of the contributing resistance factors from the new approach

The current was also modified in this new approach. Instead of the normal 10-12 periods of AC application, only one period was used. Fig. 2 shows the real time current waveforms that were measured from the experiment and used in simulation. The first value of effective current was 0.5 kA, and the current increased in steps of 1 kA until a normal welding value of 9.5 kA was reached. The concept behind the idea to use one period was to create very little bulk material resistance heating so that the contribution of the RCE at the E/S interface dominated and could be measured.

It is very important to the validity of this approach to separate the bulk heating contribution from the RCE contribution when measuring the total resistance in the welding electrodes. A schematic diagram showing the typical shape of total resistance, RCE, and bulk material resistivity over temperature can be seen in Fig. 3. The contribution of bulk material resistance will increase with temperature due to the influence of temperature on material resistivity, while the RCE will decrease with temperature if there is no characteristic peak in the RCE curve. Numerical techniques were used with modified input bulk material resistance and RCE curves to isolate the contribution of each on the total measured total resistance in the welding electrodes.

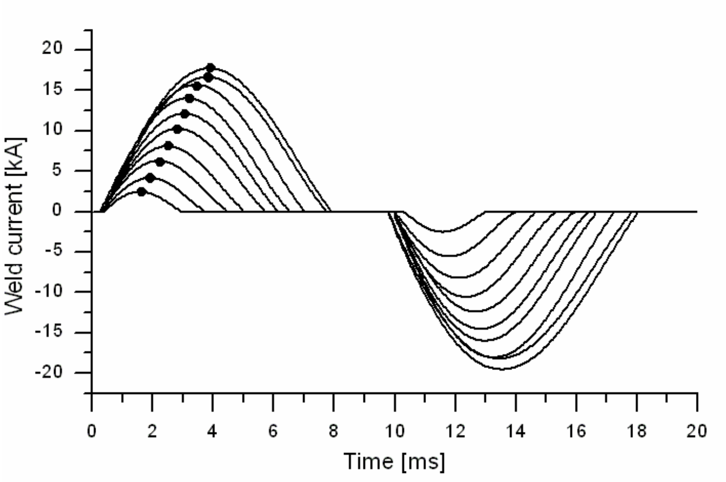

Fig. 2: Real time current waveforms from experiment which were also used in the spot welding simulation

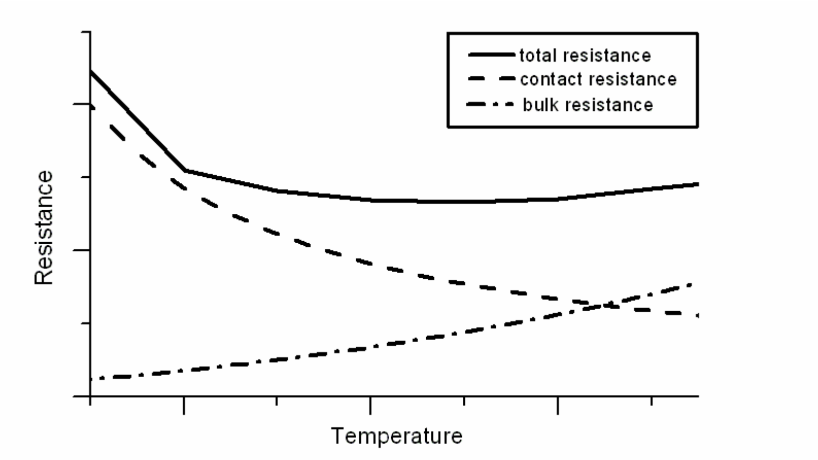

Fig. 3: Schematic diagram showing the influence of temperature on total resistance, contact resistance, and bulk resistance

NUMERICAL PROCEDURE

The finite element modelling program SYSWELD was used to simulate the resistance spot welding of 1mm single sheet uncoated dual phase steel HTC 600 X. Chemical composition and mechanical properties at room temperature of this steel are outlined in table 1.

Table 1 Chemical composition and mechanical properties at room temperature of dual phase steel HTC 600 X according to EN 10336

Chemical composition [wt%]					**Yield strength [MPa]**	**Tensile strength [MPa]**
C	**Si**	**Mn**	**Al**	**V**		
max. 0.17	max. 0.8	max. 2.2	max. 2.0	max. 0.2	340 - 420	min. 600

Two different RCE curves were used in the simulation:

- the standard RCE input data from SYSWELD (RCE curve A) for uncoated HTC 600 X steel, and
- the RCE curve which was modelled from Babu for contact between Cu electrode and uncoated steel (RCE curve B) [10].

Curve A has a classic exponential decreasing shape, while curve B has the characteristic peak in contact resistance. Fig. 4 shows the two input RCE curves, as well as the bulk material resistivity for HTC 600 X steel. A detailed description of the numerical procedure at contact surfaces used in SYSWELD is well documented and can be found elsewhere [11].

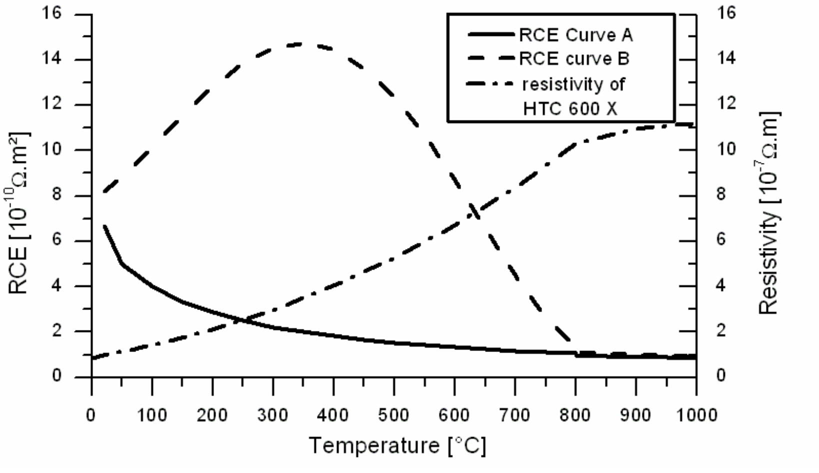

Figure 4: Two input RCE curves (A, B) and bulk resistivity used in the simulation

Strong coupling between electrical, thermal and mechanical interactions was used in the simulation which considers sink in of the welding electrodes during welding. A strong coupling ratio of 0.1 was used in the simulation, which corresponded to electro-thermal and mechanical iteration time of two ms. An electrode geometry with 5.5 mm contact face diameter and a curvature of 50 mm was used in the simulation to match the welding electrodes that were used in the experiments. This mesh was a predefined mesh from the SYSWELD and the initial contact radius was set to that of the experiment. Real time current waveforms of one period AC were input into the simulation ranging from 0.5-9.5 kA in steps of one kA. The welding force used was 3.5 kN, which also matched that from the experiment.

The input material bulk resistivity and contact resistance value were altered to isolate the contributions of each on the total resistance measured in the electrodes. In order investigate only the contribution of RCE at the E/S interface, the bulk resistivity for the steel was set to the room temperature value for the simulation. In order to investigate only the bulk resistance contribution, the RCE was set to a nearly zero value. An overview of the simulation test runs (STR) is shown in table 2.

Table 2 Overview of single sheet welding simulations

Simulation Test Run	RCE Input Curve A	RCE Input Curve B	Bulk Material Resistance for HTC 600 X	Bulk Material Resistance of constant RT Value
STR 1	x		x	
STR 2	x			x
STR 3	No RCE		x	
STR 4		x	x	
STR 5		x		x

The total resistance in the welding electrodes was calculated from voltage drop measurements taken from nodes in the electrode at the time of the peak of the first half wave of the welding current. The dots on the curves in Fig. 2 represent when the voltage drop measurements were taken. The mesh used in the resistance spot welding simulation is shown in Fig. 5, along with the nodes where the voltage drop was measured. The electrode contact radius at the E/S interface from simulation was measured and related to the total resistance and the input RCE curves.

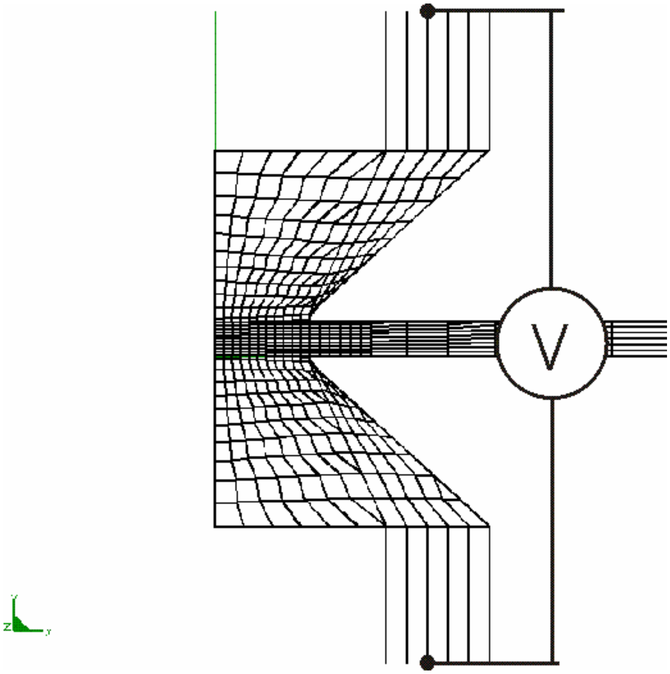

Figure 5: Mesh used in simulation showing the node of voltage measurement

EXPERIMENTAL PROCEDURE

Single sheet welding experiments were performed on cleaned 1 mm uncoated dual phase steel HTC 600 X. The welding machine used was a pedestal Schlatter Selecta with an AC 170 kVA power source. The welding electrodes used in the experimental were F16 x 20 electrodes according to ISO 5821 with a flattened contact area (diameter 5.5 mm and a curvature of 50 mm). The electrode material was A 2 / 2 according to ISO 5182 (Cu with 1% Cr and 0.1 % Zr). The squeeze time, weld time, and hold time were 6, 1, and 10 periods, respectively and the electrode force was 3.5 kN. The voltage drop was measured in the welding electrodes using a computer assisted measurement system which recorded values every 0.1 ms. The resistance was calculated using the voltage drop measurement at the time of the peak in the welding current. Cross sections were taken at the end of the welding experiments and evaluated with respect to heat affected zone as a function of welding current. Electrode imprints on the surface of single sheet experiments were examined with a stereoscope for each welding experiment, and the diameter of the imprints were recorded. The total resistance was converted to RCE using the area of electrode contact from stereoscope images. This RCE was evaluated as a function of maximum current and then compared to the simulation results.

SIMULATION RESULTS AND DISCUSSION

The total resistance curves from simulations from STR 1 and STR 4 are shown in Fig. 6. A number of important aspects of this curve must be discussed.

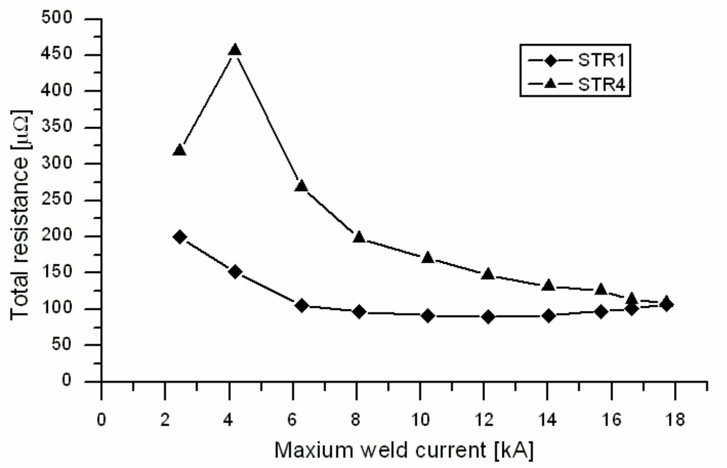

Fig. 6: Total resistance curves from simulations of two RCE input curves

First, the RCE peak from RCE curve B still remains visible in the total resistance curves. It can therefore be said that the shape of the RCE curve can be seen in the simulation in the lower maximum current range.

Considering now the medium and higher maximum current ranges, the total resistance curve shows decreasing characteristics. For STR 4, the slope is always negative, and the resistance values are thus always decreasing. However, for STR 1, the slope shows a gradual flattening and then an increase at higher currents. This point of increase represents the first point where the bulk contribution is discernable from the total resistance values in the simulation. In other words, the increase in bulk resistance with temperature outweighs the decrease in contact resistance and can thus be identified with the total resistance in the electrodes for this STR. This increase in total resistance is not seen in STR 4, which could be explained do to higher RCE.

The total resistance curves from STR 1-5 are shown in Fig. 7 and Fig. 8 for RCE curves A and B, respectively. An additional curve is added, which represents the total resistance curve from STR 1 and STR 4, minus the increase of STR 3.

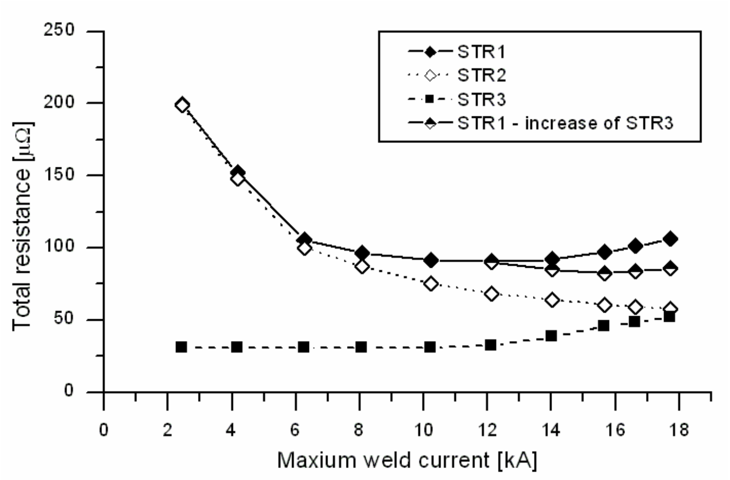

Fig. 7: Total resistance curves using RCE curve A and modified input curves

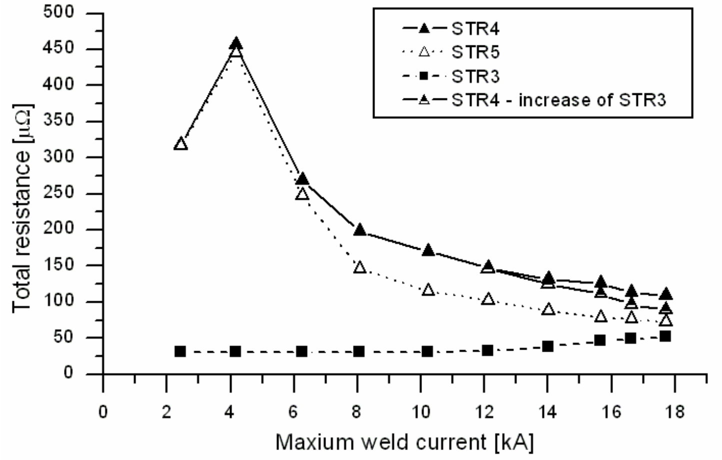

Fig. 8: Total resistance curves using RCE curve B and modified input curves

STR 2 and STR 5 are modelled with room temperature bulk resistivity, so the contribution of bulk resistance from heating is not present. A comparison of STR 2 and STR 5 curves to STR 1 and STR 4 curves, which were modelled with the bulk contribution, will now be discussed.

The total resistance difference is very small in the lower maximum current range, but gradually increases to a maximum at the highest current applied, which represents the greatest contribution of the material bulk resistance to the total resistance curve. The difference in the curves is very important, because it represents when and how the measured total resistance data in the welding electrode becomes influenced by the bulk contribution for a given RCE curve.

These results from simulation show that, up to maximum welding current of around 6 kA, the measured total resistance in the welding electrode represents contributions from mainly the RCE at the E/S interface. This is further justified when comparing STR 1 and STR 4 with the additional curve described above. The contribution of bulk resistance heating to the total resistance curve is seen after around 14 kA.

Temperature profiles were examined from simulation in the low and high current ranges. Fig. 9 shows temperature profiles at two different maximum currents from STR 4 and STR 5. It can be clearly seen that the temperature evolution is focused at the interface in the lower maximum current range (maximum current of 4.2 kA from Fig. 9), regardless of the presence of the contribution of bulk material resistance. The temperature contours from STR 4 and STR 5 are also very similar in this range. Regarding the higher current range (maximum current of 17.7 kA), there is noticeably more heating from STR 4 than STR 5, and the temperature contours are different. This is due to the bulk resistance heating in the sheet, which is much more significant in this temperature range. From the simulation results, it is proposed that only RCE contributions are present in the total resistance curve in the lower maximum current range.

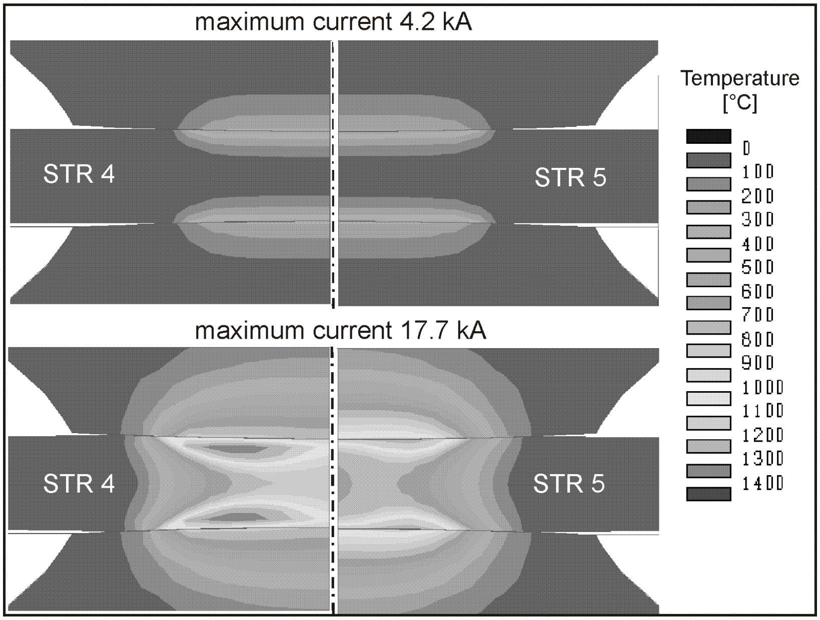

Fig. 9: Temperature isotherms at two different current values

In the upper maximum current range, the temperature distribution differs due to the presence of these contributions. Fig. 10 displays the temperature evolution at the electrode contact interface in the lower maximum current range from STR 1 and STR 4. Regarding STR 1, lower temperatures are present for the same maximum current due to lower RCE values. Therefore, it can be said that if bulk resistance contributions are proved to be excluded in the lower temperature range from the STR 4 simulation, this also holds true for the simulations from STR 1.

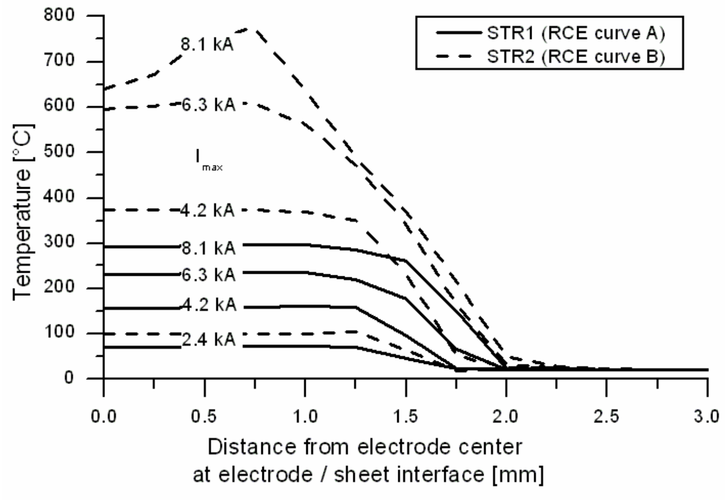

Fig. 10: Temperature measurements at the E/S interface for STR 1 and STR 4.

An effort will now be made to convert the total resistance curve from STR 4 to a RCE curve, and then compare this converted RCE curve to the input RCE curve B. The basis for this comparison is to discover at which current ranges the total resistance values are actual RCE values. In other words, the measured total resistance should resemble the input RCE data in the valid current ranges where the bulk resistance contribution is negligible. Essential to the conversion of total resistance to RCE is knowledge of the contact area of the electrode at the time of the resistance measurement from simulation.

In this present investigation, the current density was used to extract the measured electrode contact radius form the simulation using current density values in the y-direction through the electrode surface. Fig. 11 shows numerically determined current density values in the lower maximum current range from STR 4. For this investigation, the electrode radius was taken at the node of the last non-zero current density value. For maximum current values of 2.4 and 4.2 kA, the electrode radius was 1.5 mm. For maximum current values of 6.3 and 8.1 kA, the electrode radius was 1.75 mm.

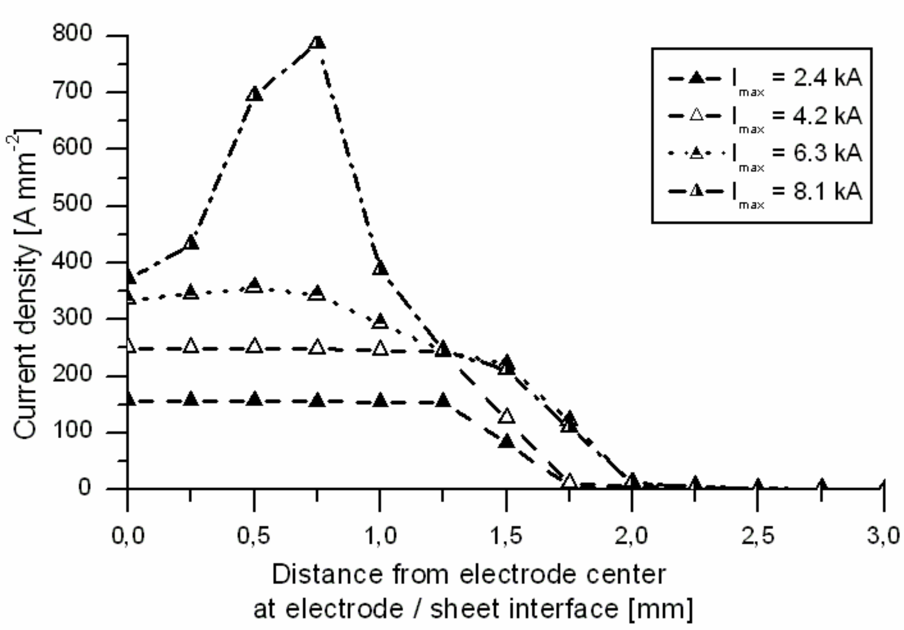

Fig. 11: Numerically measured current density through the electrode surface in the y-direction

A comparison of the measured total resistance to the input RCE data can be seen in Fig. 12. The temperature on the x-axis is the average temperature of the electrode contact surface taken from the nodes. The measured total resistance data from STR 4 is converted to RCE using the correct electrode contact radius from the simulation. Results from SRT 5 are also included to show the influence of the contribution of the bulk material resistance.

It is important to note that the room temperature bulk resistance value for steel was subtracted from the total resistance value when calculating the RCE curves, because it was known from the simulation results that only room temperature effects are present in this current range.

It can be seen that, up to the average interface temperature of 400°C, the RCE of all three curves are identical. The first deviation comes at interface temperatures higher than500°C. Although this difference in RCE remains very small, it becomes even greater at 650°C. The data points from STR 4 show a greater deviation from the input RCE data compared to STR 5 due to the heating of the sheet.

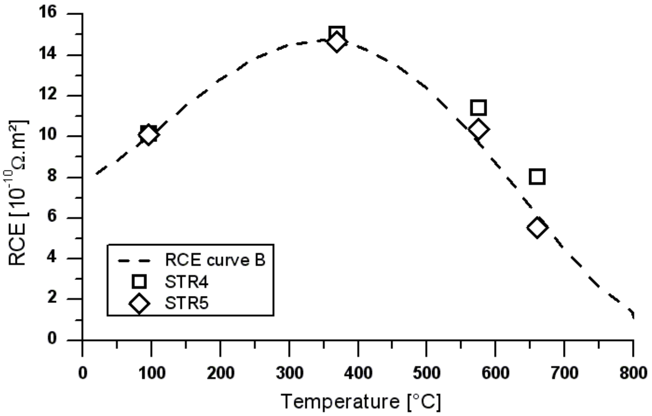

Fig. 12: The comparison of the calculated RCE curves from SRT 4 and STR 5 in the low current range compared to the input RCE curve B.

The results from Fig. 12 verify that the newly proposed method for measuring the RCE from total resistance measurement in the welding electrode hold true in the lower welding current range. It is again proposed, due to less interfacial heating, this comparison will also hold true for STR 1. Therefore, if the actual RCE curve from real welding experiments is less than the RCE curve B, this method also holds true for real experiments.

EXPERIMENTAL RESULTS AND DISCUSSION

The overall objective of this work is to compare measured resistance values from welding experiments with this numerically tested method to see if the shape and values of the curve are actually that of the RCE at the E/S interface. The total resistance curve over maximum current from welding experiments for 1 mm uncoated HTC 600 X steel is shown in Fig. 13 and compared to the total resistance curve taken from simulation. Although this curve from experiment is shifted to much lower resistance values, the characteristic peak in RCE is clearly present. This peak also occurs at the same maximum current values compared to STR 4. The difference in the resistance values could be explained by the difference in interfacial pressure. The RCE curve B was modelled by Babu for pressures in the range of 10-50 MPa [10]. An estimation of the interfacial pressures from the present experiments and from the numerical simulation using the applied electrode force and measured contact areas gives a pressure of around 500 MPa. A lower contact pressure would result in a lower asperity contact area and could account for a greater RCE.

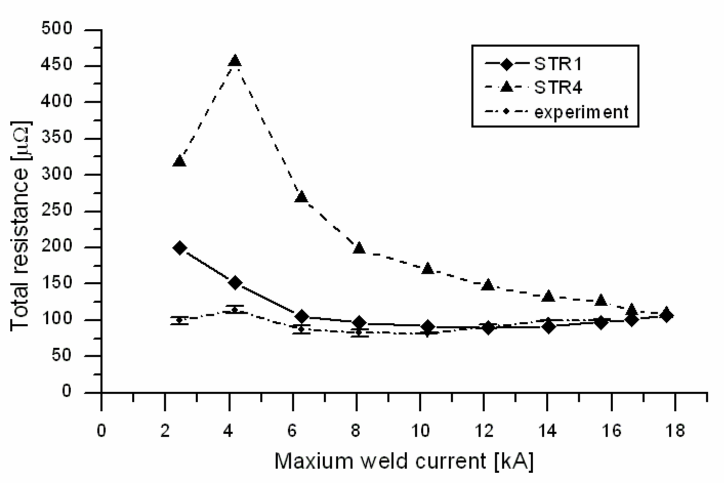

Fig. 13: Total resistance curve from experimental and simulation

An increase in the total resistance curve from experiment can be seen after a maximum welding current of around 10 kA. In other words, the contribution of the bulk resistance, which increases with temperature, outweighs the contribution of the RCE, which decreases with temperature. Remember this discussed contribution is actually the contribution that is measured in the welding electrodes, and cannot be isolated with the techniques used in simulation. However, it can be said that the peak in the total resistance curve from experiments represents the true peak in the RCE curve for uncoated HTC 600 X steel, and not a peak due to the bulk resistance increase.

A comparison of temperature evolution form experiment to simulation could further substantiate this new method for measuring RCE. Fig. 14 shows the heat affected zone (HAZ) radius as a function of maximum welding current for both simulation and experiment. The beginning of the formation of the HAZ from the experiment occurs at higher current values compared to STR 4, but lower compared to STR 1. It could be proposed that the temperature evolutions at the contact interface from the welding experiments are within the bound of the numerical analysis.

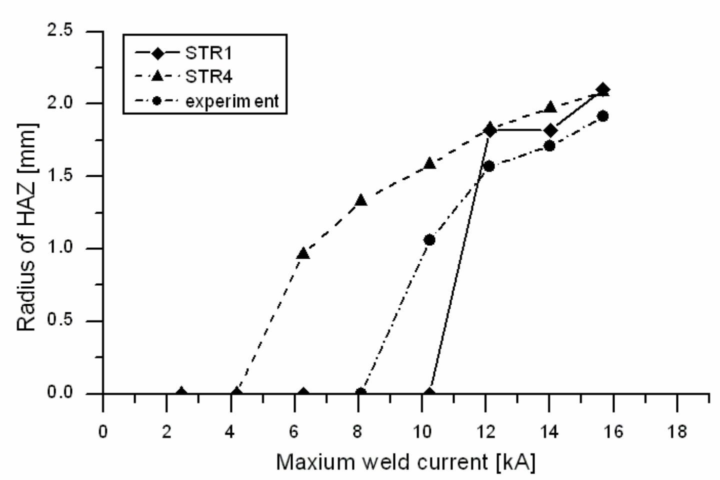

Fig. 14: Increase in HAZ radius as a function of weld current for experimental and simulation

DISCUSSION OF THE VALIDITY OF MEASURMENT TECHNIQUE

The measured total resistance from real welding experiments was multiplied by the electrode contact area and compared to the input RCE curves A and B. The results are shown in Fig. 15 using data point from the first 4 steps of welding current application, which represents the lower current range. In this range, it was proven with simulation that the calculated RCE curve (the total resistance multiplied by the electrode contact area) showed very good agreement to the input RCE curve. The resistance values from experiment are lower than the curve from STR 1, and the shape is also different. A number of factors could account for this difference, and will now be discussed.

In the real welding experiment, the electrode contact area, which was measured using the stereoscope, did not increase during the first three current applications and was taken to be 7.5 mm^2. This means there was no measured electrode sink in during the welding experiments. Also, electrode contact area was not taken during the peak of the first half wave of current application like in the simulation, rather at the end of the process. Thus, the actual area from experiment could be lower than the measured. One way to possibly overcome this problem could be to alter the spot welding simulation to have a defined electrode radius without electrode sink in during welding.

The main reason for the difference between experimental and numerical total resistance values could most likely be the difference in input RCE curves and actual RCE curves. A more accurate simulation must define the RCE as a function of interfacial pressure as well as temperature at the contact interface. The comparison of numerical and experimental techniques could be improved if the interfacial pressure influence on RCE was accounted for.

Still, it could be that the measured values are a perfect match to the real RCE values for HTC 600 X steel. The general shape and the presence of a RCE peak are clearly seen with this new approach. Using these curves in subsequent simulations would be the best way to test their accuracy. In order to do this, the temperature at the interface must be known, so that the RCE curve can be presented over temperature and not over maximum welding current.

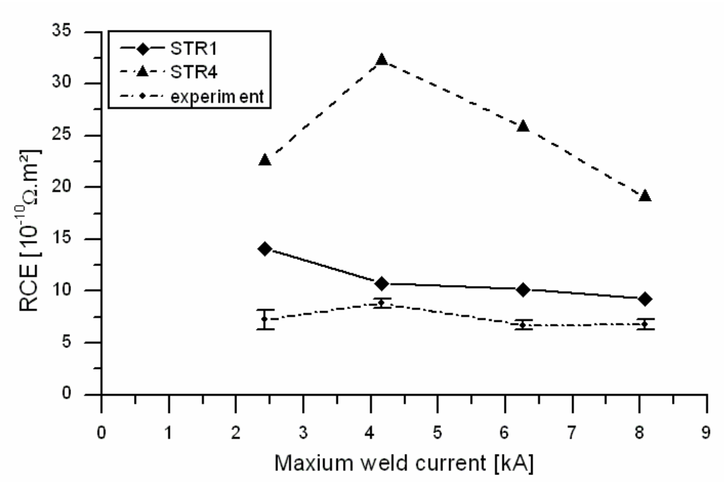

Fig. 15: Comparison of RCE values from experimental and simulation

CONCLUSIONS

Numerical methods were employed with the FEM program SYSWELD to verify the accuracy of a new approach to experimentally find the RCE at the E/S interface during resistance spot welding. The simulation of the resistance spot welding process was performed on uncoated single sheet HTC 600 X material with real time current waveforms of one period AC using two different RCE curves. The contribution of the material bulk resistance and RCE at the E/S interface to the measured total resistance in the electrodes was found for all input current values using numerical techniques.

The total resistance curve from simulation was converted to RCE using the actual electrode contact radius at the time of the measured resistance values. This curve closely resembled the input RCE curve from simulation in the lower current range, and the contribution of material bulk resistance was accounted for in RCE calculations. It was determined that the newly proposed measuring technique accurately measured the RCE from total resistance values in the electrode in the lower current range.

The total resistance curve was experimentally measured during the welding process for HTC 600 X steel using this new approach. The results showed the shape of the RCE curve at the E/S interface had the characteristic peak in resistance. This peak occurred at similar maximum current values in the simulation. The experimentally measured total resistance was found to increase in the higher current range, which was also similar to simulation results. The compared temperature profiles showed that the experiment represents a lower value estimation of interface temperatures when compared to the STR 4. From these results, it was determined that the total resistance measurement in the electrodes from the experiment represented real RCE values.

The total resistance values were converted to RCE using the electrode contact area taken from the stereoscope. The values are shifted to a lower resistance, which could be accounted for by a difference of interfacial pressure compared to the input RCE curves.

Overall, it was determined that the newly proposed method for experimentally measuring the RCE during welding is very accurate regarding the shape and possibly the values of the curve in the lower range of maximum applied currents. This proves to be a significant finding, especially for improving the accuracy of the resistance spot welding simulation and directing further research in the resistance spot welding field.

FUTURE OUTLOOK

The influence of interfacial pressure, surface oils, and metallic or organic coatings on the RCE curve can be evaluated with this new approach for measuring the RCE at the E/S interface during resistance spot welding. The knowledge of the shape and resistance values at the E/S interface can also facilitate inverse models for predicting actual interface temperature during welding in an effort to display the experimentally measured RCE curve over temperature. In order to accomplish this, standardized electrode geometries matching those from experiment should be used in the simulation in order to fully account for the influence of the electrode geometry on the current distribution. Most important, however, this technique can be implemented to determine the RCE at the S/S interface using double sheet experiments. This value is of utmost importance for weld formation during the welding process, and the use of exact RCE curves will greatly improve the accuracy of the resistance spot welding simulation.

ACKNOWLEDGEMENTS

The authors would like to thank the financial support of k-net JOIN, network of excellence for joining under the Federal Ministry of Economy and Labor, Austria. Also thank you to voestalpine Stahl GmbH, Linz, for providing material and assistance for the welding experiments.

New Method for Measuring the Electrical Contact Resistance during Resistance Spot Welding

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