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Original article

Influence of the current source on microstructure and degradation of the copper-steel interface during resistance spot welding

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Abstract: Recent investigations tend to indicate that the nature of the source of current (DC, AC low or high frequency) affects significantly the electrode wear mechanism during resistance spot welding (RSW) of steels. It has been also demonstrated that the electrical current affects microstructural transformations occurring during heat treatment of metallic materials, when performed using Joule heating systems. We explore in this work the influence of welding current (50 Hz AC or 1000 Hz Medium Frequency Direct Current, MFDC) on the degradation of the copper-steel interface during repeated instrumented RSW experiments on a automotive high strength steel. In order to analyze the contribution of current-sensitive microstructural transformations in the degradation process, model experiments are also performed on an idealized copper-steel system using controlled heat treatments with different heat sources, from lamps to Joule heating. The influence of the nature of welding current is then demonstrated, with strong potential implications on a wide variety of engineering systems exploiting Joule heating effect.

Keywords: Resistance Spot Welding (RSW); Electrode wear; Current-induced transformations; Copper alloys

Nomenclature and abbreviations

Nomenclature

AC	Alternative current
DC	Direct current
HT	Heat treatment
MFDC	Medium frequency direct current
SPS	Spark Plasma Sintering
RSW	Resistance spot welding

1. Introduction

Copper-steel interfaces can be found in a wide range of industrial processes and systems, from special purpose furnaces

for ultra-rapid thermal treatment of metallic materials to the resistance spot welding (RSW) process widely used in the automotive industry on automated assembly lines. The Joule effect is used in these systems to generate heat at the interface. The question raised in this work is related to the influence of the power source and electrical current (from direct current, DC; to alternative current, AC, with various wave shapes and frequencies) on the transformation of the materials in contact in the vicinity of the interface.

In the context of RSW of automotive steels, 50 Hz AC electrical current has long been a standard in the welding process. Nevertheless, 1000 Hz Medium Frequency Direct Current (MFDC) emerged in the last decades as a new standard for industrial RSW on automotive assembly lines, allowing more efficient energy use. Electrode wear mechanisms under 50 Hz AC current have been widely studied in the past (e.g. Tanaka et al. [1], Holliday et al. [2], Dupuy [3], Chan [4], Gauthier [5]) and distinguish two main modes of degradation:

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first, the overageing of the CuCrZr electrode alloy under the repeated influence of heat induces a softening of the material and a progressive yielding and widening of the active face under the action of the clamping force. Second, when welding galvanized steels, interdiffusion of Cu (electrode) and Zn (steel coating) might occur after repeated welding cycles and produce a brass phase at the interface, which is again detrimental for the control of the active face of the electrode. Under production conditions, this degradation is generally counteracted by gradually increasing the welding current in order to ensure a good weld quality. However, little is known in the literature on electrode wear mechanisms under 1000 Hz MFDC welding conditions, except for example in a recent study by Mathiszik et al. [6].

In the context of academic studies regarding phase transformations and new types of thermomechanical treatments of metallic alloys, it has long been assumed that the thermal cycles and applied mechanical fields alone would dictate the microstructure evolution, independently of the nature of the heat source (Joule heating systems or classical heating by radiation, convection). However, the influence of electrical current has been evidenced in the context of electromigration studies (e.g. Chen et al [7], Abé et al. [8]) and also appears to influence the kinetics of recrystallization and phase transformation in metals [9-12]. Nevertheless, the interpretation of these results is not straightforward because it is difficult to decorelate the influence of the Joule effect in itself from the influence of the nature of the electrical current and its directional effects.

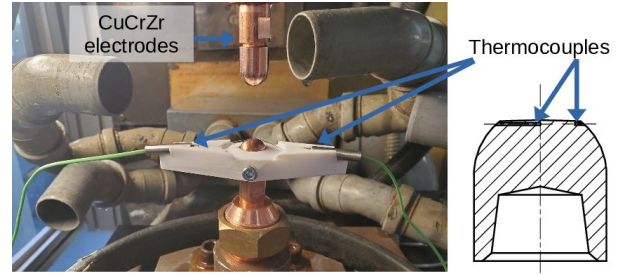
The present papers focuses first on the influence of the nature of electrical current on electrode wear during instrumented resistance spot welding. A new type of electrode defect is presented under 1000 Hz MFDC current, compared to 50 Hz AC electrode wear. The potential contribution of current-induced microstructural transformation is explored afterwards, using model experiments on sandwich Cu/Steel/Cu specimens. These are subjected to thermal cycles, with or without Joule effect, representing the accumulated time at elevated temperature at the active face of the RSW electrodes.

2. Materials and procedures

Figure 1 shows the instrumented resistance spot welding setup used to monitor temperature during the process. F1 electrodes with a 6mm tip diameter were made of a high strength, high conductivity CuCrZr alloy (RWMA Class 2). Two thermocouples (K-type) were inserted at 0.5 mm below the surface in the center and on the edge of the active face.

RSW was performed on a symmetric assembly of two martensitic press-hardened steel sheets (1.5mm Usibor1500, AISi coating). Welding was performed at the upper end of the welding range, using a 7 kA welding current, 380 ms welding

time and an electrode force of 4.5 kN (ISO 18278-2 conditions). The electrode wear study was performed using series of 300 spot welds. Each test condition was duplicated by setting the pedestal RSW machine to 50 Hz AC electrical current and to 1000 Hz MFDC current. Interrupted series up to 50, 100, 150, 200 and 300 spot welds were also performed for metallographic and profilometric analysis of the electrode wear.



Welding : 50 Hz AC or 1000 Hz MFDC

Figure 1: Instrumented resistance spot welding under 50 Hz AC or 1000 Hz MFDC electrical current.

The same CuCrZr alloy was used to produce 5mm thick copper cylinders (diameter 11mm) for use in the Cu/Steel/Cu sandwich experiments of Figure 2. The inserted steel coupon was made here of a bare DP600 sheet (1.5 mm thickness, 12 mm diameter). K-type thermocouples were inserted in the center of the Cu cylinders at 1 mm from the interface on both sides of the assembly. The Cu/Steel/Cu samples were first diffusion bonded in a Spark Plasma Sintering (SPS) furnace for 10 min at 500°C. This corresponds to the initial state of the samples for further investigation of current-induced transformations. Based on the thermal cycles recorded during the RSW experiments, the sandwich samples were then subjected to 5 min heat treatments between 500°C and 700°C. This approximates the accumulated time at high temperature in the vicinity of the active face in the RSW electrodes, after 300 welds.

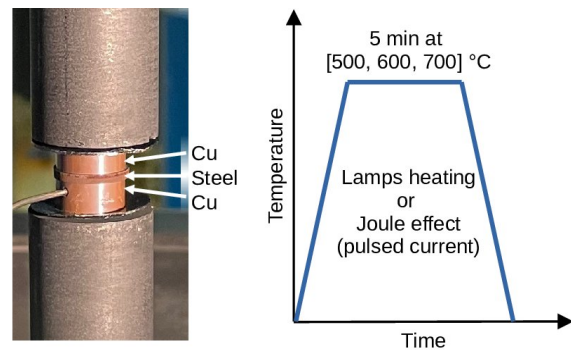


Figure 2: Model experiments on Cu/Steel/Cu sandwich samples, under lamps heating or Joule heating.

The thermal cycles (100°C/min heating rate) were carried out under two types of heat sources: lamps heating in a dedicated AET furnace and Joule heating under 67 Hz pulsed current in

the SPS furnace. The samples were then cut, polished and subjected to nanoindentation measurements (using a Berkovich tip down to 2000 nm indentation), metallography analysis in a Hirox numerical microscope and EDX analysis in a scanning electron microscope (SEM).

3. Results and Discussion

3.1 Temperature and electrode wear monitoring

Figure 3 shows the records of peak temperature in the center of the active face of the electrodes, over 300 resistance spot welds. One can see that the peak temperature remains approximately stable, at about 650°C, in the case of 50 Hz AC RSW. The situation is rather different in the case of 1000 Hz MFDC electrical current. Namely, the peak temperature remains close to the one recorded under 50 Hz AC for the first hundred spot welds only. Between 100 and 150 spot welds, 1000 Hz MFDC peak temperature steadily decreases to about 500-550°C and then stabilizes in this temperature range.

Similar stable peak temperature was recorded on the edge of the active face (second thermocouple in Figure 1) during 50 Hz AC RSW, at about 550°C. During 1000 Hz MFDC RSW, the second thermocouple broke after about 150 spot welds. It recorded a slightly lower and decreasing temperature on the edge of the active face, down to about 350°C after 150 spot welds.

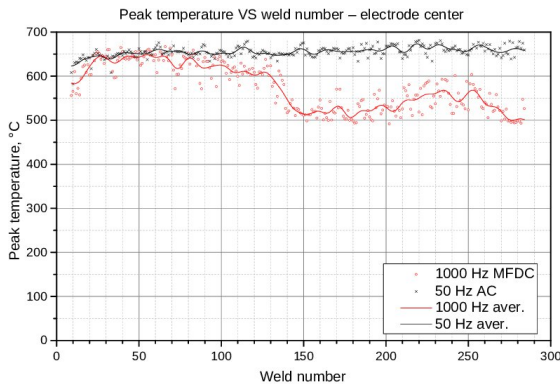


Figure 3: Peak temperature evolution over 300 spot welds in the center of the active face of the electrode, under 50 Hz AC and 1000 Hz MFDC resistance spot welding.

Figure 4 shows the evolution of the active face of the electrodes from the interrupted electrode wear analysis. Figure 4.b depicts that the active face experienced little modification after 150 spot welds under 50 Hz AC welding current, when compared to the initial cross section of Figure 4.a. However, the 1000 Hz MFDC electrode of Figure 4.c already shows significant alteration of the active face after the same number of spot welds. Namely a button is developing from the electrode

tip, with a diameter of about 4 mm and a height up to approximately 500 μm. Closer look at the metallographic cross section in the vicinity of the defect would show significant flow of matter towards the exterior of the electrode, producing the extra button height compared to the initial surface profile of the electrode tip. The button starts to become prominent in this case after about 100 welds. Note that its diameter of about 4 mm is smaller than the initial electrode tip diameter (6mm), which is uncommon compared to the usual widening of the active face over repeated resistance spot welds with a single set of electrodes [2].

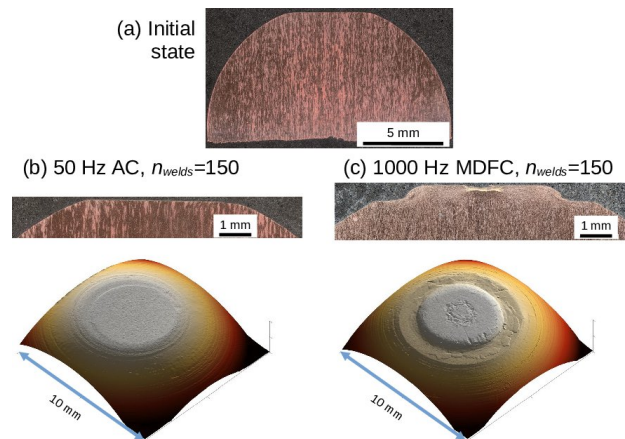


Figure 4: Electrode wear defect. (a) Metallographic cross section in a new CuCrZr electrode. (b, c) Metallographic cross section and profilometric analysis after 150 welds under 50 Hz AC current and 1000 Hz MFDC current respectively.

One should mention that the 50 Hz AC electrode also shows some alteration of the tip surface after a few hundred welds, as documented in the literature, but with no extra-height compared to the initial surface profile. It rather conforms in that case to the usual yielding, widening and alloying of the electrode tip under the combined effect of the clamping force, of heat at the interface and of the presence of the AISI coating at the steel surface.

Combining the observations and measurements of Figure 3 and 4, one can attempt to clarify the course of events and suggest that the failure of the second thermocouple at the edge of the active face during 1000 Hz MFDC welding occurred due to the flow of matter accompanying the formation of the button defect of Figure 4.c. The decrease of 1000 Hz MFDC peak temperature in Figure 3 is concomitant of the prominent button apparition on the active face of the electrode. It is however not clear at this point if the decreasing temperature, in the presence of the defect, results (i) from a larger distance of the center thermocouple to the active face or (ii) from the modification of the contact resistance and distribution of current density. Furthermore, the mechanisms behind the defect formation under 1000 Hz MFDC current need to be clarified. First, the contribution of the dynamics of electromagnetic fields in the vicinity of the

steel/electrode interface has to be assessed. Second, little is known about the cyclic deformation behavior of the electrode copper alloy under the complex multiphysics loading experienced at the active face during RSW. Finally, the contribution of current-induced microstructural transformations in the material is also unknown at this point and explored in the following.

3.2 Model interface experiments

The Cu/Steel/Cu sandwich experiments of Figure 2 were designed to highlight the potential effect of electrical current on microstructure evolution under controlled thermal cycle conditions. The present paper focuses on comparison between samples produced under lamps heating and Joule effect (SPS) conditions.

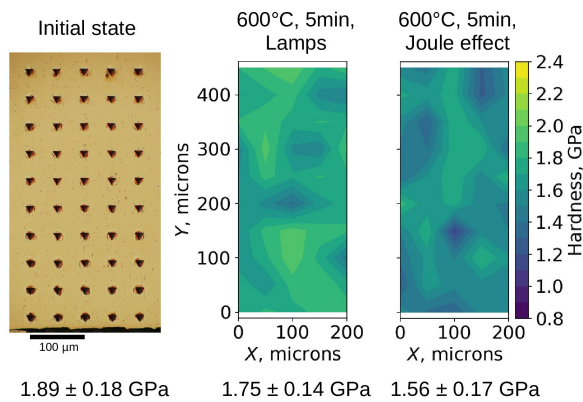


Figure 5: Nanoindentation hardness maps in the CuCrZr alloy up to 400 microns from the Cu/steel interface, after 600°C 5min heat treatment under lamps or Joule heating.

Figure 5 shows hardness maps obtained by nanoindentation in the CuCrZr alloy, in the vicinity of the interface with steel. The initial state of the samples, where the Cu/Steel/Cu sandwich was assembled by 500°C-10 min diffusion bonding in the SPS, shows a nanohardness of about 1.9 GPa compared to the as-received high strength CuCrZr alloy with a 2.1 GPa nanohardness approximately. The hardness maps after 600°C-5min heat treatment show a noticeable softening of the CuCrZr alloy down to about 1.75 GPa under lamps heating and 1.56 GPa under Joule effect conditions. One can note that the dispersion of nanohardness from one point to the next in the maps is rather high with an overall standard deviation of 0.14 to 0.18 GPa. While such dispersion is common with nanohardness measurements, providing local probing of the heterogeneous microstructure under the indenter, the maps of Figure 5 do not depict significant gradients in hardness from the interface with steel (origin of the Y-axis) to about 400 μm in the bulk of the CuCrZr alloy. However, it is worth to highlight here that the same thermal cycle performed under lamps or Joule effect

heating produces different softening of the material. Namely, the effect of pulsed electrical current used in the SPS furnace to produce Joule heating appears to accelerate the softening process (1.75 GPa to 1.56 GPa nanohardness on average).

Figure 6 shows microstructural investigations in the CuCrZr alloy in the vicinity of the interface. Figure 6.a depicts a typical metallographic micrograph of the material where coarse precipitates (approximately 1 μm in size) can be seen. The EDX maps of Figure 6.b confirms that these correspond to Cr and Zr precipitates in the Cu matrix of the CuCrZr alloy.

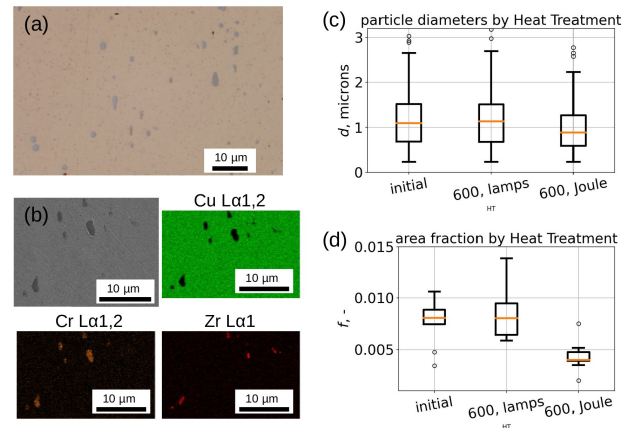


Figure 6: Microstructure analysis of the coarse Cr/Zr precipitates in the CuCrZr copper alloy. (a) Metallographic cross section; (b) EDX analysis; (c) and (d) boxplot distributions of the coarse precipitates diameter and area fraction in the different microstructural states.

Figure 6.c and 6.d show the distribution of these precipitates in the different samples. Using ten microstructure images in each sample configuration allows to obtain a representative overview of these distributions. Figure 6.c shows that the average diameter of the coarse precipitates is in the order of one micrometer, the biggest one reaching a few microns in length. Little modification of diameter distribution occurs during the different heat treatments, despite a slightly lower position of the median value (just below 1 μm) and quartiles with the Joule effect HT compared to lamps heating. Figure 6.d depicts higher differences between the samples in terms of area fraction of the coarse precipitates in the maps. Initial state and 600°C-5min sample by lamps heating present a median area fraction of coarse precipitates in the order of 0.008. It drops to about 0.004 in the case of the 600°C-5min sample obtained by Joule heating.

It is worth to mention that the coarse precipitates of Figure 6 are not the ones contributing mostly to the hardening of the alloy. Indeed, the latter is mostly influenced by nanosize precipitates and the high dislocation density in the high strength CuCrZr alloy [5]. These would require higher resolution microstructural imaging by transmission electron microscopy (TEM) for example. It is however expected at this point that the trends observed in this work regarding the effect of electrical

current on either nanohardness or coarse precipitates distribution in the CuCrZr alloy will be confirmed by on-going advanced microstructural analyses.

As a final comment, the influence of the source of heating on microstructural transformations in the electrode alloy was highlighted through the comparison of lamps heating and Joule heating by pulsed electrical current in the present Cu/Steel/Cu sandwich experiments. The setup presented in this work allows however versatile control of the power source and is currently being used to investigate the effect of DC current Joule heating compared to pulsed current in the SPS furnace.

6. Conclusions

The influence of electrical current in copper/steel interface systems was investigated in this work, in the context of resistance spot welding of steels for the automotive industry.

Electrode wear studies using 50 Hz AC and 1000 Hz MFDC RSW highlighted the development of a new type of electrode defect when welding under 1000 Hz MFDC electrical current. It appears as a prominent small button developing from the active face of the electrode and is concomitant with significant alteration of the thermal cycles at the electrode tip during the RSW process.

Among the many complex and multiphysics mechanisms at play at the steel/electrode interface during RSW, the potential contribution current-induced microstructural transformation in the electrode copper alloy was explored. Using model experiments on Cu/Steel/Cu sandwich samples subjected to identical thermal cycles, it was found that Joule effect heating affects the softening of the CuCrZr electrode alloy compared to standard lamps heating. Further experiments are on-going on this topic to control the nature of electrical current precisely and unravel its effect on the evolution of microstructure in the vicinity of the copper/steel interface.

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