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[1]Laboratoire d'Ingénierie des Matériaux de Bretagne, Université de Bretagne-Sud / UEB,

Centre de Recherche Ch. Huygens, BP 92116, 56321 Lorient Cedex, France

[2]PSA Peugeot-Citroën, DITV/PMXP/CEB/ASG, Centre Technique de Vélizy, Route de Gisy,

78943 Vélizy-Villacoublay Cedex, France

[a]denis.carron@univ-ubs.fr, [b]elise.gauthier@univ-ubs.fr, [c]cedric.pouvreau@univ-ubs.fr
[d]philippe.rogeon@univ-ubs.fr, [e]philippe.pilvin@univ-ubs.fr, [f]jacky.soigneux@mpsa.com,
[g]thomas.lety@mpsa.com

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Abstract. High strength zinc-coated steels are used for automotive applications when high corrosion resistance and weight reduction are required. Resistance spot welding is the main method to assembly auto body. Steel sheets are held together under pressure exerted by copper alloy electrodes which concentrate welding current and clamp the sheets together. But welding of high strength coated steels reduces the electrode life. Even if electrode deterioration is a well-known problem, the understanding and modelling of the complex deterioration modes at different regions of the electrode is still limited. Developing a comprehensive thermo-electrical-metallurgical-mechanical model that describes the sequential deterioration is thus lacking. This work is a preliminary study which specifically addresses microstructural evolution modelling in age hardened CuCr1Zr electrode alloy. Evolution of precipitation is simulated using two models: a Johnson-Mehl-Avrami-Kologoromov model and the Myhr and Grong model. In both cases a calibration procedure based on hardness data was involved. Short isothermal heat treatments were used to develop a 'master curve' which captures the precipitate evolution. Preliminary results about the comparison of the two models are presented.

Introduction

Resistance spot welding (RSW) is the main process to assemble steel sheets in the automotive industry. Steel sheets are held together under pressure exerted by copper alloy electrodes which concentrate welding current and clamp the sheets together. Since high corrosion resistance and weight reduction are required for vehicles, the use of high strength galvanized steels has increased during recent years. Various parameters such as number of weld spots, time interval between spots and cooling of electrode control the electrode life. But RSW of high strength coated steels causes further problems for fabricators since it requires high electrode force and longer weld time, and generate a reaction of liquid zinc with copper alloy electrode surface. As a result, the overheated electrodes deteriorate by deformation and/or by chemical reaction with the zinc coating. The diameter of electrode increases until it reaches a critical value where the current density becomes too low to make an acceptable weld. Many experimental and numerical studies have been devoted to RSW process. Literature reviews can be found in [1,2]. In particular finite element analysis, which is a powerful numerical method, has been largely used to investigate the coupled interactions that exist between electrical, thermal, mechanical and metallurgical phenomena. But even if electrode deterioration is a well-known problem [3], the understanding and modelling of the complex deterioration modes at different regions of the electrode is still limited. In particular whether deformation or chemical attack appears to be the dominant deterioration mechanism is not clear [4]. Nevertheless it has been suggested that the life of electrodes may be increased by

enhancing their softening resistance. It is thus of great interest to develop a comprehensive electrical-thermal-metallurgical-mechanical (ETMM) model that describes the sequential deterioration in the different areas of the electrode. Since softening in age hardening electrode alloys is related to metallurgical changes that occur during cumulative spot weld thermal cycles, an adequate modelling of the evolution of precipitation during welding is of major importance.

This work is a preliminary study which specifically addresses microstructural evolution modelling in age hardening CuCr1Zr electrode alloy. According to the experience in numerical simulation of RSW achieved by one of the present authors [5] the commercial finite element code SYSWELD was chosen to develop the future ETMM model. As numerous cumulative spot welds will have to be simulated, it is important to prevent time-consuming calculations. Following this idea the evolution of precipitation is simulated using two models already implemented in SYSWELD. These models consists on semi-empirical approaches that do not provide a detailed description of the precipitation evolution - as mesoscale "size class" approaches could do - but which are known to successfully predict hardness profiles after welding. The first one is a Johnson-Mehl-Avrami-Kologoromov (JMAK) model used with a time-temperature equivalence parameter [6]. The second one is an adaptation of the Myhr ang Grong model initially established for age hardening aluminium alloys [7]. Input data for these models were established by involving a calibration procedure based on hardness data. Short isothermal heat treatments were used to develop a 'master curve' which captures the precipitate evolution. Preliminary results about the comparison of the two models are presented in this article.

Microstructural modelling

Preliminary assumptions. The two models are based on the preliminary assumption that the changes in hardness during a heat treatment or a welding cycle are due to a change in the volume fraction of hardening precipitates. It is also assumed that, as for age hardening aluminium alloy [7], there is a linear dependence of hardness on particle volume fraction. The electrode material is a peak-aged CuCr1Zr alloy. The alloy composition complies with the DIN 17672 standard with Cr content between 0.5 and 1.2 wt pct and Zr content between 0.03 and 0.3 wt pct. The hardening precipitates are Cr-rich particles which can dissolve and coarsen by subsequent heat treatments [8]. The normalised fraction of dissolved Cr-precipitate in the copper matrix can then be described by the relation

$$X = \frac{HV_{\max} - HV}{HV_{\max} - HV_{\min}} \tag{1}$$

where HV is the measured hardness, HV_{max} is the hardness in the peak-aged condition and HV_{min} is the matrix hardness when no hardening precipitates are present.

JMAK model. A JMAK model used with a time-temperature equivalence parameter was developed to simulate Cu-precipitation / dissolution / coarsening phenomena in AISI 17-4 PH stainless steel during welding cycles [6]. This model is applied in this work for CuCr1Zr alloy. The isothermal time-temperature equivalence parameter is given by

$$P(T,t) = t \exp\left(-\frac{Q_d}{RT}\right) \tag{2}$$

where Q_d is the activation energy for diffusion of Cr in Cu and R is the universal molar gas constant.

Dissolved precipitate fraction follows a JMAK empirical formula that can be written as

$$X = 1 - \exp\left[\ln\left(\frac{1}{2}\right)\left\{\frac{P(T,t)}{P_{0.5}}\right\}^{m} \right] \tag{3}$$

where $P_{0.5}$ is the equivalence parameter corresponding to a fraction $X=0.5$ and m is a constant factor. A differential form of Eq. 3 has been implemented in SYSWELD as

$$\frac{dX}{dt} = m\left(\frac{1-X}{\tau(T)}\right)\left[\ln\left(\frac{1}{1-X}\right)\right]^{\frac{m-1}{m}} \quad with \quad \tau(T) = \frac{P_{0,5}\left(-\ln 0{,}5\right)^{-1/m}}{\exp\left(-\frac{Q_d}{RT}\right)}. \tag{4}$$

Myhr and Grong model. Myhr and Grong [7] developed a simple model to describe the softening occurring in the heat-affected zone of arc welded 6082 alloy. It has also been applied more recently to predict the hardness variation across 6082 [9], 2xxx [10] and 7749 [11] aluminium alloy friction stir welds. It has been shown that the model describes not only precipitate dissolution but also account for softening caused by a mix of precipitate coarsening and dissolution [11]. This model is applied here to CuCr1Zr alloy. For isothermal treatment the time required for complete dissolution of the precipitates at temperature T is related to a reference complete dissolution time t_r* at temperature T_r by

$$t^* = t_r^* \exp\left[\left(\frac{Q_s}{nR} + \frac{Q_d}{R}\right)\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \tag{5}$$

where Q_d is the activation energy for diffusion of Cr in Cu, Q_s is the metastable solvus boundary enthalpy and n is a parameter which can be dependent on X. After an initial value of 0.5, n steadily decreases in the later stages of dissolution, due to impingement of adjacent diffusion fields. A simple diffusion model for precipitate dissolution gives

$$X = \left(\frac{t}{t^*}\right)^n. \tag{6}$$

This isothermal reaction kinetic was adapted by Sarrazin [12] for anisothermal treatment and has been implemented in SYSWELD. The rate of reaction is then written as

$$\frac{dX}{dt} = \frac{n}{t_r^*} X^{1-\frac{1}{n}} \exp\left[\left(\frac{Q_s}{nR} + \frac{Q_d}{R}\right)\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad with \quad n(X) = 0.5 - aX^b \tag{7}$$

where a and b are constant factors.

Calibration of models. If some parameters as Q_d and Q_s energy terms can be found or calculated from literature data, the others parameters of JMAK model and Myhr and Grong model need to be calibrated against experimental data. In order to establish softening data for CuCr1Zr alloy, small test specimens were machined from peak aged material and subjected to short isothermal treatment at temperatures from 550 to 800°C on a 3500 Gleeble machine. After hold times between 0.5 and 100 seconds the samples were gas-quenched and the hardness measured. The hardness data were then converted to X using Eq. 1 with HV_{min} = 78 and HV_{max} = 155. For each model a ‘master curve’ was plotted which contains information about the softening kinetics over the full range of conditions.

The values for Q_d and Q_s used were 195 kJ.mol^{-1} [13] and 110 kJ.mol^{-1} respectively. Q_s was calculated using classical Gibbs-Thompson equation with enthalpy of Cr dissolution and precipitate interfacial energy values taken in [14,15].
$P_{0.5}$ = 1.25 10^{-9} s and m = 0.6 values (JMAK model, Eq. 3) were calibrated from the plot of X vs. ln P (Fig. 1). One can notice that some of the data were not well fitted by the master curve.
For the Myhr ang Grong model and following the procedure presented in [7], the hardness data were plotted as log X vs. log (t/t^*) with t_r = 20 s and T_r = 800°C. By adjusting a and b values (Eq. 7) to 0.375 and 0.11 respectively, the data converged to a single dissolution master curve (Fig. 2).

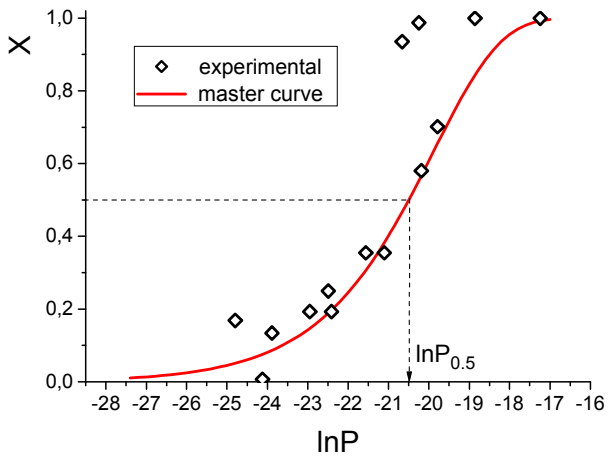

Figure 1 – JMAK model master curve for CuCr1Zr alloy.

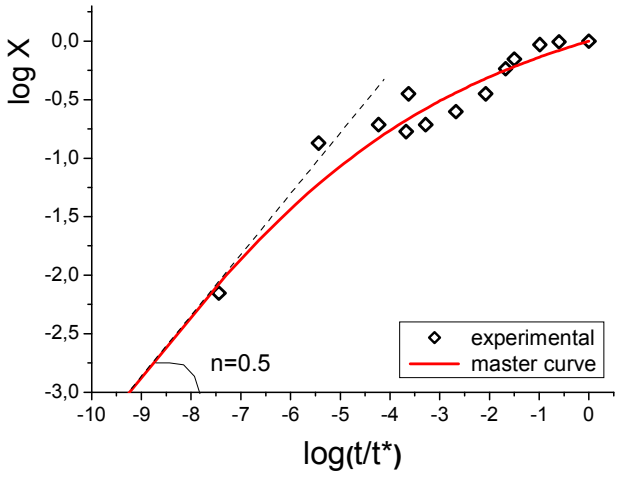

Figure 2 – Myhr ang Grong model master curve for CuCr1Zr alloy.

Application to cyclic heat treatments

Both of the models have been applied using temperatures cycles obtained from a weld thermal Gleeble simulation experiment. These experiments are carried out on an instrumented sample (Fig. 3) that has undergone a cyclic heat treatment to cumulate softening. Ten consecutive fast heating and cooling ramps were interrupted by short plateaus of 3s. The Gleeble 3500 resistance Joule heating system induces axial temperature gradients which lead to different thermal cycles along the specimen length (Fig. 4). The plateau temperatures measured by the four thermocouples were between 510 and 750°C. The heating (≈ 200°C.s^{-1}) and cooling rates (≈ 70°C.s^{-1}) are significantly lower than those experienced in a real RSW situation but are considered to be sufficiently high to prevent any microstructural evolution on heating and cooling.

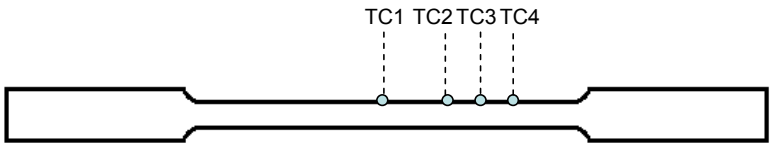

Figure 3 – Geometry of the reduced central section cylindrical sample used in the Gleeble simulation experiment (TC1, TC2, TC3 and TC4 refer to the positions of the thermocouples).

Calculations were performed in SYSWELD code with JMAK and Myhr and Grong models to simulate microstructural evolutions in the sample (Fig. 5). Since the CuCr1zr alloy used for the Gleeble simulation experiment has not exactly the same composition than the one used for calibration, hardness has been predicted from calculated softened fraction X using Eq. 1 with slightly modified HV_{min} and HV_{max} values. These values are in accordance with the experimental hardness in peak-aged and fully softened condition respectively. Predicted hardness values have

been satisfactorily compared with the measured data at the thermocouple locations (Table 1). Both of the two models capture the progressive softening of the alloy but predicted microstructure evolution during cycling is quite different (Fig. 5). In particular the Myhr and Grong's model predicted softened fraction seems overestimated from the first plateau. The JMAK model predictions seem to be more reasonable. Further validation of the models is nevertheless required to confirm this assertion.

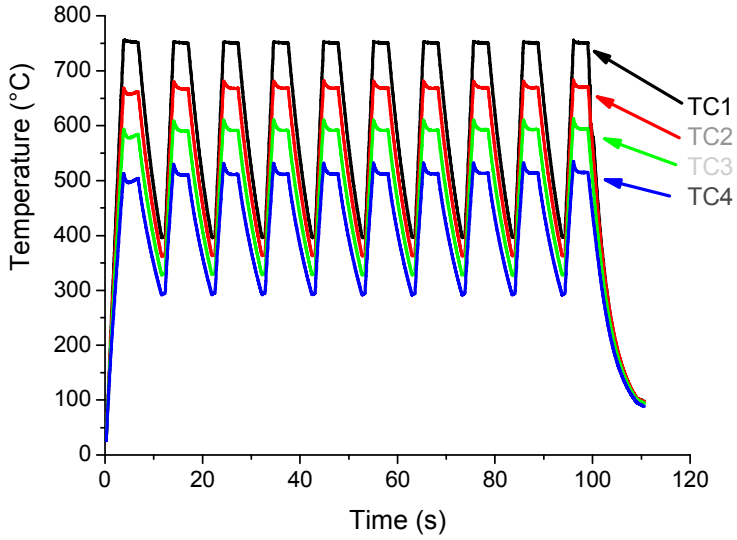

Figure 4 – Recorded thermal cycles during the Gleeble simulation experiment.

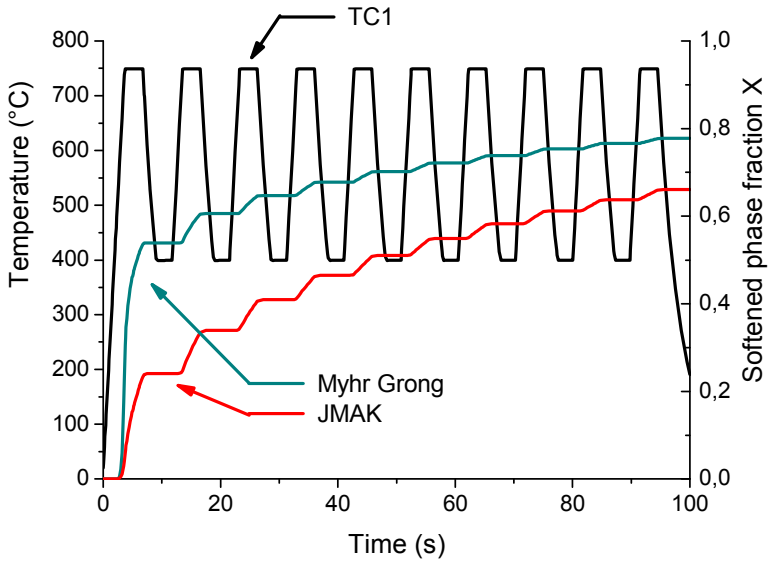

Figure 5 – Predicted microstructure evolution at TC1 location during the Gleeble experiment.

Table 1 – Comparison between predicted and measured hardness and softened fraction X for CuCr1Zr alloy after the Gleeble simulation experiment.

	Experimental			JMAK		Myhr and Grong	
	plateau temp. [°C]	measured hard. [HV0.3]	X	predicted hardness	X	predicted hardness	X
TC1	750	115	0.66	115	0.66	107	0.77
TC2	670	136	0.37	140	0.31	133	0.41
TC3	590	153	0.14	155	0.10	152	0.15
TC4	510	155	0.11	161	0.02	161	0.02

Conclusions

In this study the softening of CuCr1Zr alloy was predicted using two models: a JMAK model and the Myhr and Grong model. In both cases a calibration procedure based on hardness data was involved and master curve were plotted to identify some of the models' parameters. A comparison between predictions and a weld thermal Gleeble simulation experiment has shown that although both of the two models capture the progressive softening of the alloy, the softened fraction evolution predicted with JMAK model seems to be more reasonable. Nevertheless, before to select one of the two models for electrode softening prediction in RSW, further validation is required. In particular, completing the experimental data base by isothermal treatments at short time and high temperature and achieving resistivity and differential scanning calorimetry measurements could improve the calibration procedure and the significance of the master curves. Instrumented RSW tests would be also mandatory to fully validate the chosen model.

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