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Application of Direct Resistance Heating in Hot Forging and Analysis of Processing Parameters based on Thermo-electro-mechanical Coupling FEM

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Abstract: A series of experiments were designed in order to directly heat the billet of 42CrMo4 to the forming temperature in the dies prior to forming and continue to heat the billet during the forming process. Processing parameters during heating and forming were investigated by experimental method and thermo-electro-mechanical coupling FEM. The experimental results show that prior to forming the billet could be rapidly heated to forming temperature under relatively low initial contact pressure, and the heating temperature was proportional to the square of the current intensity. When the heating current remained constant, the heating temperature could not increase with heating time. During the forming process, the billet cooling rate slowed down and the forming time was extended due to the continuous resistance heating during forming. Finally, an incrementally coupled thermo-electro-mechanical model has been developed to analyze the hot-forging process by direct resistance heating. To obtain the transient temperature field prior to forming, a simple model of contact resistance was used in the thermal-electrical simulation, in which the electrical conductance of the contact resistance was proportional to the heating temperature. Contrasted the experimental results and the simulation results, it was found that they coincided well.

Keywords: resistance heating, hot forging, thermo-electro-mechanical model, contact resistance

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Introduction

Hot forging is widely used in industry because of low forming load and high formability of metal at high temperature. In the regular hot forging process, the billet is usually heated in a furnace at first, especially in the case of open die forging, and than transported into the forming dies. The billet is cooled rapidly in the air and must therefore be heated to a higher temperature, which leads to an increase in energy costs. On the other hand, the billet is rapidly cooled during the forming process due to the heating loss suffered by the conduction to the dies and by its radiation to the environment. This results in an increase of forming load and time. Thus, it is desirable to have a novel hot forging system which can heat the billet directly to the forming temperature in the dies prior to forming and continue to heat the billet during the forming process due to less energy consumption and very fast heating.

In Refs [1] and [2], the resistance heating was more conducive to direct heating than other heating methods such as induction heating and laser heating because of its higher energy efficiency and less dies shape limitations. Furthermore, it can be used with great flexibility and efficiency for high resistivity materials. Numerical simulations of direct heating of the billet in the dies using resistance heating are studied. The electro-upsetting [3, 4, 5, 6] is a typical example of the utilization of direct resistance heating in metal forming, but it is limited in local forming. The application of direct resistance heating to mushy state forming of aluminum alloy was studied by Maki et al. [7]. He performed his experiments in copper dies. In Refs [5, 8, 9, 10, 11, 12, 13, 14], the resistance heating was applied to warm and hot forming of high-strength steel sheets in order to improve spring back and formability. Yanagimto et al. [8] designed a continuous hot forming system for high-speed forming of high-alloy metal sheets and bars. However, the heating in Refs [4] and [3] was only applied prior to forming. The direct resistance heating has also been used in the resistance sintering technique [8, 15, 16, 17, 18] and the research on yield behavior of steel under rapid heating [4, 19, 20]. However, there is little research on the development of a system in the forging field, which can heat the billet during the forming process.

In this work, an experimental device was designed for direct heating of the billet during the forming process. Therefore, the objective of the present study is to investigate the effects of direct heating on the heating temperature and the final shape of the billet during forming. Eventually, the ultimate goal of this study is to develop a hot forging system that would not only heat the billet in the dies but also achieve isothermal forging. The paper primarily presents the experimental details and the simulation of the innovative hot-forging method. In order to study the effect of the initial contact pressure and the current strength on the heating temperature, the heating process before forming was studied firstly. Then, the billet was heated in the dies and then upset in the case of resistance heating or without resistance heating during forming. Finally, an incrementally electro-thermo-mechanical finite element model was used to study the hot forging process with direct resistance heating.

Experiment procedure

Experimental apparatus

The experimental setup used in this study is shown in Figure 1. The copper electrode having a thickness of 2.0 mm was placed in the groove of the die holder to prevent deformation of the electrode. The cylindrical billet was sandwiched between the dies. The billet, dies, electrodes and power supply formed a series circuit. When the DC current flowed through the dies and the billet, they were heated due to the Joule heating effect.

The entire device was set at the Zwick /z150 testing machine (maximum load of 150kN) to provide a certain pressure. The insulator was positioned between the setup and the testing machine to protect the test machine from current, as shown in Figure 1(b). The die made of heat-resistant molybdenum alloy (TZM) had a diameter of 120 mm and a height of 30 mm. All the experiments carried out in the air. To measure the temperature distribution of the device, two NiCr-NiSi thermocouples (diameter 0.5 mm) were used. As shown in Figure 1(a), the thermocouple No. 1 was located at the center of the billet (diameter 1 mm, depth 3 mm), indicating the temperature of the billet. The thermocouple No. 2 was located on the die surface and represented the temperature of the die.

Materials

The billet material is 42CrMo4, and the thermoforming temperature field is 850~1200 °C. Due to the power supply limitation, a cylindrical billet with a diameter of 6 mm and a height of 8 mm was used in the heating and upsetting experiments. The chemical composition of 42CrMo4 is shown in Table 1.

Table 1: Chemical compositions (mass%) of 42CrMo4.

C	Si	Mn	Cr	Mo
0.38–0.45	0.17–0.37	0.50–0.80	0.9–1.20	0.15–0.25

Heating experiments

The resistance heating was controlled by current intensity. DC power was supplied by the TSQLG 400-8 /2000 (maximum output of 8 v × 2000 A), resulting in a constant current. The initial conditions for the heating and

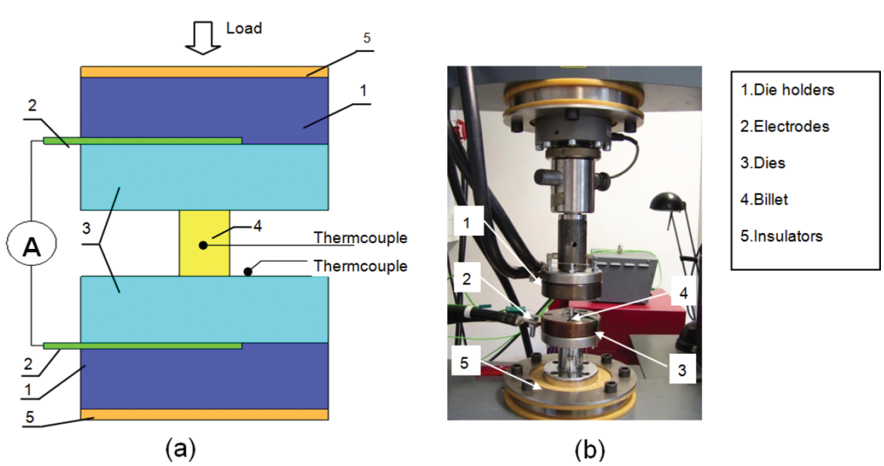

Figure 1: (a) Scheme and (b) photo of the experimental setup.

upsetting experiments were made up of the initial temperature and the contact pressure. In all experiments in this study, the initial temperature of the billet and the dies was room temperature. The initial contact press can be manually changed.

Upsetting experiments

In the upsetting experiments, the billet was heated to above 1000 °C in the dies, then kept at that temperature for about 5 s, and subsequently formed at a constant speed. After the upsetting, the billet was cooled down in the dies until it reached room temperature. Due to the relatively small size of the billet and the high cooling rate, the speed of the upper die was set at 1 mm/s to avoid excessive cooling during forming. When the maximum forming force reached 30 kN, the upsetting process stopped.

In order to determine the effect of the resistance heating during forming, two types of upsetting experiments were performed: (a) the resistance heating stopped before upsetting (case a) and (b) the constant resistance heating was applied during heating and upsetting (case b).

Experimental results and discussion

Analyses of heating process

It is one of the key issues of the system, whether the billet can be heated to the forming temperature in a short time or not. According to the Joule's laws, the heat generated in the billet depends on the current intensity, resistance and heating time. In addition, the heating dissipation of the billet depends on the conduction to the dies on the contact area and the radiation to the environment.

To improve the understanding of the heating process, a typical heating and cooling process under a current intensity at 400 A using the above described system was shown in Figure 2 (initial contact pressure: 5.3 MPa). The whole process can be divided into three stages, namely preheating, holding and cooling. During the preheating stage, the temperatures of the billet and the die rapidly increased to 262 °C and 63 °C in about 10 s at a current intensity of 400 A. The temperature of the die was much lower than that of the billet due to the larger volume and lower resistance of the die. Therefore, it was apparent that the temperature gradient between the billet and the die was steep. In addition, the minimum temperature of the billet occurred at the edge as a result of the heat loss through conduction and radiation.

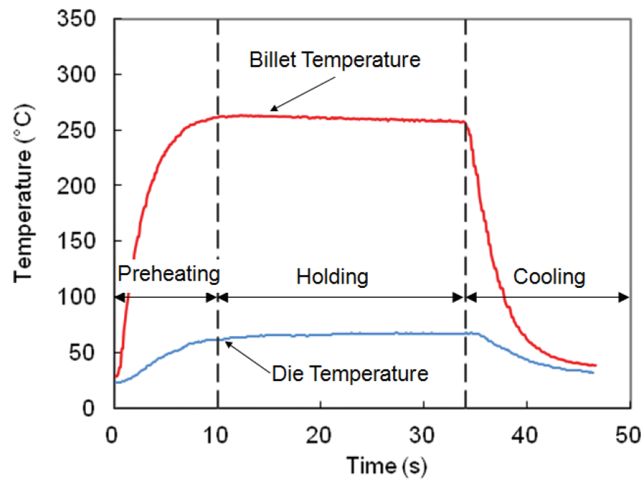

Figure 2: Time history of temperature in the resistance heating process.

At the holding stage, the temperature of the billet and the die was stabilized so as to strike a balance between the heating generation and dissipation. It can be observed that the heating temperatures cannot increase with the heating time at the holding stage. When the current was stopped during the cooling stage, the temperature of the billet rapidly reduced at a rate of about 60 °C/s due to the high thermal conductivity of the billet and the die.

Effects of the initial contact pressure on the heating process

The billet holding temperature at a current intensity of 400 A for different initial contact pressures was shown in Figure 3. The experiments show the heating temperature

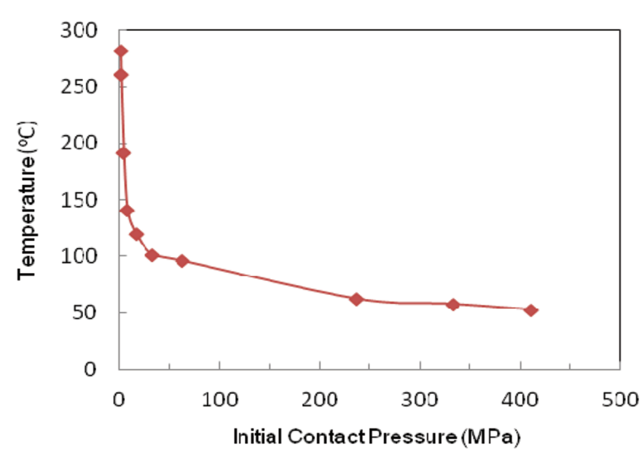

Figure 3: Effect of initial contact pressure on the billet holding temperature.

decreases as initial contact pressure increases. The effect of the initial contact pressure on the heating temperature can be explained as follows: Increasing the contact pressure consequently decreases the contact resistance and increases the heat transfer between the billet and the die due to the increase in the contact area.

It can be observed that the heating temperature is rapidly reduced as the initial contact pressure increases until the pressure reaches about 50 MPa. As the initial contact pressure increases above 50 MPa, the heating temperature tends to change slightly. This indicates that the smaller initial contact pressure is favorable for obtaining high temperature at the same current intensity. In addition, it can be said that due to the larger forming pressure, it is difficult to heating the billet during the upsetting process. Although the smaller initial contact pressure improves the heating temperature, it tends to result in an increase of local contact, which causes a rapid increase in the temperature of the surface. In this study, the initial contact pressure of about 3 to 15 MPa is optimal for good contact and higher heating temperature.

Effects of the current intensity on the heating process

The heating temperature for different current intensities is shown in Figure 4 (initial contact pressure 5.3 MPa). As can be observed in the graph, the heating temperature was significantly increased by increasing the current intensity. Figure 5 shows the relationship between the rise of the billet temperature at the holding stage and the square of the current intensity. It is clear that the rise in temperature is proportional to the square of the current intensity. Therefore, the heating temperature can be adjusted by changing the current intensity.

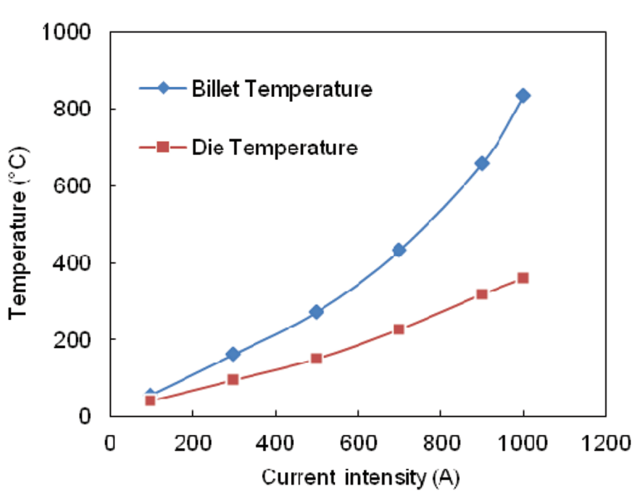

Figure 4: Effect of current intensity on temperature variation.

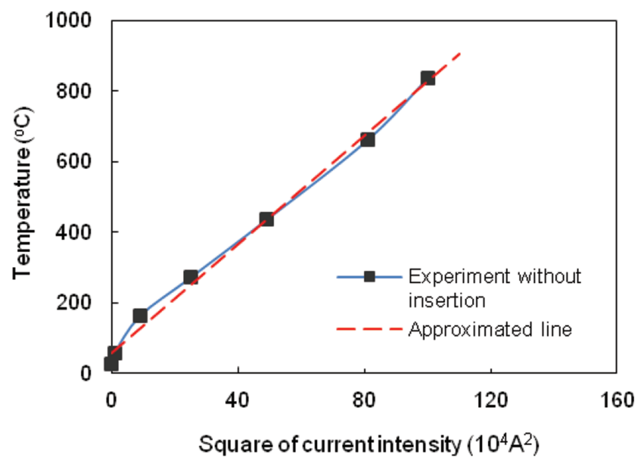

Figure 5: Relationship between the billet heating temperature and the square of current intensity.

Based on the above results, it can be concluded that the final heating temperature depends on the initial contact pressure, the current intensity during the heating process. The smaller initial pressure favors a higher heating temperature at the same current intensity. The heating temperature is proportional to the square of the current intensity at a certain initial contact pressure.

Analyses of upsetting process

The temperature history of the billet directly affects the forming process and the final shape of the billet. Two types of upsetting experiments were examined (see Figure 6). In case **a**, the resistance heating stopped before upsetting. In case **b**, the resistance heating continued during heating and upsetting to investigate the effect of the resistance heating during forming. In both cases, the current intensity was 1000 A and the initial pressure was 3.5 MPa. It can be observed that the billet can be heated to above 1000 °C in about 10 s.

After keeping the temperature for about 5 s, the upsetting test began and the temperature of the billet decreased significantly during the upsetting process. When the maximal forming force reached 30 kN, the upsetting process stopped. It was reported that the contact resistance was very sensitive to the interfacial conditions including roughness, oxide, pollution, hardness [19], and hence different heating temperatures were obtained in case of using the same heating parameters for different billets. As can be seen in the figures, the cooling rate was about 334 °C /s and 290 °C /s during the

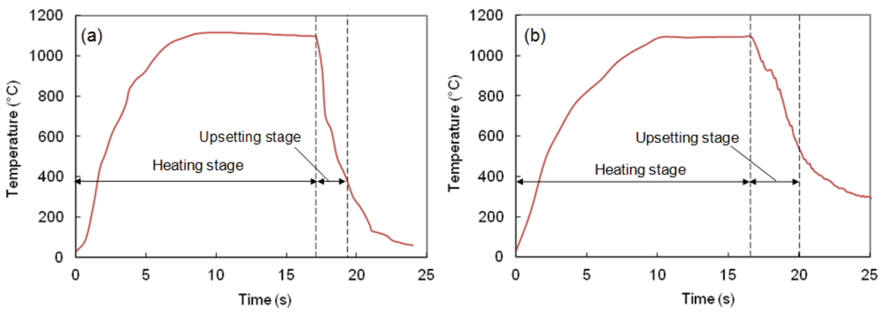

Figure 6: The forming process for (a) upsetting without resistance heating, (b) upsetting with resistance heating.

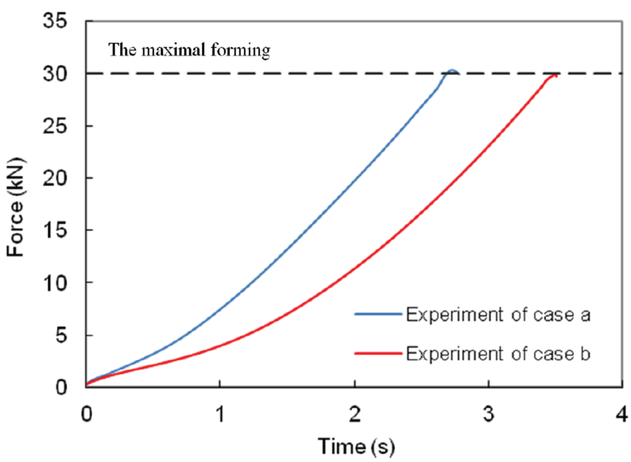

Figure 7: Forming time and forming force of different cases.

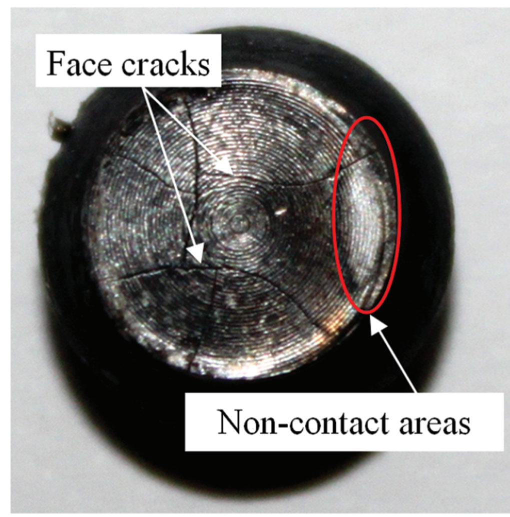

Figure 8: The billet face quality in the experiment of case b.

upsetting process in two cases. The final billet height values after upsetting were 5.2 mm and 4.5 mm respectively. This finding means that the continuous application of resistance heating during forming results in a significant reduction in the cooling rate, which extends the forming time as shown in Figure 7.

Effect on the forming quality

Many surface cracks and non-contact areas were observed on the formed billet surface (see Figure 8). The reason of the cracks was that the surface suffered from a large pressure at a relatively low temperature. In the experiments, the phenomenon of the non-contact areas is unavoidable because the surfaces of the billet are roughened and the hardness of two materials is large. In addition, the die's plastic deformation happened at the contact area because of the low temperature and large forming pressure. Higher current intensity and lower forming speed are considered to improve the forming quality.

Based on the results of both upsetting experiments described above, it is obvious that the billet can be heated to a forming temperature in about 10 s by using this system and the resistance heating during forming reduces the cooling rate and increases the forming time.

Numerical modeling

From the above analysis of the experiments, it is clear that the direct resistance heating method is feasible. Thus, in the following, the simulation related to this process will be presented and discussed. The properties of the 42CrMo4 and TZM used in the simulation process are shown in Table 2.

Finite element model

As shown in Figure 9, the two-dimensional axis-symmetric model to simulate the hot-forging process with direct resistance heating was developed. For the analysis, several assumptions are adopted to simplify the calculation and reduce the calculation time: (1) direct current (DC) is applied directly at the top of the upper die, and the electric potential is zero at the bottom of the lower die instead of

Table 2: Material properties for the simulation.

		Temperature (°C)					
		100	300	500	700	900	1100
42CrMo4	Electric resistivity ($\times 10^{-8}\Omega\cdot m$)	27.89	47.62	67.34	87.11	106.84	126.58
	Specific heating (J/(kg.°C))	490	568	665	900	600	645
	Density (kg/m^3)	7822	7751	7680	7604	7570	7480
TZM	Electric resistivity ($\times 10^{-8}\Omega\cdot m$)	5.78	11.39	17.65	23.23	29.83	35.64
	Specific heating (J/(kg°C))	250	265	274	291	300	320
	Density (kg/m^3)	10,200					

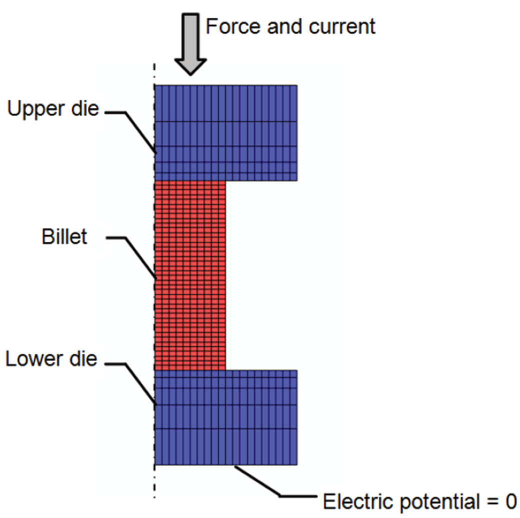

Figure 9: Finite element model of the experimental setup.

the function of the electrodes; (2) the die external diameter is changed to 18 mm and the height is changed to 10 mm. The outer surfaces of the dies are always kept at room temperature during the simulation; (3) the mechanical deformation of the die is neglected during the resistance heating process; (4) the decrease of the contact resistance with temperature is considered during the resistance heating prior to forming, and the contact resistance is constant during forming process.

Procedure of the simulation

Since the process is a thermo-electro-mechanical system, the corresponding modeling deals with a complex coupling of thermal, electric and mechanic phenomena. However, the true thermo-electro-mechanical model has not been reported at present. An incrementally coupled thermo-electro-mechanical model was used in the paper, which was composed with several electrical-thermal analyses and one thermal-mechanical analysis. The heating process prior to forming was first calculated by the electrical-thermal analysis, and the calculated temperature field was transferred to the thermal-mechanical analysis in order to calculate the displacement and the stress in a small increment. Afterwards, the displacement and the temperature of every node were transferred to another electrical-thermal analysis, which was used to calculate the temperature development after the increment. The updated temperature field was then transferred to the thermal-mechanical analysis for the calculation of the displacement and the temperature. This process continued until the forming process was finally completed.

The electrical-thermal and thermal-mechanical analyzes were implemented by the coupled thermal-electrical modeling and the coupled temp-displacement modeling in ABAQUS, respectively. 643 nodes and 550 elements were employed in the analysis. The thermal-mechanical analysis is divided into several parts in order to input and output the temperature field and displacement at every increment. The data transfer between the two analyses was carried out by the self-compiling programs. In this study, the heating time prior to forming was 17 s and the forming time was 4 s. The time increment during forming was 0.2 s.

Contact resistance model

The contact resistance at the interface has a dominant effect on the heating temperature during the resistance heating. Several models have been developed to deal with the contact resistance [4]. However, the availability of these models is limited because the parameters in the models are difficult to confirm. In the paper, a simple model of the contact resistance has been proposed in which the electric conductance of the contact resistance (σ_c) is proportional to the heating temperature, which can be expressed as follows:

$$\sigma_c = a_1 T + a_2 \tag{1}$$

where a_1 and a_2 are the parameters signifying the interface quality, material and contact pressure, T represents the interface temperature. For the resistance heating process under a certain initial contact pressure, the contact pressure increases with the increase of the temperature due to the thermal expansion, this suggests that the increment of the contact pressure is a function of the heating temperature. As a result, the contact resistance at a certain initial contact pressure can be expressed with a temperature-dependent model. Finally, the contact resistance can be obtained by the following equation:

$$R_c = 1/(\sigma_c A) \tag{2}$$

where R_c represents the contact resistance and A represents the contact area. In the simulation, the interface between the die and the billet is ideal. In the approach, the parameters a1 and a2 are generated by comparing the simulated and experimental heating temperatures at different currents and a certain initial contact pressure. The parameter a1 is 0.87 and a2 is 132 by the heating and forming process of Figure 6(b).

Figure 10 shows the holding temperature distribution and the temperature history at different locations by the contact resistance model at the current intensity of 1000 A. Three locations in the system are: (1) the center of the billet, (2) the center of the billet edge and (3) the lower edge of the billet. As can be seen in Figure 10(a), the temperature distribution of the billet was non-uniform. The highest temperature occurred at the middle range of the billet and the lowest temperature of the billet occurred at the edge of the billet at the end of the heating stage. As shown in Figure 10(b), the contact region between the billet and the die (point 2, 3) reached the stable stage more quickly during the heating stage. Then, the temperature of the billet center (point 1) increased slowly until the holding stage was reached.

Simulation of the forming process

Figure 11 shows the comparison of temperature distribution at the billet center between the experimental and modeling results. Although the conformity between the simulation and the experiment was good, the model tended to overestimate the temperature in the heating stage. One possible reason is that the reduction of the contact resistance in the simulation is slower than that in the experiment. The comparison of the cross-section shape between the experiment and the simulation is performed in Figure 12, and it is found that the simulation result is highly corroborated with the experimental result.

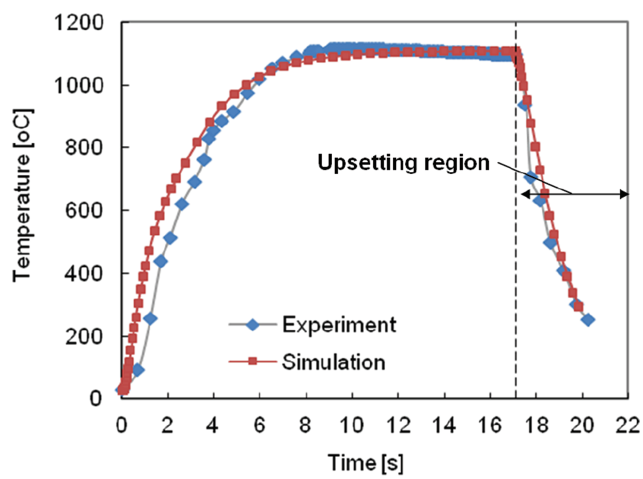

Figure 11: Time dependence of the temperature in the center of the billet in the experiment and the simulation.

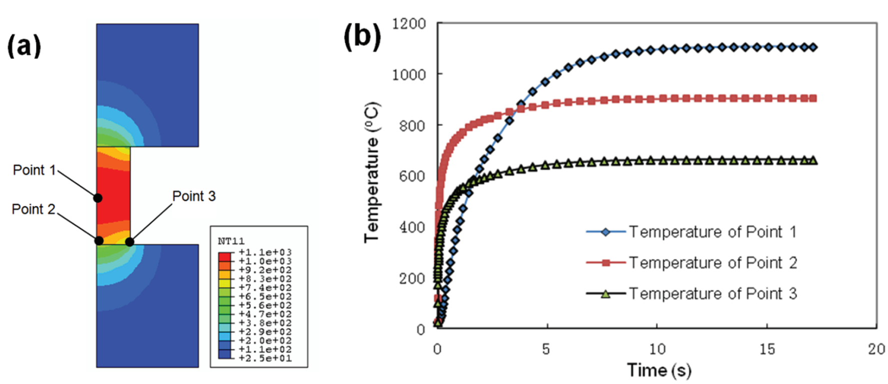

Figure 10: Predicted heating temperature during heating stage: (a) temperature distribution at the end of the heating stage and (b) temperature history at different points.

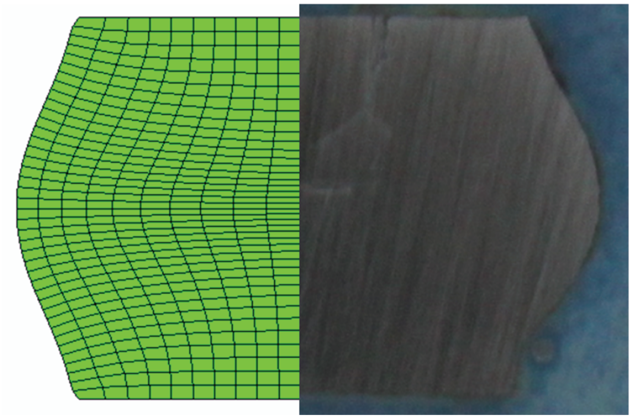

Figure 12: Comparison of the section shape between the experiment and the simulation.

Conclusion and outlook

In the present work, an innovative hot forging method with direct resistance heating was analyzed. The incrementally coupled thermo-electro-mechanical model of the hot-forging process by direct resistance heating was developed by the finite element method. The results are as follows:

1. With this experimental equipment, the billet can be heated to above 1000 °C in about 10 s in the dies.
2. The heating temperature is influenced by the initial contact pressure, the current intensity. Low initial contact pressure and high current intensity are useful for obtaining higher temperature. Moreover, the heating temperature is proportional to the square of the current intensity at a particular initial contact pressure.
3. The resistance heating during forming process effectively decreases the billet cooling rate and extend the forming time. Surface cracks, local contact and the die's plastic deformation occur during forming.
4. The incrementally coupled thermo-electro-mechanical model of the hot-forging process by direct resistance heating was developed, the consistency between the simulation and the experiment was satisfactory.
5. In the coupled thermal-electrical modeling, a simple model of the contact resistance was implemented in order to simulate the resistance heating, whose parameters were simple and easy to attain by the experiments.

In order to approach the goal of isothermal forging by the resistance heating, the continuous resistance heating process must be further studied by numerical and experimental methods.

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