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An Experimental Study Determines the Electrical Contact Resistance in Resistance Welding

Gleeble® machine experiments evaluated the influence of pressure, temperature, and metal properties on resistance welding

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ABSTRACT. Electrical contact resistance is of critical importance in resistance welding. In this article, the contact resistance is experimentally investigated for welding mild steel, stainless steel, and aluminum to themselves. A parametric study was carried out on a Gleeble® machine, investigating the influence on the contact resistance of interface normal pressure, temperature, and base metal.

Introduction

Contact resistance is one of the most critical parameters in resistance welding. Welding heat in resistance welding is generated by Joule heating, which is proportional to the total resistance of the weldment. Contact resistance varies to a great degree during welding, and it is the main component of the total resistance in a large part of the weld time. It is therefore valuable to have an insight into the dynamics of contact resistance during welding, and in numerical modeling, the contact resistance model is a key factor to success.

The contact resistance at the interface between two metals normally includes the following two contributions: constriction resistance and film resistance. When two metal surfaces each with a certain roughness are brought into contact, the real contact area of the mutually deformed asperities is much smaller than the apparent area as long as the normal pressure is below the yield stress of the softer material. When a current runs through the interface, the current flow lines bundle together passing through the separated conducting spots of real contact. This constriction of the electric current by the contact spots reduces the volume of metal used for electrical conduction locally at the interface, hence giving rise to a resistance named the constriction resistance. The film resistance is due to less-conductive surface films such as oxides, oil and water vapor, etc.

Contact resistance has drawn the attention of many researchers. Yet, despite numerous studies, most of which are experimental, contact resistance is still not well addressed. It is influenced by many factors like base metal, pressure, temperature, surface conditions, etc., and it is highly dynamic.

Some experimental studies were carried out to obtain a deeper insight on contact resistance in resistance welding (Refs. 1–17). The studies fall into two groups, which may be called the static and the dynamic methods, respectively. In the static method, the contact resistance across the interface is measured under well-controlled conditions, keeping the main parameters such as load, temperature, etc., constant during measurement. The parameters can be changed over a range to obtain their influence on the contact resistance.

Examples of the static method are in Refs. 1–5, among which Refs. 3–5 only deal with static resistance at room temperature. In this method, measurements are made under the state of equilibrium, and each parameter of interest is known. It is thus possible to determine the effect of a particular variable. The drawback is that the influence of dynamic effects on the contact resistance is not considered, and the process differs from resistance welding.

The dynamic method has been employed by more authors (Refs. 6–17). In this method, the contact resistance is examined in situ during resistance welding. Dynamic variation of contact resistance is recorded together with the simultaneous variation of many factors in the process. The contact resistance is often presented as a function of time, and sometimes as a function of load or temperature. However, all the concerned parameters change simultaneously during the welding process. This makes it impossible to extract the influence of a particular variable. In this view, the analysis on the influence of individual factors on contact resistance is not meaningful, but misleading in empirical works based on the dynamic method. These studies are, however, still of significance because they help gain better insight into the dynamics of the process. In this sense they are valuable, but none of them has led to a mathematical model that can be applied in numerical simulation.

The original objective of the current work was to establish a model of contact resistance that can be applied in simulation of resistance welding. Presented in this article is the experimental method, as well as the influence of interface normal pressure and temperature on contact resistance in welding carbon steel, stainless steel, and aluminum to themselves. Ef-

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KEYWORDS

Gleeble Machine
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Film Resistance
Static Method
Dynamic Method
Temperature
Pressure

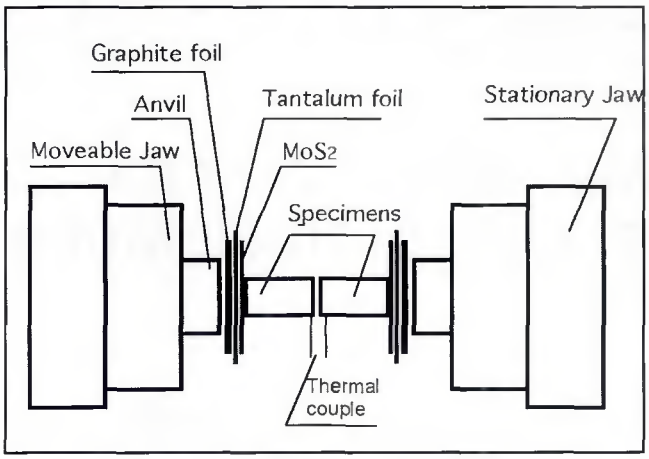

Fig. 1 — Schematic setup of the experiments.

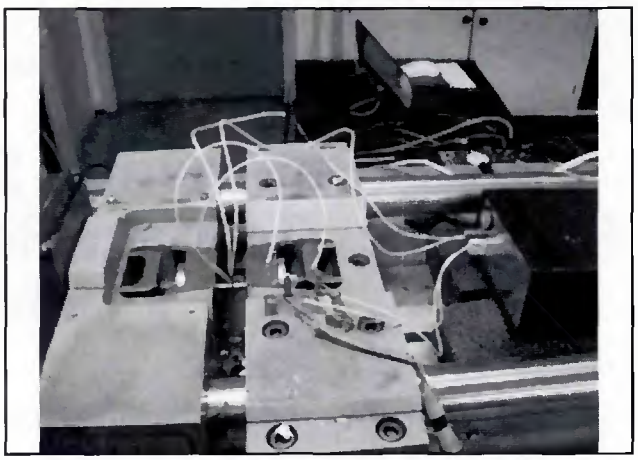

Fig. 2 — Experimental setup.

forts are made to ensure a systematic parametric study in a process resembling resistance welding.

Experimental Method

In order to investigate the influence of interface normal pressure and temperature on contact resistance, the static method is employed for the experiments.

Test Equipment

In the experiments, the temperature at the interface should change over a wide range, from room temperature to near the melting point, and the normal pressure at the interface should also vary significantly, covering the pressure range in real resistance welding.

To fulfill these purposes, dedicated equipment is required to heat the specimens and load them together. Presses equipped with furnaces were used by some researchers (Refs. 1, 2), yet the Gleeble® system (Refs. 18, 19) may be a better choice.

The Gleeble system is a dynamic testing machine that can simulate a wide variety of thermal/mechanical and metallurgical situations. Samples can be heated and mechanically loaded following a prescribed program, while the parameters of interest are measured and recorded for later analysis. The process of loading and heating can be controlled accurately and efficiently. Another benefit from employing the Gleeble machine is that it heats the specimens by resistance heating, exactly as in resistance welding. The identical mechanism of heating may provide the experiments with a better analogy to the real resistance welding process. Using the Gleeble machine in testing, we can make parametric studies of contact resistance during a process similar to resistance welding.

Specimens

The specimen metals are low-carbon steel W.Nr.1.0037 (≈ AISI 1018), stainless steel W.Nr.1.4301 (≈ AISI 304), and aluminum Al 99.5, semihard (≈ AA 1050). The materials chosen are widely applied in industry, and their mechanical and electrical properties cover a wide range. All the specimens of each particular metal were made from the same batch of bars and stored in air after machining.

The test specimens are circular cylinders with dimensions ø7.5 × 6 mm. They were produced by fine turning on a lathe from round rod of specified diameter using cutting fluid during machining. The surface roughness of the steel and stainless steel specimens was $R_a = 1.0 \pm 0.5$ µm, whereas the roughness of the aluminum specimens was $R_a = 2.0 \pm 1.0$ µm. The specimens were rinsed with compressed air after machining to remove excessive lubricant. Afterward they were stored in a dry, indoor atmosphere for approximately two months before use to ensure formation of a stable oxide layer. No subsequent cleaning, rinsing, or degreasing was carried out prior to the experiments, ensuring a surface condition similar to industrial conditions.

Physical Setup

The experimental setup is schematically illustrated in Fig. 1, and a photo is shown in Fig. 2.

Referring to Fig. 1, the specimens are compressed between two plane, overhanging anvils mounted in the Gleeble machine. One of the anvils is fixed to the movable jaw. During the tests, the Gleeble resistance heats the specimens to the specified temperature and adjusts the load according to the program. The voltage drop across the faying surface between the specimens and the current are measured, thus enabling calculation of the contact resistance using Ohm's law. This whole procedure of loading and heating is controlled by a Gleeble Programming Language (GPL) program, and measurement of temperature, load, and deformation is done with the GPL program as well (Refs. 20, 21).

Accuracy of temperature measurement is crucial in the experiments. The temperature is measured using thermocouple wires (Chrome-Alumel or Type K) that are percussion welded to the samples, one to each of the two specimens at a distance of 0.5–1.5 mm from the interface — Fig. 1.

In order to control the test temperature, special measures are taken to minimize the temperature gradient through the specimens. First, tantalum foils are placed between the anvils and specimens for thermal insulation. Second, the anvils are made of tungsten carbide, which is electrically conductive but of poor thermal conductivity, and the jaws to hold the anvils are made in stainless steel (hot jaws). Third, measurements are not started until a certain period of heating to allow for sufficient heat transfer within the specimen. In addition, graphite foil is placed between the anvils and the tantalum foil, and molybdenum disulphide powder is brushed on the other surface of the tantalum foil facing the specimen in order to reduce friction

Measurements

During each experiment, the following parameters are measured:

- Force
- Deformation of specimens
- Interface temperature
- Heating current
- Voltage drop across the interface

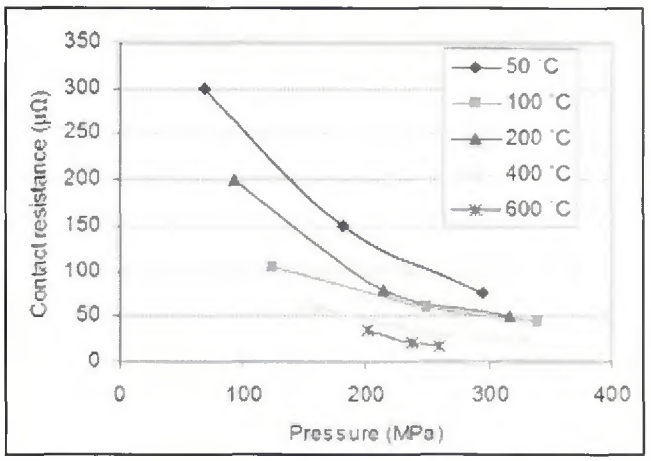

Fig. 3 — Contact resistance of mild steel contacts vs. pressure and temperature.

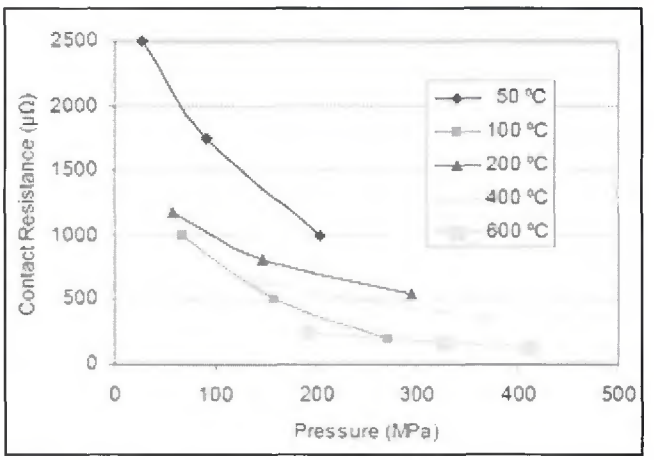

Fig. 4 — Contact resistance of stainless steel contacts vs. pressure and temperature.

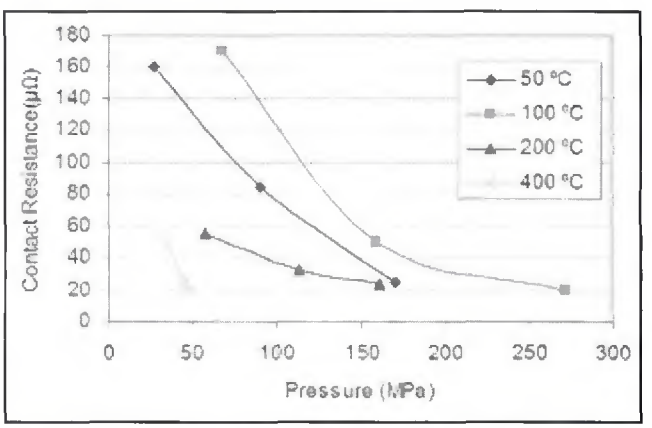

Fig. 5 — Contact resistance of aluminum contacts vs. pressures and temperature.

Among these, the first three parameters are recorded with the control unit of the Gleeble, while the others are measured by additional transducers. The heating current is measured using a Rogowski coil (TECNA – 1430) encircling the specimens. The voltage drop is measured using two wires connected to each side of the faying surface. The wires are percussion welded to the specimens as close as possible to the interface.

The signals are collected with a data-acquisition board (DAQPad-6020E from National Instrument) connected to a PC. A program is written based on LabView® to configure the device, define the settings of measurement, and record the parameters. The current for heating is a 50-Hz AC supply in the Gleeble. To ensure that enough data samples are recorded, the sampling rate is 10,000 per second in the experiments. The resistance is calculated in each half cycle by Ohm's law using RMS values of voltage and current.

During each test, the interface temperature is kept constant. The load is changed in two ways, i.e., stepwise and continuously. In the former method, the load is changed stepwise in three steps and maintained in 2 seconds for each load level. In the latter method, the load is increased continuously. The initial heating time to establish temperature equilibrium is 30 seconds for all tests.

Results and Discussions

Figures 3–5 list the results from stepwise loading. For steel-to-steel contact, the experiments are carried out at five different temperatures. Figure 3 shows the measured contact resistance vs. the normal pressure and temperature.

It can be seen that the interface normal pressure has great influence on the contact resistance. As a general rule, the contact resistance decreases with increased normal pressure. This applies to all tested temperatures. For instance, at 50°C, the contact resistance decreases from 300 to about 75 μΩ when normal pressure increases from 70 to 295 MPa. The rate of decrease in contact resistance with pressure is less steep at high pressures than at low ones.

Temperature also plays an important role. The test results show that the contact resistance is highest at 50°C, and decreases at 100°C, increasing at 200°C, and then drops consistently after 200°C. This may be due to easier film rupture at high temperature as a result of smaller flow stress of the base metal. The surface film is usually less deformable.

Another observation is that the variation in resistance due to varying temperature is less pronounced as pressure increases. This is probably due to the fact that increasing pressure leads to considerable deformation leading to larger contact area and rupture of the surface films.

Figure 4 illustrates the contact resistance between stainless steel specimens, which is much higher than that of the steel-to-steel counterparts under similar conditions — Fig. 3. This must be attributed to the higher electrical resistivity and flow stress of stainless steel. Pressure reveals similar influence as on steel contacts and so does temperature. There is a local peak of contact resistance at around 200°C.

The contact resistance of aluminum samples is shown in Fig. 5. Again, similar influence of pressure and temperature is observed. The magnitude of the contact resistance between aluminum specimens is smaller than that of steel and stainless steel because of smaller electrical resistivity and flow stress of aluminum, and contact resistances at all temperatures approach the same value with increasing pressure for aluminum contacts.

Figures 6 and 7 illustrate the results from continuously changing load. Figure 6 shows the results from stainless steel contacts. As a general trend, the contact resistance decreases when the normal pressure increases. The influence of pressure is more pronounced at low temperature. At 50°C, contact resistance decreases rapidly with an increase of pressure. At high temperatures, the gradients of the curves are smaller. Beyond 1000°C, the variation of contact resistance is minimal, with the normal pressure varying in a much smaller range. There is a local ridge of contact resistance at around 400°C.

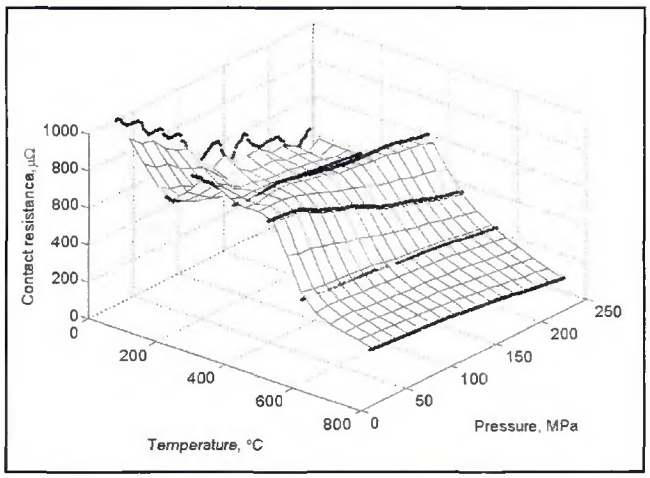

Fig. 6 — Contact resistance at different temperatures and pressures (stainless steel).

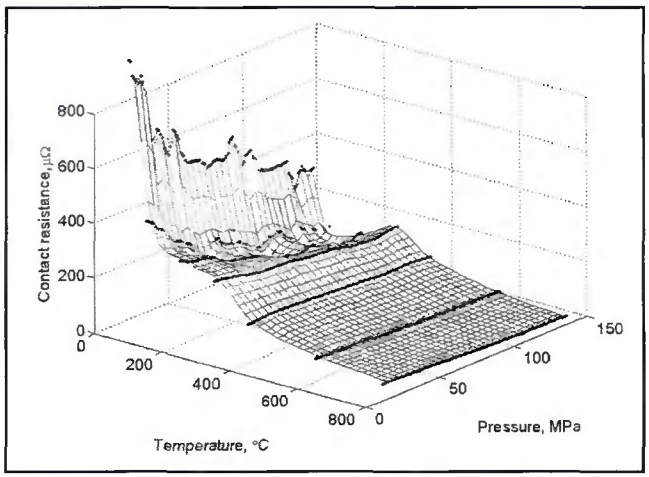

Fig. 7 — Contact resistance vs. temperature and normal pressure (steel).

The experimental results from mild steel contacts are shown in Fig. 7. The results look very similar to those for stainless steel. At low temperatures, the resistance-pressure curves are much steeper than at high temperatures. There is a local ridge at around 300°C.

In all the cases, the influence of interface normal pressure is similar. Pressure has an effect in at least two aspects: enlarging the real contact area and facilitating rupture of the surface film. The former effect helps to decrease the constriction resistance, and the latter decreases the film resistance. The total contact resistance is thus lowered when the pressure is increased. At high pressures, when the real contact area approaches the apparent one and the surface film has been ruptured to a large extent, both effects become less influential.

Temperature affects contact resistance in several aspects. The mechanical properties change with temperature and so do the electrical properties such as the resistivity. Under the same load, the real contact area is larger at higher temperature since the metal is softer, implying smaller constriction resistance. On the other hand, the resistivity increases with temperature for many materials, and this increases the constriction resistance. The surface films are also influenced by temperature. At high temperatures, some surface contaminants like oil and water vapor will be burned off; other relatively thick contaminant layers such as oxides can be ruptured more easily because of softer base metal, leading to smaller contact resistance; and, at the same time, the oxidation layer may grow at a higher rate when temperature is higher, resulting in larger contact resistance. The overall influence of temperature on the contact resistance is a joint effect among these factors. For each of the three metals investigated, a local peak in contact resistance is observed, showing that the increase of resistivity prevails the decrease of flow stress in a certain range of temperature.

Conclusions

A parametric study was carried out on the influence of interface normal pressure, temperature, and metal properties. The experiments were performed with a Gleeble machine, which provides similar conditions as resistance welding.

The influence of pressure is quite consistent in the experiments — contact resistance decreases when pressure increases, while the influence of temperature is more complex. The contact resistance is not always dropping with increasing temperature as a result of the joint effects of the electrical and mechanical properties of the base materials and those of the films.

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