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Hot Hydroforming of 22MnB5 Tube by Resistance Heating

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To promote the application of high strength steels in automobile bodies, the practicability of hot hydroforming of tube by resistance heating is illustrated. From the results of experiments conducted to measure temperature distributions of the tube during the forming process, a method to improve temperature uniformity has been proposed and achieved. Validity was evaluated by examining the effects of hot gas forming on the microstructure and hardness. Results indicate an obvious temperature difference along the axial direction for two cross-sectional shapes: the temperature in the middle zone of the tube is higher than that at its ends. Both thermal convection and cross-sectional shape have only a limited effect on the temperature distribution. The main reason for non-uniform temperature distribution is the heat transition between the electrodes and the tube ends. The temperature difference decreased as the heating rate increased. In contrast, the temperature distribution was even along the circumferential direction for both cross-sectional shapes. Adjusting the contact resistance is a useful method of reducing the temperature difference. In this study, the temperature difference was successfully decreased to 20°C, while reaching a maximum temperature of 750°C, which is adequate for both forming and quenching. A rectangular component was formed to validate the practicality and efficiency of tube hot hydroforming by resistance heating. The hardness and microstructure met the requirements of 22MnB5, which demonstrates both the forming efficiency and quantity advantages of hot gas hydroforming by resistance heating.

INTRODUCTION

With increasing demands to reduce carbon emissions and weight in automobiles,[1] 22MnB5 steel is widely used in body-in-white components for its weight advantages and high structural performance.[2,3] However, the application of 22MnB5 for hollow components, which are one of the three major body structures, has been limited in recent decades. It is generally accepted that tube hydroforming is an efficient technology for manufacturing hollow components, but there are insufficient studies focusing on the hydroforming of 22MnB5 tube, given its very high flow stress compared with that of aluminum alloys or low carbon steels.[4,5]

It has recently been shown that hot hydroforming can be used to overcome the forming difficulties of 22MnB5 at room temperature. Nevertheless, this technology introduced a new problem, in that traditional pressure media, such as oil and water,

can only be used at temperatures below 300°C.[6] This method was therefore only used for aluminum and magnesium tube hot hydroforming in its early years. In 2004, Fukuchi[7] proposed a new forming technology—hot gas hydroforming—which uses gas as a pressure medium. Although this overcame the limitations of the forming process and the temperature could be increased significantly,[7] the technology still could not meet the requirements for manufacturing 22MnB5 components. It is impossible to carry out the quenching treatment owing to the high temperature of the die,[8] and the heating time is too long owing to the large amount of energy needed for die heating, which greatly decreases production efficiency. These factors have hindered the wide utilization of hot gas hydroforming in the automobile industry.

Efforts have recently been made to promote the application of 22MnB5. Mori et al.[9] optimized hot gas hydroforming by using resistance heating instead of
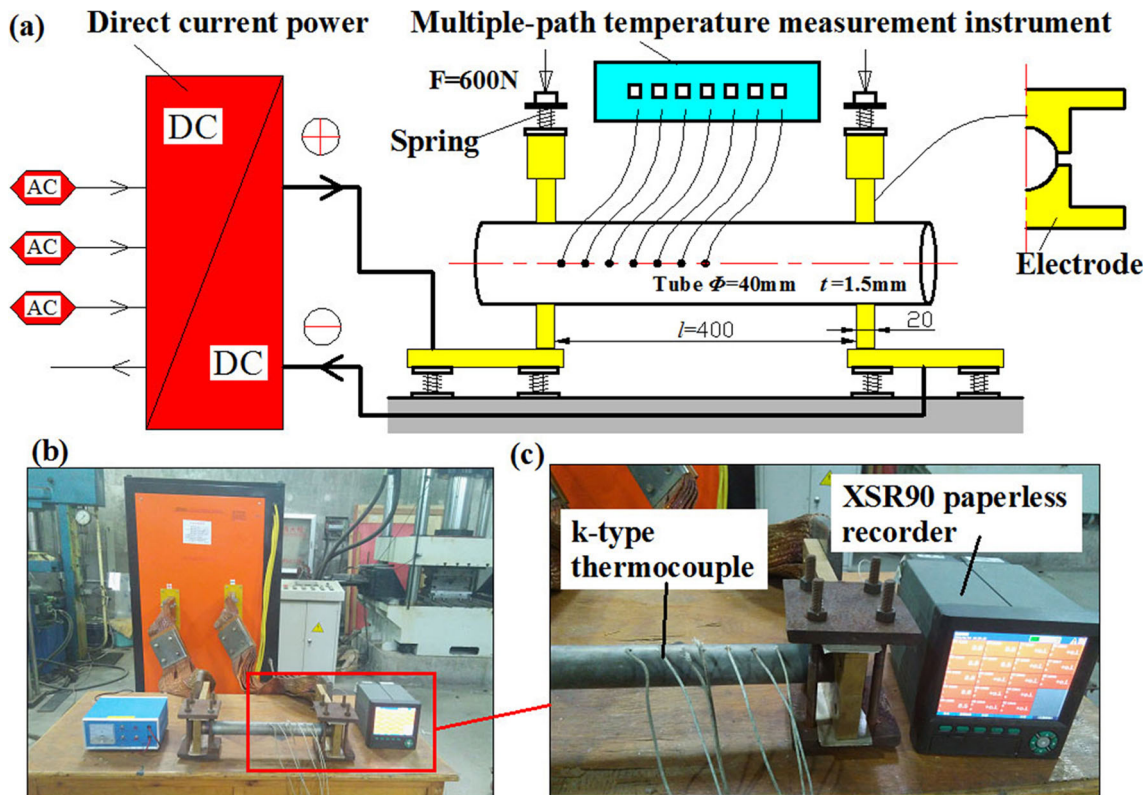
Fig. 1. Experimental apparatus: (a) schematic; (b) experimental apparatus; (c) partial enlarged detail.
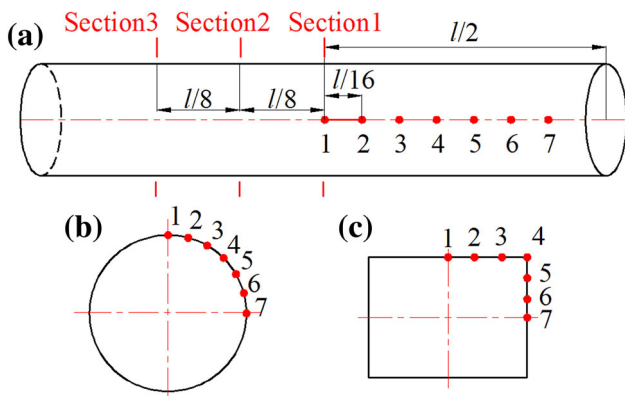

Fig. 2. Test positions: (a) along the axial direction; (b) along the circumferential direction of the circular sample; (c) along the external surface for the rectangular sample.

important and complex, and directly affects the formability and final quenched performance of formed tubes. Furthermore, the effect of resistance heating on the microstructure and properties of the material is still unknown.

In this study, the temperature field characteristics of the resistance heating process were studied, with the aim of improving the practicability and efficiency of tube hot hydroforming. The practicality of this method is validated by demonstrating its effects on the microstructure and properties of the product. Resistance heating is confirmed to be practical for hydroforming of tubes.

EXPERIMENTAL METHODS

In this study, welded 22MnB5 tubes with 50.0 mm outer diameter and 1.5 mm wall thickness were used. The ends of the tubes were clamped to 25-mm-long copper electrodes. The contacting length of the electrodes in the hoop direction was 98%, and the electrodes were contacted with the tube using a clamping force of 600 N. The distance between the electrodes was 400 mm. A constant direct current power supply was used for resistance heating. The experimental apparatus is shown in Fig. 1.

The test tube was coupled to devices for process monitoring and data recording, allowing the tube temperature to be measured by two devices: a

a heater embedded in the die. The practicability of this heating method has been validated for hot sheet stamping.[10] Mori further demonstrated the efficiency of resistance heating and pointed out that the heating time can be reduced to less than 5 s,[11] which could significantly improve energy utilization and production efficiency. The above studies were, however, limited to sheet-forming processes. There are important differences between stamping technology and tube hydroforming. For the tube hot gas hydroforming process, the temperature distribution is more
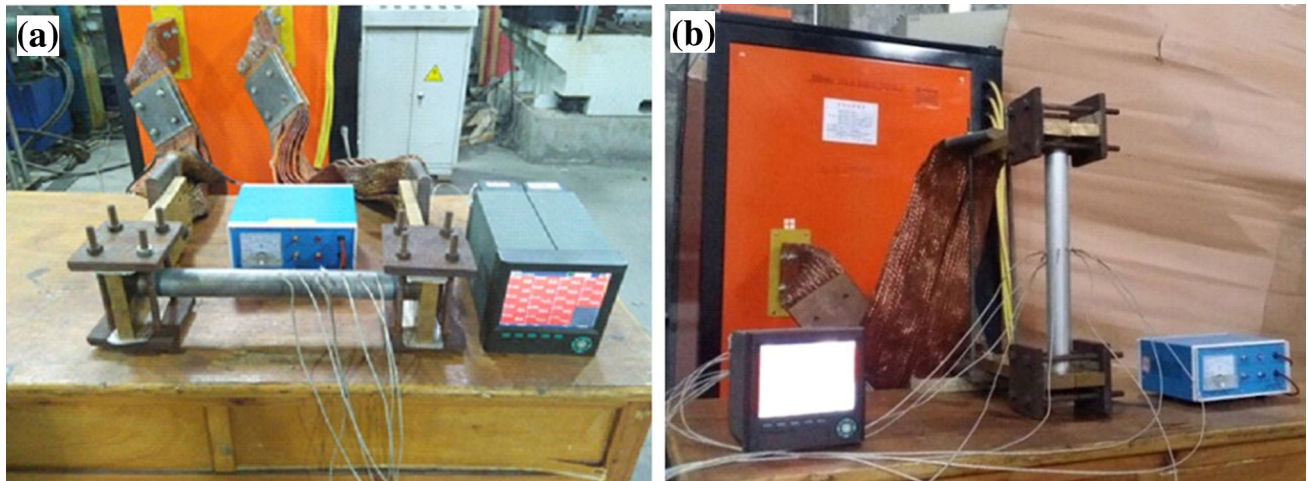
Fig. 3. Test position and experimental apparatus, showing (a) horizontal and (b) vertical alignment of the tube axis.
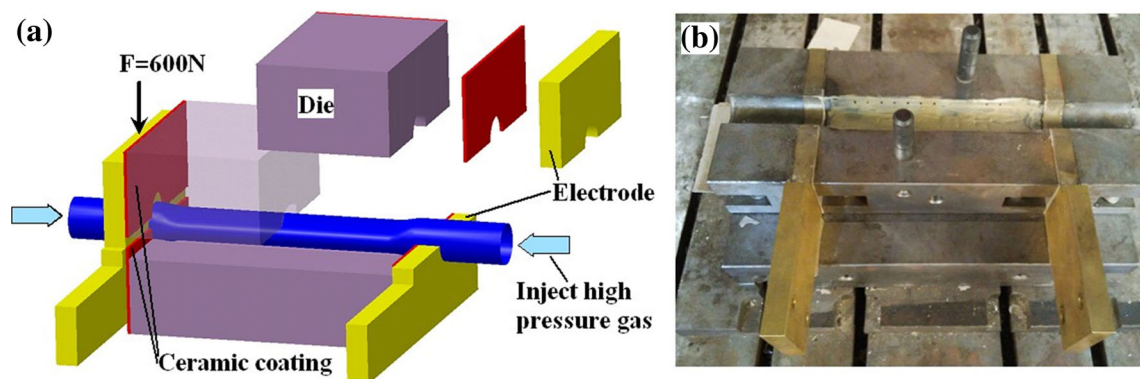

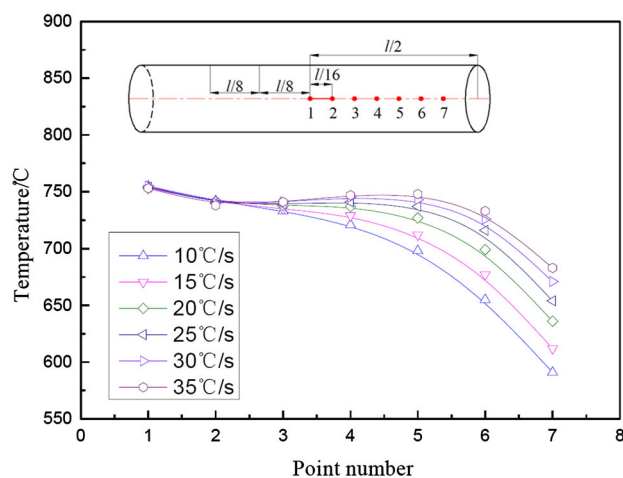Fig. 4. Schematic of tube hot hydroforming by resistance heating: (a) assembly picture; (b) photograph.

Fig. 5. Temperature distribution along the axial direction.

contact temperature measuring device, via a K-type thermocouple with a response time of 0.24 s, and a new type of measuring recorder, via a XSR90 paperless recorder with a scan period of 0.1 s. It was therefore possible to record heating curves over

the entire process and gather precise knowledge of the thermal behavior of the component during the process. The measurement accuracy of the K-type thermocouple was $\pm 1°C$ when the temperature was below 800°C. In this study, the heating rates ranged from 10°C/s to 35°C/s, which meant that the maximum measurement error would be less than 8.4°C, i.e., $0.24 \times 35 = 8.4$, which is acceptable for heat forming of 22MNB5.

The temperature distributions along the axial and circumferential directions were measured at different heating rates. Circular and rectangular cross-section tubes were selected to illustrate the effect of section shape on the temperature distribution. Taking advantage of the symmetry of the structures, the temperature distributions of one-half or one-quarter zones were measured and recorded. The measurement positions are shown in Fig. 2. The effects of thermal convection were determined by placing the tube axis both horizontally and vertically, as shown in Fig. 3.

The most significant advantage of resistance heating is that it enables the integration of forming and heat treatment to be feasible and practical.
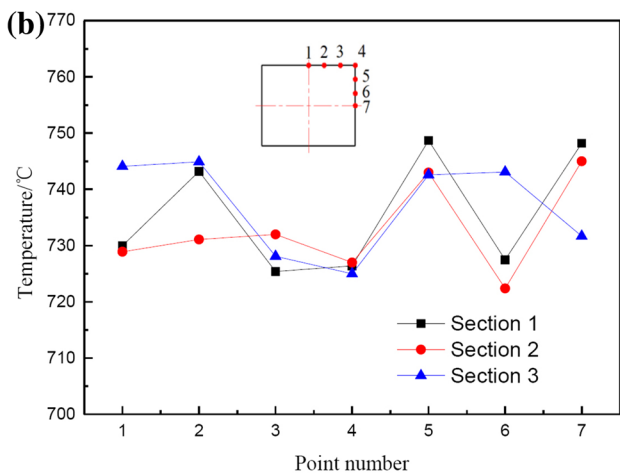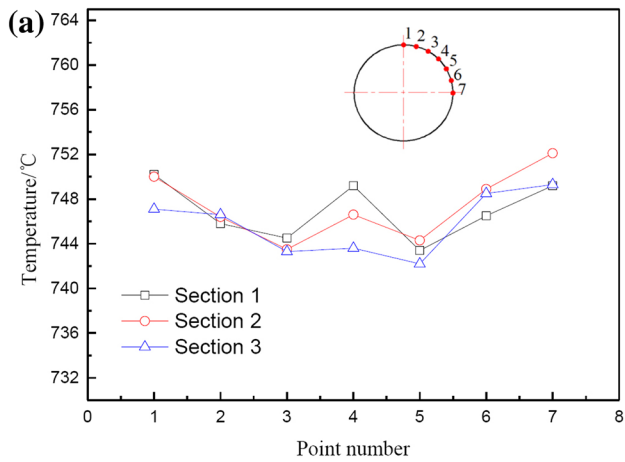
Fig. 8. Temperature compensation by insertion of a 0Cr18Ni9 slab at the end of the tube.

Fig. 6. Temperature distribution along circumferential direction for (a) circular and (b) rectangular cross-sections.
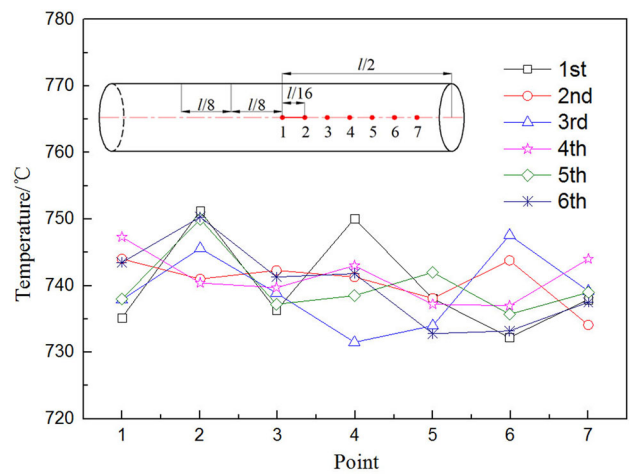
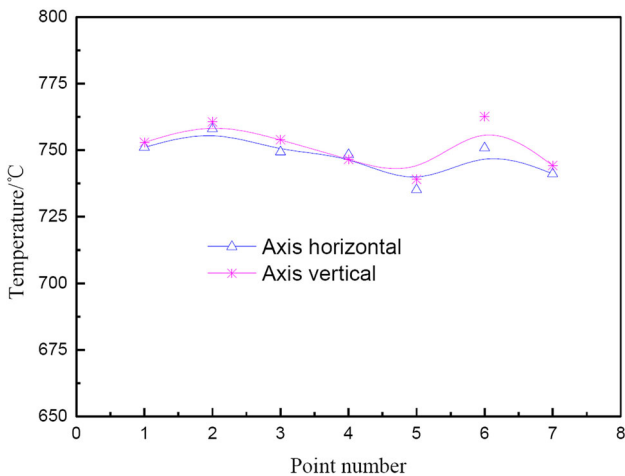Fig. 9. Temperature distribution after compensation.

Fig. 7. Effect of thermal convection on temperature distribution for horizontal and vertical tube axis configurations.

Fig. 10. The specimen, showing points of analysis along the axial and inner circumference directions.

When embedding an electrode into the die, a ceramic coating is applied to insulate the die from the electrode, as shown in Fig. 4. The tube can be heated thro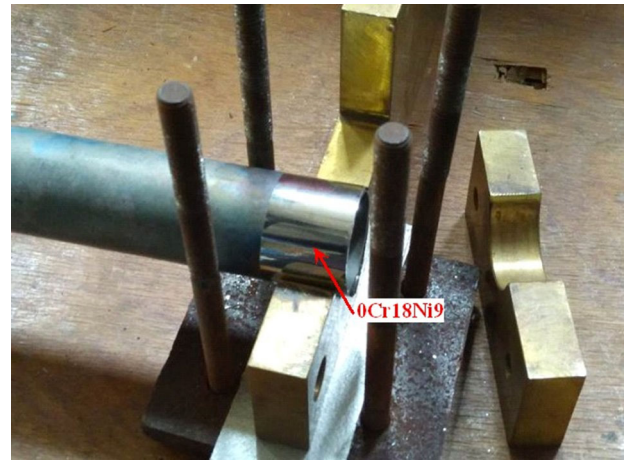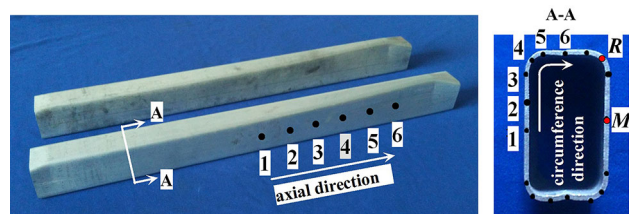ugh the die cavity, while the die remains at a low temperature because no current passes through it. Once the tube has been heated to a certain temperature, the current is switched off and high-pressure gas is injected into the tube, which then bulges and is attached to the inner surface of the die. Quenching can therefore be carried out simultaneously because the die is still at a low temperature. As a result, forming and heat treatment are completed in a single step, which greatly improves production efficiency and shape accuracy.
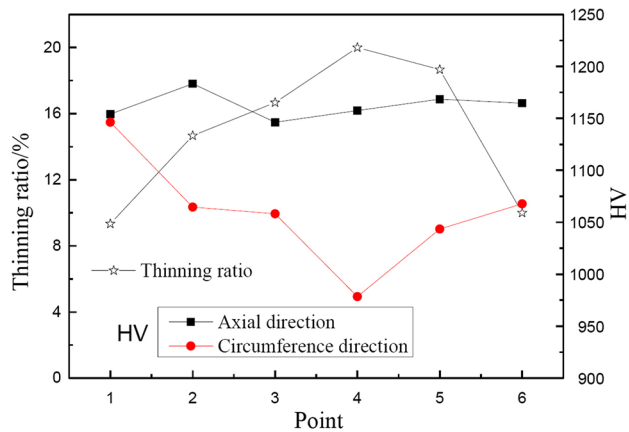
Fig. 11. Distributions of thickness and hardness in axial and circumferential directions for the test specimen.

EXPERIMENTAL RESULTS

Temperature Distribution Along Axial Direction

Figure 5 shows the temperature distribution along the axial direction for resistance heating. The highest temperature, which is about 750°C, is recorded in the middle zone of the tube; however, the temperature is only about 650°C at the tube ends. The main reason for this non-uniform distribution of temperature is that heat was transferred between the electrodes and tube ends during the heating process owing to the high thermal conductivity of copper. As a result, the temperatures of tube ends are lower than that of the middle zone. The temperature difference decreased with increasing heating rate. Because the heat transition cannot be avoided, this temperature difference cannot be completely eliminated only by increasing the heating rate.

Temperature Distribution Along Circumferential Direction

Figure 6 shows the temperature distributions for the different cross-sectional shapes, measured at a heating rate of 30°C/s. For each shape, three cross-sections along the axial direction, i.e., "Introduction", "Experimental Methods", and "Experimental Results" sections, were measured, as shown in Fig. 2. The temperature fluctuated slightly along the circumferential direction for all cross-sections, with a maximum amplitude of about 20°C. If there is no thermal convection, the uneven temperature distribution is unexpected because the three cross-sections are subjected to the same conditions. Thermal convection experiments were therefore carried out to explore the reasons for this observation. As shown in Fig. 3, vertical placement of the tube axis provided a good method to investigate the effect of thermal convection. In this configuration, the variation of temperature distribution had no dependence on thermal convection along the

circumferential direction. The effect of thermal convection can therefore be obtained by comparing the difference in temperature distribution between the horizontal and vertical placements of the tube.

Effect of Thermal Convection

A comparison of the temperatures measured at various points with a circular tube placed horizontally and vertically is shown in Fig. 7, using a heating rate of 30°C/s. There is only a very small difference in both the magnitude and the trends of the temperature for the two configurations. It can be concluded that the temperature fluctuation along the circumferential direction is mainly due to measurement error owing to the measuring accuracy of the thermocouple. With respect to the quenching treatment, such a difference in temperature is small enough to be neglected because it does not induce any structural transformations.

METHOD TO IMPROVE TEMPERATURE DISTRIBUTION

From the above discussion, it is evident that heat conduction is the main reason for the non-uniform temperature distribution. According to the Second Law of Thermodynamics, it is impossible to prevent heat conduction; temperature compensation is therefore the only way to reduce the temperature difference. An increased resistivity was designed and applied to achieve temperature compensation. As shown in Fig. 8, a thin 0Cr18Ni9 slab, with a thickness of 0.1 mm, was attached to both tube ends. The test was repeated six times to obtain good repeatability and ensure validity of data. The temperature distribution after compensation is shown in Fig. 9. It is clear that the temperature distribution greatly improved, even though a small difference of 20°C still existed along the axial direction. According to the process specifications for forming and quenching of 22MnB5, a 20°C difference is fully acceptable because the permitted temperature difference exceeds 50°C. Figure 9 also shows good repeatability of results for the six tests. It can therefore be concluded that adjusting the contact resistance is a practical method of achieving a uniform temperature field.

PERFORMANCE ANALYSIS

Experiments were carried out to validate the practicality of tube hot hydroforming by resistance heating. The specimen was a rectangular component with a width of 6 mm, as shown in Fig. 10. An initial tube blank with a thickness of 2.0 mm and diameter of 30 mm was selected to carry out the experiments. The blank was first heated to 750°C by resistance heating from the die. The current was then switched off and gas was injected into the tube at high pressure (4.5 MPa) for 5 s. The die was manufactured from 45 steel.
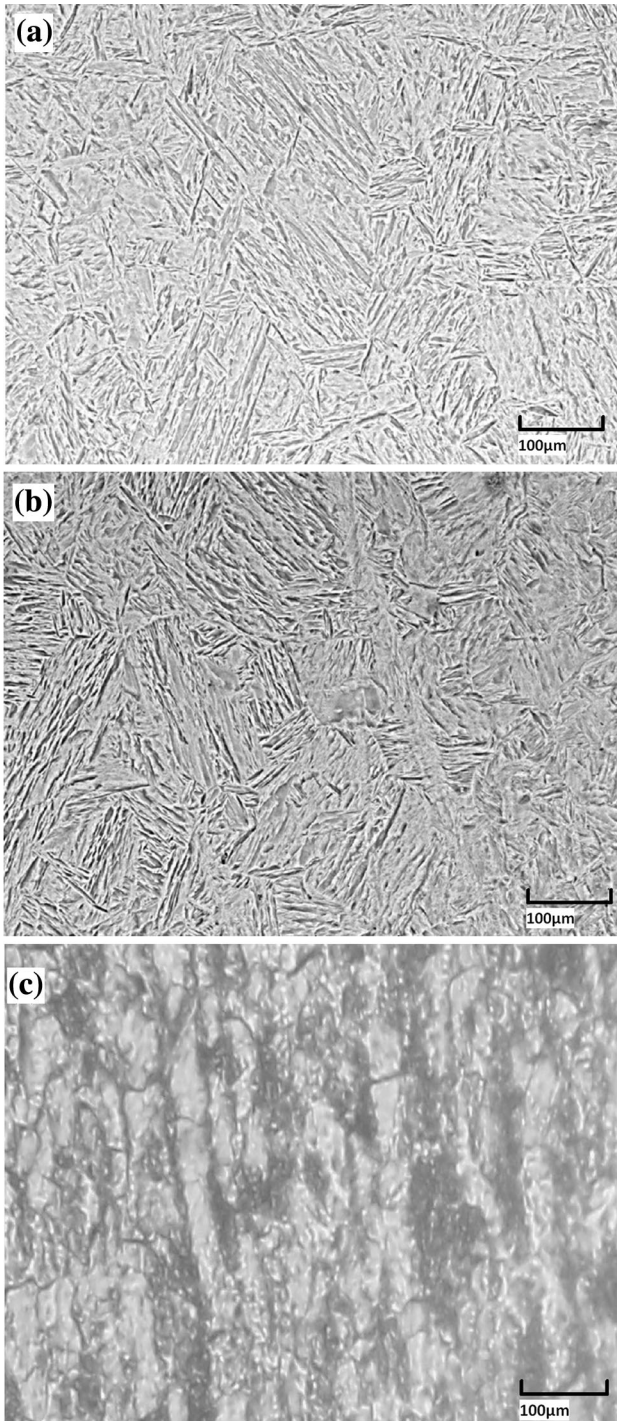
Fig. 12. Microstructures of (a) point R, (b) point M, and (c) original specimen.

Figure 11 shows the values of thickness and hardness around one-quarter of the inner surface of the specimen. It is obvious that the thickness distribution is similar to that of traditional hydroforming. Maximum thinning occurred in the radial zone of the corner, which is the most likely area for bursting to occur. Preforming is therefore still important for tube hot hydroforming by resistance heating.

Hardness is evenly distributed along the axial direction, but fluctuates along the circumferential direction. This is mainly caused by differences in cooling times attributed to the deformation sequence along the circumferential direction. Nevertheless, the hardness distribution meets the requirements for 22MnB5, illustrating the validity and practicality of tube hot hydroforming by resistance heating.

The microstructures of the tube before and after quenching were analyzed by scanning electron microscopy, as shown in Fig. 12. The original microstructure consisted of fine-scale columnar and equiaxed grains with obvious texture direction. The material at point M was all transformed to martensite. Material at point R was transformed into a mixture of a large amount of fine-needle martensite and a small amount of bainite, which explains why the hardness near point R is lower than that at point M.

It is worth noting that, for tube hot hydroforming by resistance heating, there is no need to move the tube blank from the furnace to the die, and therefore no temperature drop occurs between the heating and forming processes. A temperature of 750°C is therefore adequate for both the forming process and quenching treatment, offering higher energy utilization and production efficiency.

CONCLUSION

1. In the tube resistance heating process, the temperature distribution does not depend on the shape of the component or thermal convection, which is desirable and convenient for hot hydroforming. Heat conduction is inevitable, which induces a slightly non-uniform temperature distribution: the temperature in the middle zone is larger than that at the tube ends. This temperature difference can be decreased and almost eliminated by adjusting the contact resistance between the electrodes and the tube. The measured temperature differences are acceptable when used in practical manufacturing.

2. The main reason for non-uniform temperature distribution is the heat transition between the electrodes and tube ends. The temperature differences can be decreased to a certain extent by increasing the heating rate. For 22MnB5, the temperature difference decreased from 150°C to 50°C along the axial direction, corresponding to an increase in heating rate from 10°C/s to 50°C/s. It is worth noting that the temperature distribution was even along the outer surface of the samples for both circular and rectangular shapes.

3. Experimental results indicated that a uniform temperature field can be practically achieved by adjusting the contact resistance between the

tube and electrodes. In this study, the maximum temperature difference was successfully decreased to 20°C for a maximum temperature of 750°C, which satisfied the requirements of both the forming process and quenching treatment.

4. Experiments were carried out for tube hot hydroforming by resistance heating. A temperature of 750°C is adequate for both forming and quenching because of the absence of a temperature drop between the heating and forming processes. The hardness and microstructure met the requirements for 22MnB5, demonstrating important advantages of this method for both forming efficiency and quantity.

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