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Gas forming of ultra-high strength steel hollow part using air filled into sealed tube and resistance heating

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ABSTRACT

A new gas forming process of ultra-high strength steel hollow parts using air filled into sealed tubes and resistance heating was developed to omit the subsequent heat treatment. In this process, a sealed quenchable steel tube was rapidly resistance-heated to improve the formability. By applying die-quenching for holding at the bottom dead centre of a press, the formed part had very high strength, a hardness of 450 HV10 equivalents to a tensile strength of 1500 MPa. In addition, the dimensional accuracy of the formed part was improved by the increase in internal pressure for heating and compression of air filled into the sealed tube. To increase the hardness, the formed tube was cooled with air blowing during holding at the bottom dead centre and the corner of the die was optimised as to be in contact with the tube. The oxidation on the outer surface of the formed part was prevented by forming in a case filled with CO_2 gas.

1. Introduction

To improve the fuel consumption of automobiles, the reduction in weight of automobile parts becomes more demanding. For the reduction, the use of high strength steel sheets increases mainly for body-in-white parts. On the other hand, not only strength but also rigidity is required for suspension parts, and thus hollow structures are advantageous to the rigidity. In addition, high strength hollow parts are useful for cabin ones to protect passengers for collision. Although tube hydroforming is increasingly employed to manufacture hollow parts, it is not easy to hydroform high strength steel tubes due to small ductility and high strength. Sorine et al. (2008) have improved the hydroformability of high strength steel tubes by optimising force for axial feeding.

In hydroforming, tubes are bulged by high internal pressure and then formed with tools. A large amount of bulging brings about rupture for high strength steel tubes having small ductility. To prevent the rupture, comparatively low internal pressures without bulging are employed, and tubes are formed with a punch and die. Nikhare et al. (2009) have exhibited the effectiveness of low pressure in hydroforming of high strength steel tubes by comparison with high pressure forming. Abedrabbo et al. (2009) have prevented the thinning of high strength steel tubes in hydroforming using low internal pressure. Ueno et al. (2008) have controlled the internal pressure without a booster for generating internal pressure by balancing decrease in internal volume of the tube and discharge in water from a high strength steel tube during hydroforming.

Warm and hot forming processes are useful for improving the formability of workpieces having low ductility at room temperature. Mori et al. (2005) have largely heightened the formability of ultra-high strength steel sheets by resistance heating. On the other hand, Yuan et al. (2006) and Manabe et al. (2010) have developed warm hydroforming processes of aluminium and magnesium alloy tubes having small ductility, respectively. However, warm tube hydroforming has limitations of heating temperature because of pressure media such as oil and water, generally below 300 °C.

The limitation of the heating temperature in tube forming can be removed by utilising gas as a pressure medium. Although the gas pressure is much lower that the liquid pressure, gas is available to low flow stress of tubes in hot forming. Fukuchi et al. (2005) have developed a gas forming process of aluminium alloy tubes heated around 400 °C to produce automobile suspension parts. However, it is not easy to simultaneously control the heating temperature and the internal pressure during gas forming (Keigler et al., 2005). The time of deformation of tubes in gas forming is too short to control both temperature and pressure, i.e. only 0.2 s (Maeno et al., 2011a, 2011b). Maeno et al. (2009) have simplified a controlling scheme using resistance heating in gas forming of an aluminium alloy tube by means of air filled into a sealed tube. In this scheme, the tube was bulged by internal pressure of air with the decrease in flow stress of the heated tube without control of internal pressure during forming.

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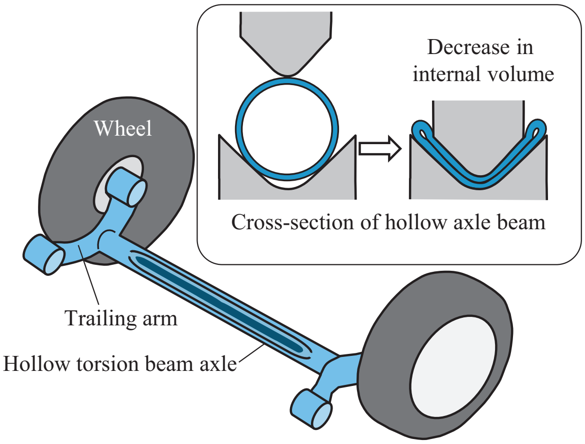

Fig. 1. Hollow torsion beam axle used in automobile rear suspension.

Although the heating temperature and internal pressure in gas forming of aluminium alloy tubes are comparatively low, the temperatures and pressures become higher for steel tubes. Vadillo et al. (2009) have investigated the formability of steel tubes in gas forming. Neugebauer and Schieck (2010) have produced hollow parts having a tensile strength of 1.5 GPa by die quenching using holding at a bottom dead centre of a press in gas forming of quenchable steel tubes. Vadillo et al. (2010) have gas-formed tubes with dies without bulging of tubes as well as low pressure hydroforming under simultaneous control of heating temperature and gas pressure, whereas the simultaneous control is not easy.

In the present study, a new gas forming process of an ultra-high strength steel hollow part using air filled in a sealed quenchable steel tube and resistance heating was developed to produce ultra-high strength steel hollow parts. The effect of the internal air pressure on the forming shape and the die quenchability was investigated in forming of V-shaped hollow parts. In addition, the improvement of hardenability by cooling using air blowing and the prevention of oxidation of tubes by forming in a case filled with CO_2 gas were performed.

2. Gas forming of ultra-high strength steel hollow parts using air filled into sealed tube and resistance heating

2.1. Production approach of ultra-high strength steel hollow parts

High strength suspension and cabin parts are desirable for the reduction in weight and the improvement of crash safety of automobiles. For example, hollow torsion beam axles used in rear suspensions are produced from steel tubes as shown in Fig. 1. In the hollow beams, the rigidity is adjusted by changing the cross-sectional shape in the axial direction to heighten comfortability of driving. The tube is conventionally formed into a V shape with a punch and die in low pressure hydroforming. As the punch stroke increases, the internal volume of the tube decreases, and thus the internal pressure is controlled by discharging a pressure medium from the tube during forming. The formed beams are generally heat-treated to obtain the required strength (Linnig et al., 2009).

Hot stamping of quenchable steel sheets becomes widespread for the production of ultra-high strength steel body-in-white parts (Karbasian and Tekkaya, 2010). In hot stamping, not only low forming load, no springback and high formability but also high strength is attained. The stamped parts are hardened by die quenching using holding at a bottom dead centre of a press, i.e. approximately a tensile strength of 1.5 GPa (see Fig. 2(a)). However, if hot stamping is applied to hollow products, desired shapes and rapid cooling for die quenching are not obtained because it is difficult to hold the tube with the sufficient contact pressure by dies. Hence the reaction force from inside of the tube such as internal pressure is needed. Ultra-high strength steel hollow parts can be produced without additional heat treatments by introducing die quenching into tube gas forming as shown in Fig. 2(b). Since it is not easy to simultaneously control heating temperature and internal pressure in a short forming, air filled into a sealed tube developed by Maeno et al. (2009) is employed to simplify the controlling scheme as shown in Fig. 2(c). The internal air pressure in the sealed tube increases with the decrease in internal volume of the tube during forming, and thus the formed tube is formed into a desired shape of the product and is die-quenched by sufficient contact with the punch and die. Since the internal pressure during forming is not controlled, the process control becomes simple. Consequently, the production cost decreases due to the elimination of the additional heat treatment and the equipment becomes simple.

In this process, rapid resistance heating is employed to control the temperature of the tube during forming. Mori et al. (2011) have employed resistance heating for spline forming of an ultra-high strength gear drum to raise the temperature of a side wall of a cup. Since the cross-sectional area of side walls in cups and tubes is constant in the axial direction for passage of current, the side walls are uniformly resistance-heated.

2.2. Experimental procedure

A gas forming process of ultra-high strength steel hollow parts using air filled into a sealed tube and resistance heating was developed. A miniature V-shaped hollow torsion beam axle of about 1/4 the size of the actual ones was dealt with as an example of gas forming as shown in Fig. 3. The middle of a quenchable steel tube was formed into a V shape with the punch and die. The apparatus was composed of electrodes, a punch, a die and plugs, and was installed in a 1500 kN CNC servo press. The CNC servo press was synchronised with the power supply for resistance heating, and the tube was formed with the punch and die after 0.3 s from the end of resistance heating. Each end of the tube was sandwiched between the two semicircular copper electrodes under a load of 640 N generated by the springs, and the contact length of the electrodes was 90% of the circumference of the tube. The punch and die were not in contact with the tube during resistance heating to avoid the heating of the tools. The plugs having an O-ring and a valve were inserted in both ends of the tube. The initial internal pressure of air filled into the sealed tube with a hand inflator before resistance heating was changed, and the pressure was not controlled during forming. The internal air pressure, temperature and forming load were measured with the Bourdon type pressure gauge, the thermography and the load-cell, respectively. In case of the measuring of the temperature , the tube was coated with the black body paint to stabilise the emissivity coefficients.

Hot stamping processes of quenchable steel sheets have been simulated by the finite element method. However, the material constants such as flow stress, coefficient of friction, heat transfer coefficient, etc. used for the calculation are functions of temperature and it is very difficult to measure the material constants accurately. Eriksson et al. (2002) have performed finite element simulation of hot stamping processes using mechanical and thermal properties measured from experiments, and indicated the need for further improvements of measurement. Hu et al. (2013) have reported that the thickness of oxide scale greatly influenced the interfacial heat transfer coefficient in hot stamping. Although thermo-mechanical material models during hot stamping have been developed, the accuracy of the measured material constants is crucial for the accuracy of the calculated result. Particularly it is not easy to simulate the deformation behaviour of the softened tube by heating against the rising internal pressure of the heated air, i.e. not