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Smart hot stamping of ultra-high strength steel parts

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Abstract: Smart hot stamping processes of ultra-high strength steel parts have been developed to overcome difficulties in the present hot stamping process. Using rapid resistance heating, the stamping equipment became considerably simpler than that using furnace heating. The formability was improved by high speed hot stamping using a mechanical servo press in comparison with the conventional process using a hydraulic press. Parts having a different distribution of strength were produced by tailored die quenching using local bypass resistance heating. Die-quenched steel parts and ultra-high strength steel sheets were sheared by reducing the flow stress in the shearing zone using local resistance heating. An ultra-high strength steel gear drum was produced by hot spline forming using resistance heating of side wall of a cup. V-shaped hot forming using sealed air was developed to produce ultra-high strength hollow axle beams used for suspensions of automobiles. A one shot hot stamping process consisting of resistance heating, forming, shearing and die quenching was applicable to comparatively small high strength steel parts.
Key words: hot stamping; ultra-high strength steel; die quenching; tailored die quenching; spline forming; tube forming; one shot forming

1 Introduction

An effective approach for improving the fuel consumption of automobiles is to reduce the weight of automobiles. Because the high strength steel sheets are considerably cheaper than the aluminium alloy sheets, the use of high strength steel sheets for automobile body panels remarkably increases. Although the high strength steel parts have superior mechanical properties, stamping operations become difficult due to the high strength [1−3]. As the strength of the sheets increases, the forming load increases, and thus the springback becomes large, particularly for the ultra-high strength steel sheets. In addition, small formability, short tool life and delayed fracture are problems. Specially, cold stamping operations of ultra-high strength steel sheets having a tensile strength above 1.2 GPa have not been established yet.

By heating sheet metals, the stamping operation becomes easy due to the decrease in flow stress and the increase in ductility. The hot stamping of quenchable steel sheets is attractive for forming of ultra-high strength steel parts [4]. As shown in Fig. 1, the sheets are heated in the furnace, then the heated sheets are stamped, and finally the formed sheets are held at the bottom dead centre for the die quenching. The stamped parts are punched and trimmed. The hot stamping has the following advantages.

1) The forming load is considerably reduced due to the decrease in flow stress.

2) Almost no springback is caused.

3) The formability is largely increased due to the increase in ductility.

4) The tensile strength of the formed parts is approximately 1.5 GPa due to the die-quenching.

Since the sheets are soft during the forming and the formed parts are hard, the hot stamping is an attractive forming process. On the other hand, the disadvantages of the hot stamping are as follows.

1) The scale on the surface of the stamped part is remarkable due to heating at about 950 °C [5], and thus the shot blasting is required to remove the scale.

2) Aluminium coated sheets for preventing the oxidation at high temperatures are comparatively expensive.

3) The productivity is low due to the ejection from the furnace and the die quenching.

4) The equipment is large and expensive.

5) The formed parts are trimmed and punched by laser cutting, and thus the cost of the cutting becomes high.

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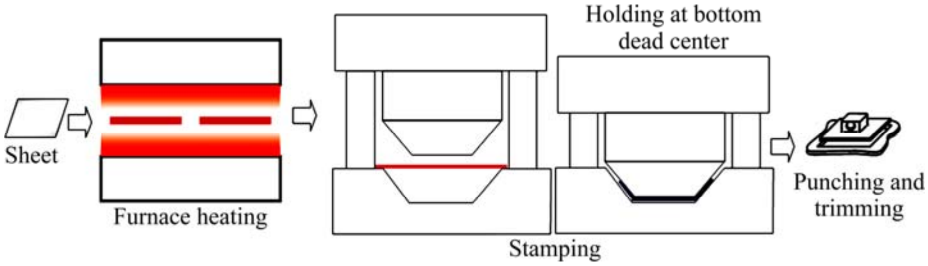

Fig. 1 Sequence of hot stamping of quenchable steel sheet

6) The application of the shot stamping is still limited to production of body-in-white parts of automobiles.

In this work, smart hot stamping processes are introduced.

2 Rapid resistance heating

In the hot stamping, the heating approach of the steel sheets is crucial. Although the drop in temperature in bulk workpieces used for the forging is comparatively small, that for the sheets metals after the ejection from the furnace is very rapid due to large surface area. In addition, the oxide scale on the surface of the sheet is crucial. The aluminium coated sheets having high oxide resistance are expensive, and the size of the furnace becomes large due to slow formation of the intermetallic compound on the surface of the sheet during the heating. For rapid laser heating, uniform temperature in the sheet is difficult, and the infrared heating is not very rapid.

The resistance heating using direct passage of current through the sheet [6−8] has the following advantages as shown in Fig. 2.

1) The heating is very rapid, only a time of 2 s to a heating temperature of 900 °C.

2) The oxide scale hardly forms due to the rapid heating (see Fig. 3).

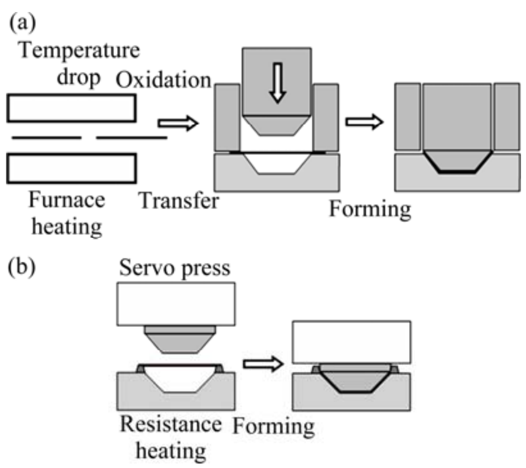

Fig. 2 Comparison between hot stamping processes using furnace heating (a) and resistance heating (b)

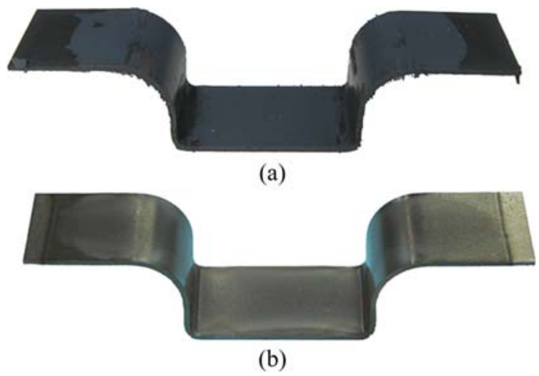

Fig. 3 Comparison between hat-shaped sheets by hot-stamping processes using furnace heating (a) and resistance heating (b)

3) The heating apparatus is comparatively simple.

4) The rapid heating is appropriate to synchronisation with a press.

5) The temperature is easily controlled by adjusting the electrical power.

The most serious disadvantage of the resistance heating for the hot stamping is to limit the applicable range to square sheets. The change in cross-sectional area in the current direction for non-square sheets brings about non-uniform distribution of temperature, i.e. the temperature is high for small and low for large cross-sectional areas, respectively. The industrial application of the resistance heating to the hot stamping is still limited.

3 High speed hot stamping using mechanical servo press

Since the temperature of the heated sheet is decreased after the ejection from the furnace, it is desirable to stamp the sheet quickly. Particularly, the sheet is rapidly cooled by the contact with tools during the stamping.

The hot-stamped parts for low and high stamping speeds are compared in Fig. 4 [9]. In this stamping, a mechanical servo press having the function of controlling the ram motion was employed. For the low speed, 26 mm/s, in the hot stamping, the sheet fractures due to large difference between flow stresses of the contacting and non-contacting regions, whereas the fracture is prevented for the high speed, 149 mm/s, in the hot stamping, because of small decrease of temperature. In the hot stamping, the formability is largely influenced by the distribution of temperature. It is found that the formability is improved by the increase in stamping speed.

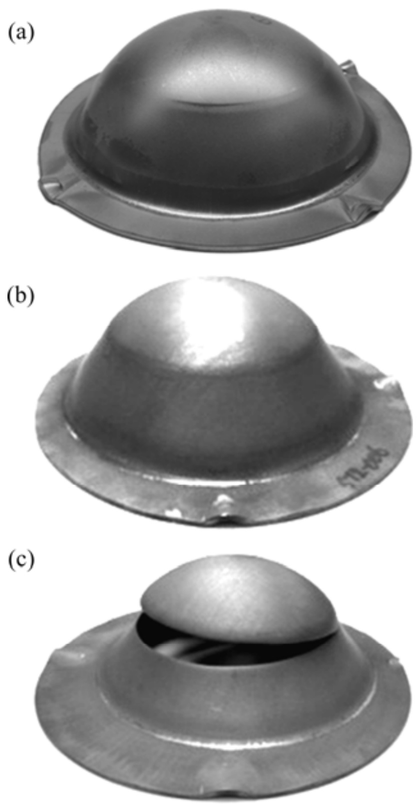

Fig. 4 Cold and hot-stamped parts: (a) Cold stamping, 26 mm/s; (b) Hot stamping, 149 mm/s; (c) Hot stamping, 26 mm/s

Since the holding at the bottom dead centre is required for the die quenching in the hot stamping, controllable hydraulic presses are conventionally employed, whereas the stamping speed for the hydraulic presses is not high. Mechanical servo presses become increasingly common. The application of servo presses to the hot stamping is attractive to improve the formability in the hot stamping due to the high speed stamping. In addition, digital linkage with other machines is comparatively easy, e.g. the linkage with the resistance heating leads to a smart hot stamping process.

4 Tailored die quenching

In the conventional hot stamping process, a whole body of a stamped part is quenched with dies, and thus the whole body becomes highly strong. This leads to the limitation of application to high strength body-in-white parts having high crash safety for protecting passengers. For example, in sliding parts, high strength is required only in the vicinity of sliding plane, and the prevention of quenching is desired except for this vicinity to increase fracture toughness. Most of mechanical parts require high strength around corners because of concentration of stress. On the other hand, laser cutting having low productivity is generally employed for the quenched parts after the stamping, because the parts are too hard to shear. When the cut portions of the stamped part are not quenched, the laser cutting is replaced with the shearing having high productivity.

A tailored die quenching process using bypass resistance heating in hot stamping for producing ultra-high strength steel parts having a strength distribution was developed [10]. In the resistance heating of the sheet shown in Fig. 5, non-electrified portions by contact with copper bypasses with a low resistance were not heated, whereas portions not in contact with the bypasses were heated by the passage of current and were quenched by holding tools at the bottom dead centre. The bypass resistance heating was stable as partial heating, and the electrical power loss was small.

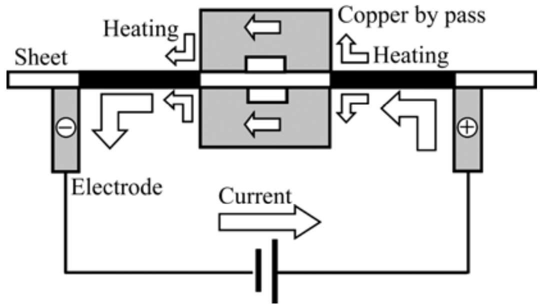

Fig. 5 Bypass resistance heating in hot stamping for producing ultra-high strength steel products having strength distribution

Hot hat-shaped bending using the bypass resistance heating was performed to form a product having a high strength around the corners (see Fig. 6). A hat-shaped product having a tensile strength of approximately 1.5 GPa at the corners was formed, and the input energy and punching load in the bottom portion were considerably smaller than those for the whole heating. The tailored tempering with grooved tools having partial control of cooling speed was developed [11].

5 Punching using local resistance heating

Although the stamped automobile body panels are punched to make many holes for the joining, paint removing, attachment, etc., it is not easy to punch die-quenched parts having high strength. The tool life is

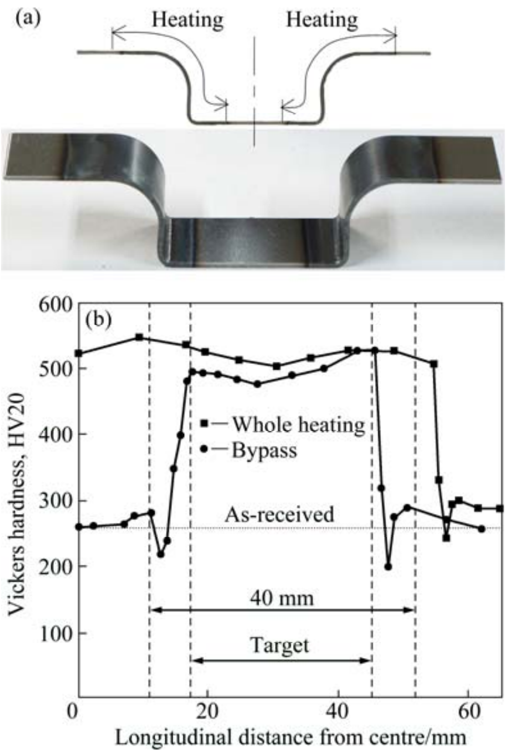

Fig. 6 Hot hat-shaped bent sheet using bypass resistance heating (a) and distribution of hardness in sheet (b)

remarkably reduced by large punching load, and worn tools bring about the deterioration in dimensional accuracy of the punched hole and in the quality of the sheared edge. In addition, the punching of the die-quenched parts has a risk of delayed fracture induced by tensile residual stress. Although the laser cutting is generally employed for the die-quenched parts, the productivity is low and the production cost is high, particularly for many small holes in automobile body panels.

The die-quenched steel sheets having high strength are heated to decrease the flow stress of the sheets just before the punching [12]. Since deformation in the punching is limited to the circular shearing zone of the hole, only this zone is heated by passing electric current as shown in Fig. 7. In Fig. 7(a), the current is passed between the electrode pins in the sheet holder and the knockout electrode not in contact of the punch and die with the sheet, and the circular shearing zone of the hole is uniformly heated [13]. This heating approach is employed for the punching of comparatively large holes and trimming. The heating of the punch and die is prevented by no contact with the sheet during the heating, and the sheet is punched just after finishing the heating.

Although many small holes for passing bolts and rivets are required for the automobile body panels, the knockout electrode does not have enough space for passing electric current for the small holes. Therefore, a pair of rectangular electrodes is placed to heat the hole region in the sheet locally as shown in Fig. 7(b) [14]. For the small holes, the heating energy is small even for the heating of the hole region, and the structure of the electrodes becomes simple. In the heating using the pair of rectangular electrodes, however, the current expands in the sheet, and thus the temperature in the sheet becomes non-uniform. Electrical conditions are controlled to obtain the uniform temperature in the circular shearing zone of the hole.

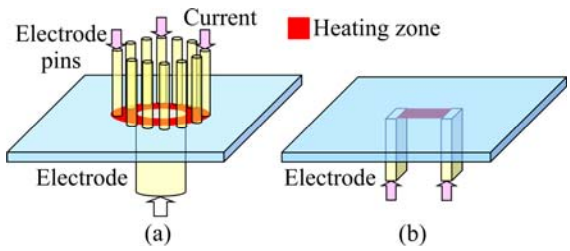

Fig. 7 Local resistance heating of hole region for punching: (a) Large hole and trimming; (b) Small hole

The effect of the current on the temperature distribution around the shearing zone measured after 0.3 s from the end of resistance heating by an infrared thermography is given in Fig. 8. For the current I=4.1 kA, the temperature is concentrically distributed, namely, the temperature in the circular shearing zone becomes uniform. By controlling the electrical conditions, the uniform temperature in the shearing zone can be obtained with the pair of rectangular electrodes, even if the electrode pins located along the shearing zone shown in Fig. 7(a) are not used. The pair of rectangular electrodes is a much simpler structure than the electrode pins and knockout. In addition, the expansion of current is prevented by the minimum distance between the electrodes.

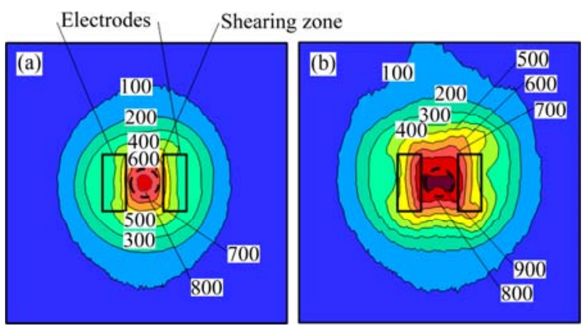

Fig. 8 Distribution of temperature around shearing zone measured after 0.3 s from end of resistance heating by infrared thermography (Unit: °C): (a) I=4.1 kA; (b) I=10 kA

The relationship between the punching load and the heating temperature in the shearing zone is shown in Fig. 9. As the heating temperature increases, the punching

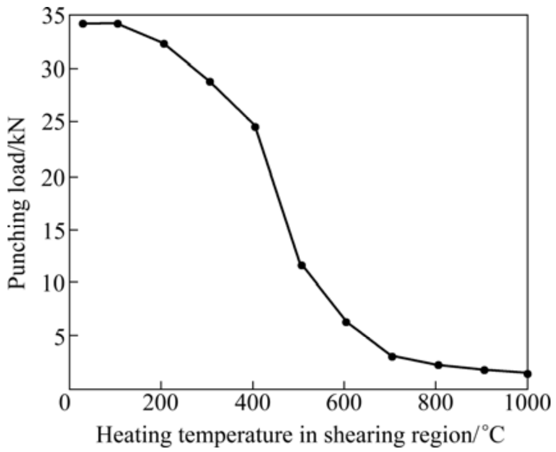

Fig. 9 Relationship between punching load and heating temperature in shearing zone

load decreases due to the decrease in flow stress. The punching load for T=500 °C is about 1/3 for the cold punching.

Since punched die-quenched parts have the risk of delayed fracture, this risk is removed by heating the shearing zone, namely, the tensile residual stress and hardness in the sheared edge are decreased and the surface quality is improved. The relationship between the delayed fracture time and the heating temperature in the shearing zone is given in Fig. 10, where the delayed fracture time is the time from the soak of the sheet in the acid to the visual observation of fracture. Above 500 °C, no fractures were observed up to 1450 min. It was found that the resistance heating is effective in not only the reduction in punching load and the improvement of surface quality of the sheared edge but also the prevention of the delayed fracture.

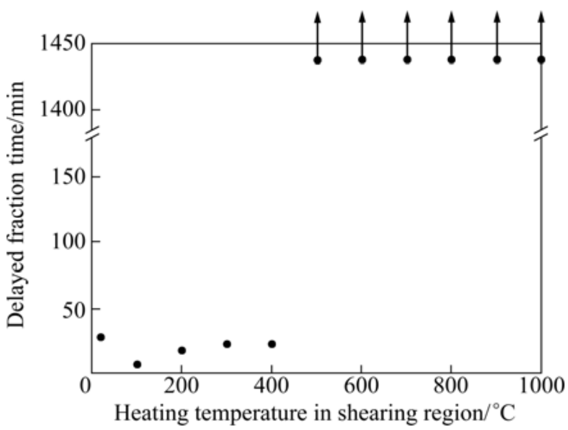

Fig. 10 Relationship between delayed fracture time and heating temperature in shearing zone

6 Hot spline forming of gear drum

Gear drums used in automobile transmission are mainly produced by bulk forming from plates instead of conventional forging from billets. A plate is drawn into a cup, and then the side wall of the cup is formed into a gear shape by ironing as shown in Fig. 11. The forging from billets is inappropriate to the production of parts having small thickness such as gear drums due to large change in shape, and thus the application of bulk formimg from plates having thicker thickness than sheets gradually increases.

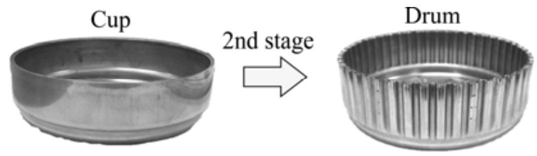

Fig. 11 Gear drum formed by ironing of side wall of cup

Although gear drums are made of mild steel sheets having high formability, it is desirable to produce the gear drums from the high strength steel sheets owing to the reduction in the weight of automobiles. However, the spline forming of high strength steel cups having low formability is difficult due to severe deformation, in particular ultra-high strength steel cups.

To improve the formability in the spline forming of ultra-high strength steel gear drums, the side wall of a cup formed into a gear shape is heated by the resistance heating (see Fig. 12) [15]. The corner and edge of the side wall are in contact with the upper and lower electrodes, respectively. When the thickness of the side wall is kept uniform by applying ironing in the deep drawing of the cup, the side wall is uniformly heated by the electrification, namely, the cross-sectional area of the side wall is uniform in the current direction. In addition, no heating of the bottom of the cup has the function of preventing the rapture in the bottom during the spline forming. The applicable range of the resistance heating is extended to the spline forming.

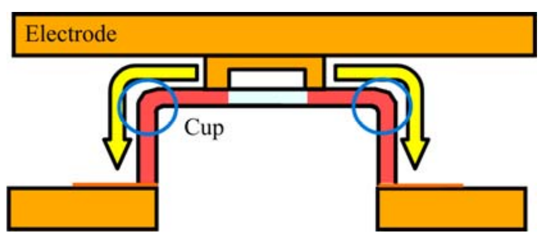

Fig. 12 Resistance heating of side wall in hot spline forming of gear drum

The hot spline forming of a die-quenched gear drum using the resistance heating is shown in Fig. 13. The side wall of the resistance-heated drawn cup is ironed and then die-quenched. Since the resistance heating is very rapid, the cup is hardly oxidized.

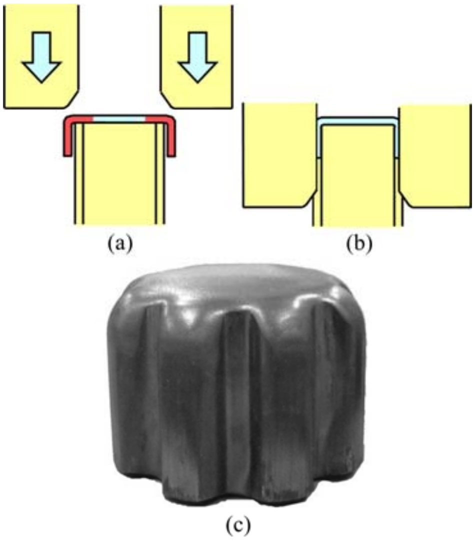

Fig. 13 Hot spline forming of die-quenched gear drum using resistance heating: (a) Heating at 900 °C; (b) Die quenching; (c) Formed drum

7 V-shaped hot forming using sealed air

The hot stamping is employed for forming not only steel sheets but also steel tubes. Since oil and water are conventionally used as pressure media in hydroforming of tubes, the heating temperature is limited. To increase the forming temperature, air is employed as pressure media [16]. Although the hot tube forming using air is similar to the hydroforming, the limitation of the heating temperature is removed.

V-shaped hollow axle beams used for suspensions of automobiles are conventionally formed by the cold hydroforming of tubes, and then the formed beams are quenched to increase the strength. The axle beam is produced by a hot tube forming process using sealed air shown in Fig. 14. The formability is improved by the heating, and the additional heat treatment is eliminated by the die quenching.

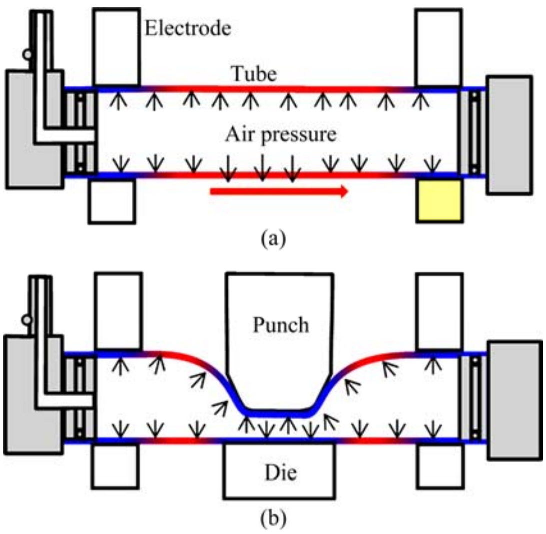

Fig. 14 V-shaped hot forming using sealed air: (a) Resistance heating; (b) Forming and die quenching

The steel tube having sealed air is resistance-heated, then the middle of the tube is formed with a punch and die into a V shape, and finally is die-quenched by holding of tools. The produced V-shaped hollow axle beam is shown in Fig. 15. Although the tube fractures for the cold forming, the tube is successfully formed by the hot forming, and the dimensional accuracy is improved because of no springback.

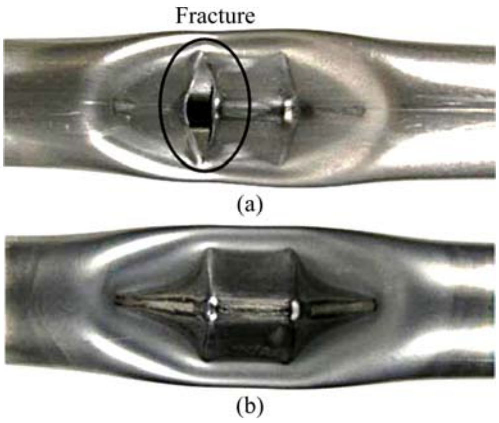

Fig. 15 V-shaped cold and hot-formed tubes using resistance heating: (a) Cold forming; (b) Hot forming

8 One shot hot stamping consisting of resistance heating, forming, shearing and die quenching

To decrease the production cost, net-shape forming processes without cutting are desirable in industry. Forging from comparatively thicker sheets or plates increasingly becomes common. In plate forging, thinning and thickening of sheets are performed to form complicated cross-sectional shapes, and thus mild steel and aluminium alloy sheets having low flow stress are generally employed. Because parts requiring high strength are heat-treated after the forming, the production cost becomes large.

The application of the present hot stamping process is limited to large body-in-white parts. This process is not appropriate for comparatively small parts, because the drop in temperature for these parts after the ejection from the furnace is very large.

A one shot hot stamping process of ultra-high strength steel parts consisting of rapid resistance heating, forming, shearing and die quenching was developed to produce comparatively small high strength steel parts (see Fig. 16). A rectangular sheet was resistance-heated to obtain a uniform distribution of temperature, and just after the end of heating, a sequence of forming, shearing and die quenching was performed by one shot to prevent the drop in temperature.

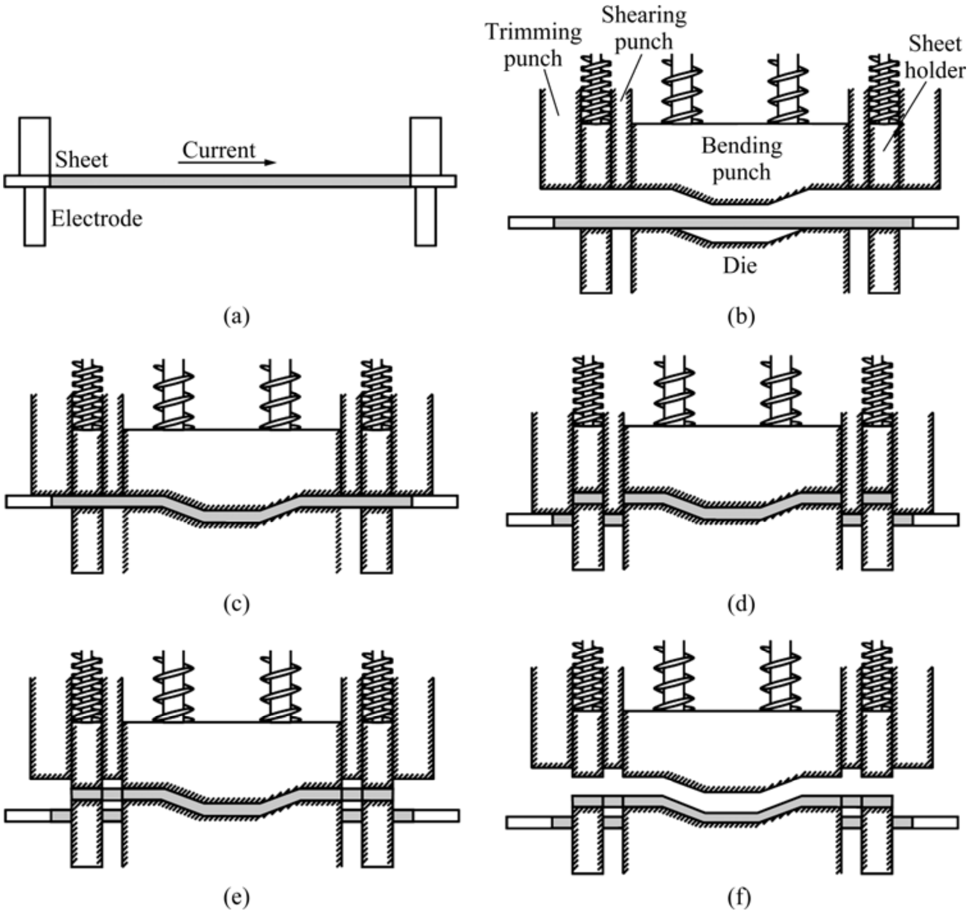

Fig. 16 One shot hot stamping process of ultra-high strength steel parts consisting of rapid resistance heating, forming, shearing and die quenching: (a) Resistance heating; (b) Setting; (c) Bending; (d) Shearing; (e) Die quenching; (f) End

An ultra-high strength stainless steel part was produced by the one shot hot stamping operation consisting of the heating, bending, shearing and die quenching (see Fig. 17). No springback of the produced part was observed by the holding at the bottom dead centre of the press. The Vickers hardness of the part was HV 580.

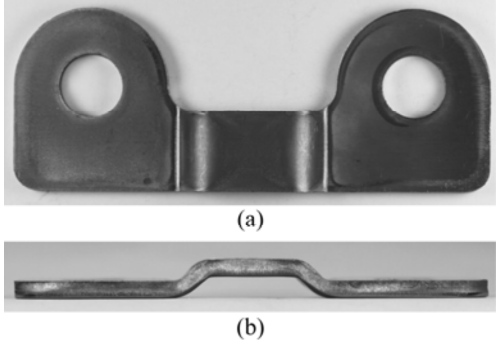

Fig. 17 Ultra-high strength stainless steel part produced by one shot hot stamping: (a) Front; (b) Side

9 Conclusions

Although the hot stamping processes are attractive as a key technique for the reduction in weight of automobiles, this technique is not still established. The improvement of productivity and the low cost of the equipment and stamping sheets are requisite for increasing the use of hot stamping. It is desirable to extend to the applicable range of hot stamping. The heating of sheet metals having high strength and low ductility at room temperature facilitates the stamping operation, e.g. hot stamping of titanium alloy sheets is remarkable, because of the increase in production of airplane titanium alloy parts.

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新型超高强度钢零件热冲压技术

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摘　要：为克服现今热冲压的难题，开发了一种高强度钢零件的新型热冲压技术。利用快速电阻加热，该热冲压技术所需的设备比电炉加热的设备更简单。与传统液压加工相比，该工艺采用机械伺服高速冲压可以提高成形性。通过具有局部旁路电阻加热的剪切模具，制备了具有不同强度分布的零件。局部电阻加热使得剪切区的流变应力减小，从而使模具淬火钢零件和超高强钢板的剪切更容易。通过对杯壁进行电阻加热，利用热齿键成型技术制备了超高强度钢齿轮盖。同时，还通过热冲压成型制备了汽车用中空导流槽。一次热压成形工艺包括电阻加热、成形、剪切和模具冷却等流程，该工艺适用于相对较小的高强度钢零件。

关键词：热冲压；超高强度钢；模具淬火；剪切模淬火；齿键成型；管成型；一次成型

(Edited by HE Yun-bin)