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RESEARCH ARTICLE

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Hot semi-punching and cold scrap removing processes for hot stamping of ultra-high strength steel parts

Ken-ichiro Mori*, Tomoyoshi Maeno, and Takuya Suganami

Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Aichi 441-8580, Japan

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Abstract – Hot semi-punching and cold scrap removing processes for hot stamping of ultra-high strength steel parts were developed to eliminate laser cutting having low productivity after hot stamping. A quenchable steel sheet is semi-punched without separation of punching scraps during hot stamping, and subsequently, the scraps are removed from the hot-stamped part at room temperature. For hot semi-punching, additional channels for taking the punching scraps out of dies are not required. Minimum remainder without separation of punching scraps and no clearance between the die and punch were optimal for the hot semi-punching process. The hot punching and cold removing loads of the quenched sheet were considerably smaller than the cold punching load, the quality of the hole edge was high and the delayed fracture around the sheared edge was prevented. Hot semi-punching and cold scrap removal were applied to a hot hat-shaped bending process.

Key words: Hot stamping, Ultra-high strength steel part, Hot semi-punching, Cold scrap removing

1. Introduction

To improve the passenger protection for collision of automobiles, the use of high strength steel parts in the body-in-white increases, and hot stamping of quenchable steel sheets is appropriate for producing these parts. Eriksson et al. [1] measured material data in hot stamping of boron steel sheets and simulated a hot bending process of a tubular beam. Hein [2] explained the specific requirements for simulation of hot stamping processes. Geiger et al. [3] measured basic characteristics in hot stamping of the boron steel sheet. Mori et al. [4] prevented the springback in bending by heating ultra-high strength steel sheets. Bariani et al. [5] examined the improvement of formability by hot stamping. Merklein et al. [6] observed deformation behaviour of a quenchable steel sheet in hot stamping.

Although stamped automobile body panels are punched to make many holes for joining, paint removing, attachment, etc., it is not easy to punch die-quenched parts having high strength. The tool life is remarkably reduced by large punching load, and worn tools bring about the deteriorations in dimensional accuracy of the punched hole and in quality of the sheared edge, as described by So et al. [7]. Valls et al. [8] evaluated wear resistance in cold shearing for various tool materials and coatings, and Nothhaft et al. [9] examined the influence of the punch chamfer. In addition, punching of the die-quenched parts has a risk of delayed fracture induced by tensile residual stress and rough fracture surface of the sheared edge. Although 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. Fritz [10] summarised recent improvements of productivity and production cost for laser cutting of the die-quenched parts. The laser cutting length of the hot-stamped parts is minimised by predicting the size and shape of the blank from those of the product in order to reduce the production cost.

If hardening of punching portions in hot stamping is locally prevented, the problems for cold shearing of hot-stamped parts can be solved, as described by Picas et al. [11]. Mori and Okuda [12] developed a tailored tempering process with grooved tools for forming a product having a strength distribution. Mori et al. [13] developed a tailored die quenching process of steel parts having strength distribution using bypass resistance heating in hot stamping. Maeno et al. [14] prevented hardening of a trimmed flange by slow cooling using spacers thicker than the sheet. On the other hand, Mori et al. [15] developed a punching process of ultra-high strength steel products using local resistance heating, and Mori et al. [16] extended local resistance to punching of small holes of a die-quenched sheet by controlling the temperature distribution.

Since heated sheets are soft, So et al. [17] punched the sheets during hot stamping. In punching during hot stamping, the structure of tools becomes complicated, because hot stamping including die quenching is generally a one-shot process.

*e-mail: mori@plast.me.tut.ac.jp

A large cooling speed in die quenching is required to attain high strength of stamped products. In addition, it is not easy to design additional channels for taking out punching scraps from dies, because dies used for hot stamping have cooling channels for die quenching. Choi et al. [18] half-trimmed a sheet during hot stamping to improve tool performance, and subsequently performed complete trimming at room temperature.

In the present study, hot semi-punching and cold scrap removing processes for hot stamping of ultra-high strength steel parts are developed to eliminate laser cutting having low productivity after hot stamping. The deformation behaviour of a quenchable steel sheet in hot semi-punching and cold scrap removing was examined.

2. Hot semi-punching and cold scrap removing processes

To eliminate laser cutting generally used in the hot stamping operation, a quenchable steel sheet is semi-punched during hot stamping, whereas the punching scraps are not removed from the hot-stamped part as shown in Figure 1. Subsequently, the scraps are removed from the hot-stamped part at room temperature. The semi-punching scraps slightly remain in the hot-stamped part to transfer to the cold scrap removing process. Since the scraps are not removed during hot stamping, additional channels for taking out punching scraps are not necessary for the hot-stamping dies. The cold scrap removing load is small due to the slight remainder. Naturally the hot semi-punching load is also small due to small flow stress of the heated sheet.

Firstly, a hot semi-punching operation without forming was performed to examine the deformation behaviour in semi-punching and cold scrap removing. The experimental setups of hot semi-punching and cold scrap removing are shown in Figure 2. A non-coated quenchable steel sheet 22MnB5 (C: 0.21, Mn: 1.2, Si: 0.25, B: 0.0014 mass%) having 1.6 mm in thickness was employed for the experiment, and the tensile strength and elongation of this sheet measured from the tensile test are shown in Figure 3. The 70 mm square sheet was heated at 1100 °C for 240 s with an electrical furnace and was punched at 850 °C after manual transference to the dies. Since the square sheet is too small, the temperature of the sheet rapidly decreased for 5 s during the manual transference. The sheet was fully austenitised because the Vickers hardness of the die-quenched sheet was about 470 HV0.3. A 1500 kN CNC servo press was used for stamping. The amount of remainder in semi-punching was adjusted by inserting a shim spacer between the punch and the press slide, and the remainder rate r to the sheet thickness was changed. For example, $r = 10\%$ means $1.6 \times (1 - 0.1) = 1.44$ mm in punch stroke. The diameters of the punches used in the hot semi-punching and cold scrap removing operations were equal, and the diameter of the die hole for cold scrap removing was larger than that for hot semi-punching due to easy positioning. It is easy to remove the scrap due to a small amount of remainder.

The conditions used for hot semi-punching are shown in Table 1. Since the sheet is not completely punched in semi-punching, no clearance between the punch and die is available without collision of the punch with the die. The diameter of the die shown in Figure 2a is determined from the clearance of hot semi-punching.

3. Results of hot semi-punching and cold scrap removing

3.1. Hot semi-punching

The hot semi-punched sheet for $c = 0\%$ and $r = 10\%$ is shown in Figure 4. The punching scrap remains in the sheet. A remarkable oxidation scale appeared on the surfaces because of the non-coated steel sheet.

The range of separation of the scrap for the different remainder rates and clearances is shown in Figure 5. For $r = 10\%$, the scrap separated from the sheet in $c = 10\%$, complete punching, whereas no separation occurred in $c = 0\%$.

The diameters of the semi-punched hole and scrap are given in Table 2. The punched holes expanded from the diameter of the punch of 5.95 mm, because the periphery of the sheet was early cooled by sandwiching between the upper and lower dies, and then the region around the hole was cooled. On the other hand, the scrap became smaller due to the shrinkage.

The deformation behaviour during hot semi-punching was calculated by the commercial FEM software LS-Dyna. The distribution of normal stress in the radial direction is illustrated in Figure 6. The normal stress in the radial direction the shearing region for $c = 0\%$ is highly compressive, and the compressive stress is larger than that for $c = 10\%$. This leads to delay of the separation.

The relationships between the hot semi-punching load and the remainder rate and between the cold scrap removing load and the remainder rate for $c = 0\%$ are shown in Figure 7, where the cold punching load of the die-quenched sheet is shown as a comparison. The hot semi-punching load is considerably lower than the cold punching load. In addition, the cold scrap removing load is also small, less than 1 kN, and thus pneumatic and hydraulic cylinders are enough for cold scrap removing.

3.2. Cold scrap removing

The cross-sections and surfaces of the holes after cold scrap removing are shown in Figure 8. For $c = 10\%$ and $r = 10\%$, the scrap separated from the sheet as shown in Figure 5, complete and single punching. As the remainder rate decreases, the quality of the hole improves, because the surfaces of the hot-punched and cold-removed edges are burnished and fracture ones, respectively, i.e. the quality of edges by cold punching of die-quenched sheets is considerably low. For $c = 0\%$ and $r = 10\%$, the surface is almost burnished. The semi-punched hole was hardly deformed by cold scrap removing due to the small remainder. No burr appeared, whereas the rollover became large due to hot semi-punching. Since the remainder is necessary only for the transference to the cold scrap removing process, the minimum remainder rate

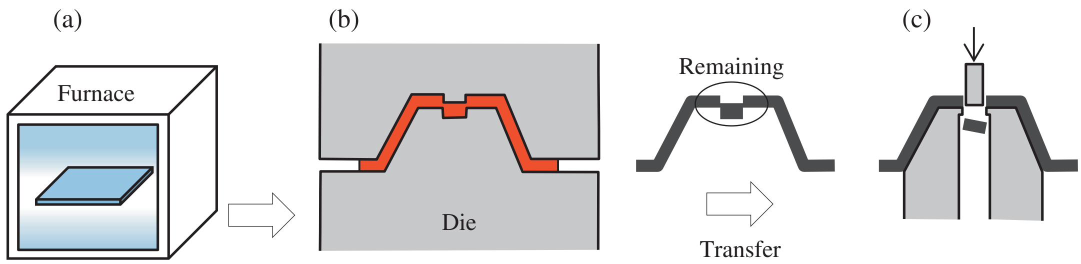


Figure 1. Hot semi-punching and cold scrap removing in hot stamping of ultra-high strength steel part. (a) Heating, (b) hot semi-punching in hot stamping and (c) cold scrap removing.

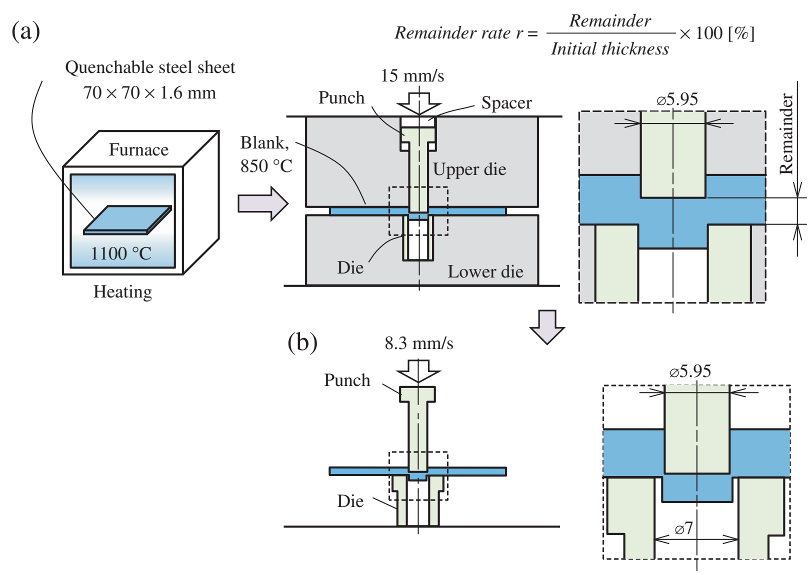


Figure 2. Experimental setup of (a) hot semi-punching and (b) cold scrap removing.

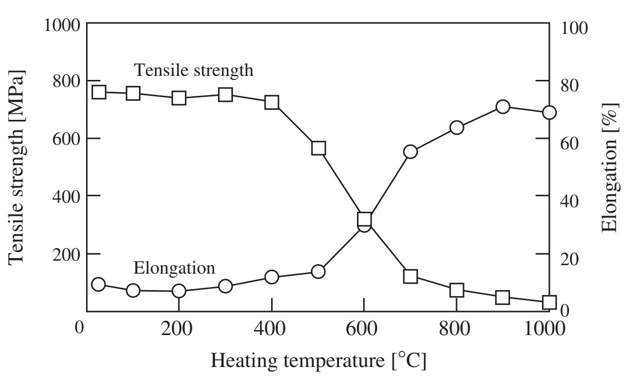


Figure 3. Variations of tensile strength and elongation with heating temperature for quenchable steel sheet 22MnB5.

Table 1. Conditions used for hot semi-punching.

Heating temperature	1100 °C
Forming temperature	850 °C
Punch speed in hot semi-punching	15 mm/s
Holding time at bottom dead centre	5 s
Remainder rate	r = 5–50%
Clearance	c = 0, 10%

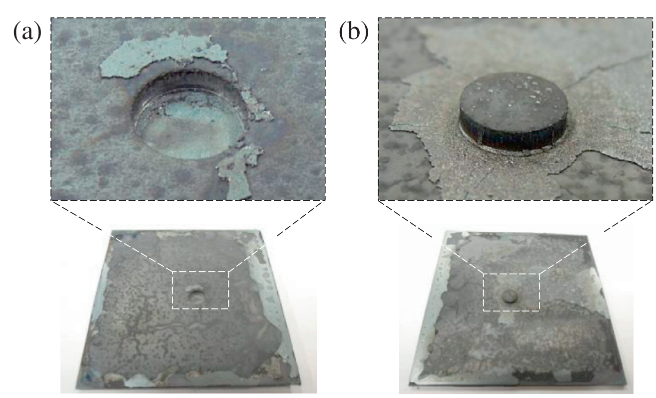


Figure 4. Hot semi-punched sheet for c = 0% and r = 10%. (a) Punch and (b) die sides.

is optimal, i.e. c = 0% and r = 10%. On the other hand, the burr for single punching of c = 10% and r = 10% is larger than that for c = 0% and r = 10%.

The surfaces of the holes after cold scrap removing and laser cutting are shown in Figure 9. In laser cutting, the power was 280 W and the speed was 800 mm/min. Although the rollover was prevented for laser cutting, a mark was

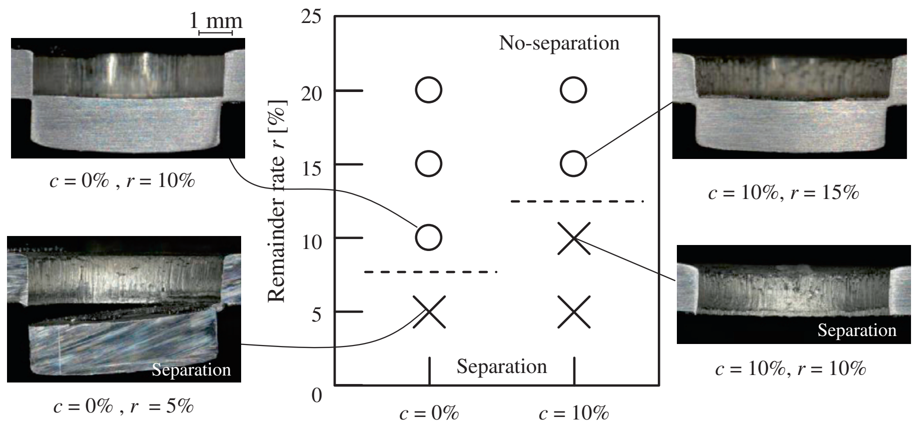
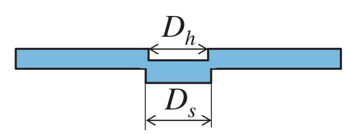


Figure 5. Range of occurrence of separation for different remainder rates and clearances.

Table 2. Diameters of semi-punched hole and scrap.

c	0%				10%		
r	10%	15%	20%	50%	15%	20%	50%
D_h [mm]	6.1	6.15	6.1	6.15	6.15	6.1	6.15
D_s [mm]	5.9	5.85	5.85	5.9	6.25	6.25	6.2



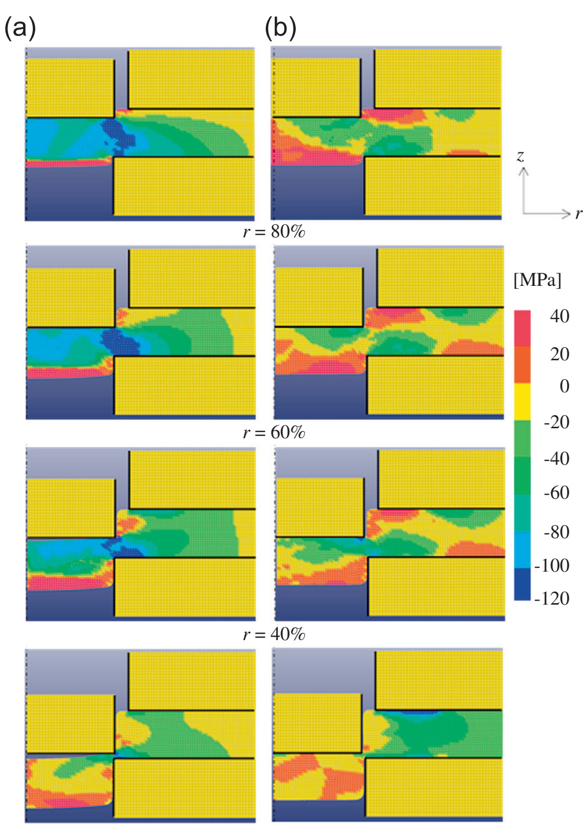


Figure 6. Distribution of normal stress in radial direction calculated by FEM software. (a) c = 0% and (b) c = 10%.

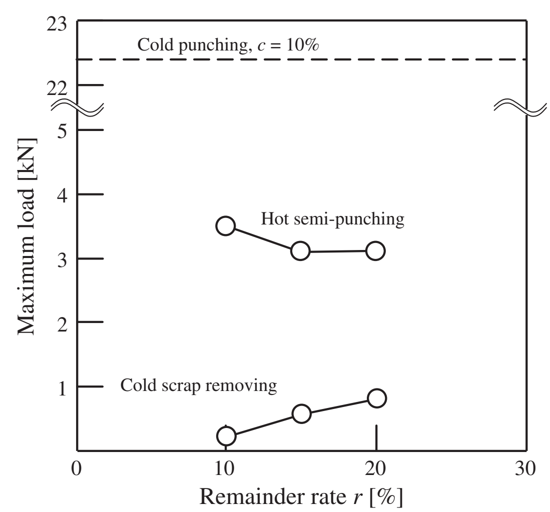


Figure 7. Relationships between hot semi-punching maximum load and remainder rate and between cold scrap removing maximum load and remainder rate for c = 0%.

caused at the end of cutting by scanning in the hoop direction.

The distribution of Vickers hardness in the thickness direction around the hole edge is shown in Figure 10, where the hardness of the die-quenched sheet without punching, fully far from the hole, is indicated as a comparison. Although the hardness was decreased from that of die quenching by laser cutting, the drop in hardness was not observed for hot semi-punching and cold scrap removing.

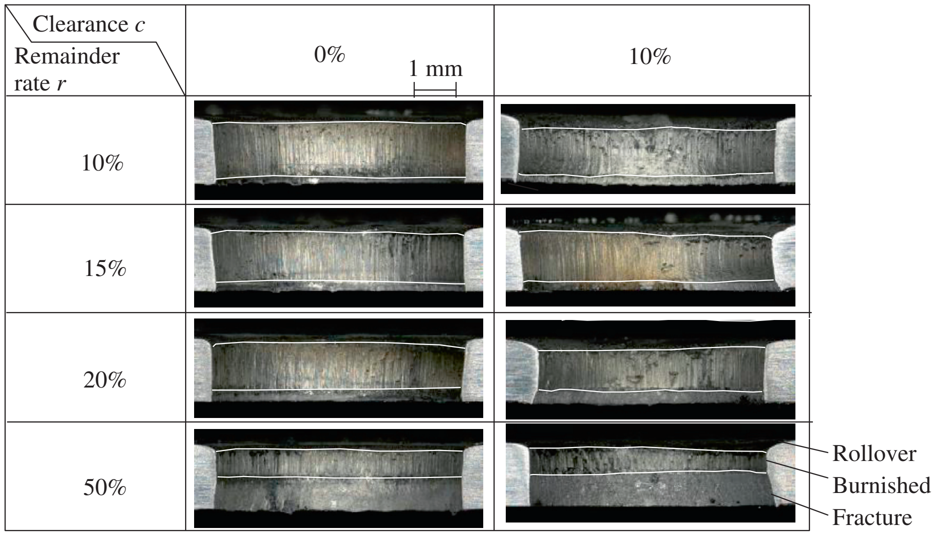


Figure 8. Cross-sections and surfaces of holes after cold scrap removing.

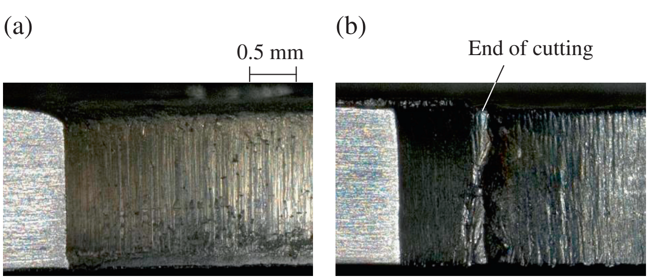


Figure 9. Surfaces of holes after (a) cold scrap removing for c = 0% and r = 10% and (b) laser cutting.

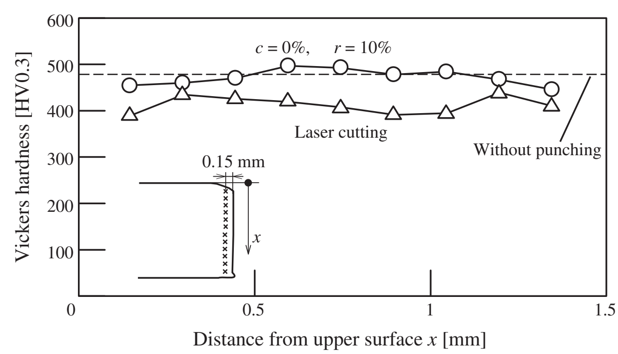


Figure 10. Distribution of Vickers hardness in thickness direction around hole edge.

The delayed fracture times around the hole edge for cold punching and hot semi-punching and cold scrap removing are shown in Figure 11, where the delayed fracture time is the time from the soak of the sheet in the 35% hydrochloric acid to the visual observation of cracks. Although cracks were caused for cold punching, the occurrence of cracks was prevented by heating for hot semi-punching.

4. Hot hat-shaped bending including semi-punching

Hot semi-punching and cold scrap removing were applied to the hot hat-shaped bending process shown in Figure 12, and the flat top and inclined flange were semi-punched. The non-coated quenchable steel sheet 22MnB5 having 1.6 mm in thickness used in Chapters 2 and 3 was employed for the experiment. The sheet was resistance-heated for hot hat-shaped bending including semi-punching. The heated blank was transferred to the bending dies with a pneumatic cylinder. The conditions used for the hot hat-shaped bending process including semi-punching are given in Table 3.

To prevent the collision of the upper die with the lower die, the remainder rate for c = 0% was increased to 15%. For conventional sheets 22MnB5 sheets having a thickness between 1.0 and 2.6 mm for hot stamping, c = 0% and r = 15% are appropriate. The punch head for the inclined flange was inclined to 10° parallel to the inclined flange.

The hat-shaped sheet having the semi-punched top and flange is shown in Figure 13. Since the heating time was considerably shortened by resistance heating, 3.3 s, the oxidation of the hat-shaped sheet was comparatively small. Not only the flat top but also the inclined flange was semi-punched with the inclined head punch without separation from the sheet. Cold-rolled sheets without annealing are austenitised even for the short heating time of 3.3 mm, because the grains are fine.

The cross-sections and surfaces of the top and flange holes after cold scrap removing are shown in Figure 14. The top hole is similar to that without forming shown in Figure 8, whereas a non-uniform burr in the hoop direction was caused for the flange hole. Since the diameter of the semi-punched hole increases as shown in Table 2, the burr in the flange hole is prevented by increasing the diameter of the punch for that of the hole. It is desirable to optimise the dimensions of the tools used for cold scrap removing.

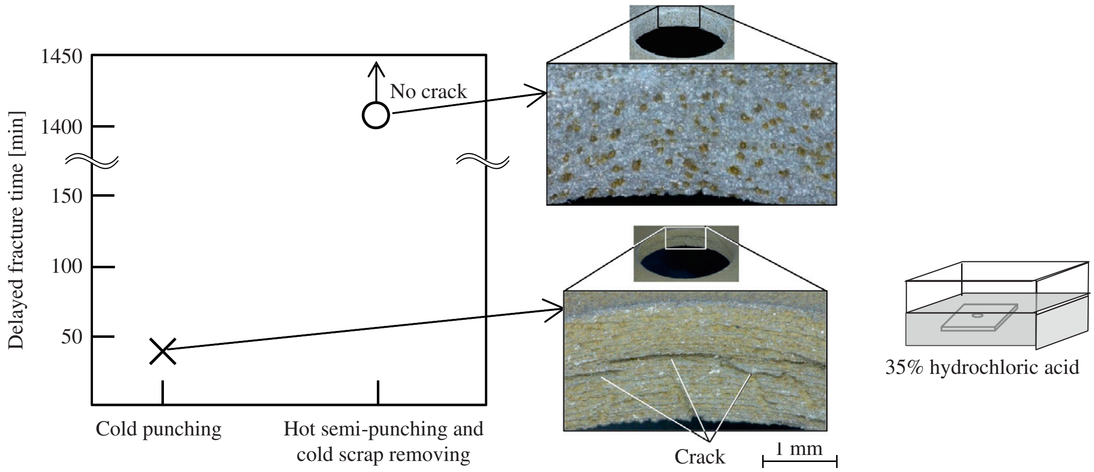


Figure 11. Delayed fracture times around hole edge for cold punching and hot semi-punching and cold scrap removing.

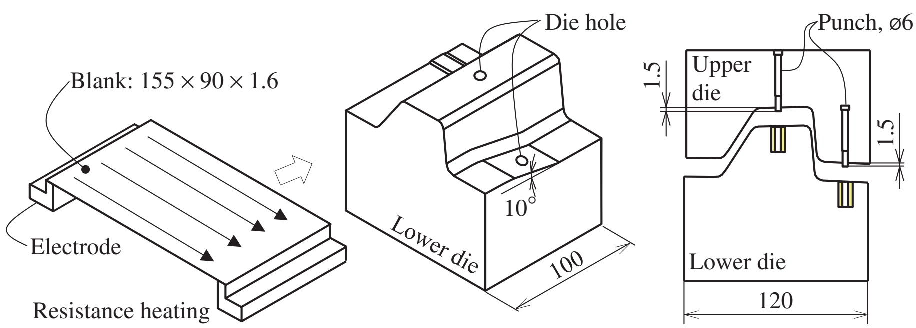


Figure 12. Hot hat-shaped bending including semi-punching.

Table 3. Conditions used for hot hat-shaped bending including semi-punching.

Heating temperature and time	930 °C and 3.3 s
Current for heating	7.7 kA
Transferring time	2.0 s
Bending temperature	850 °C
Holding time at bottom dead centre	5 s
Bending speed	70 mm/s
Clearance	c = 0%
Remainder rate	r = 15%

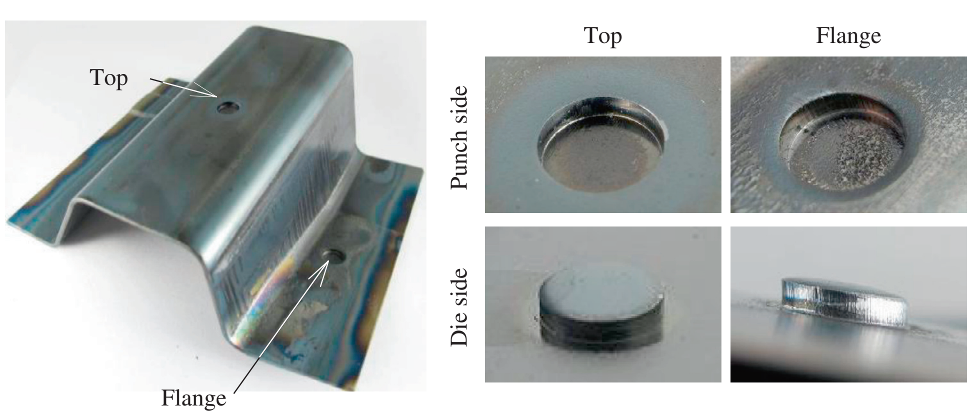


Figure 13. Hat-shaped sheet having semi-punched top and flange.

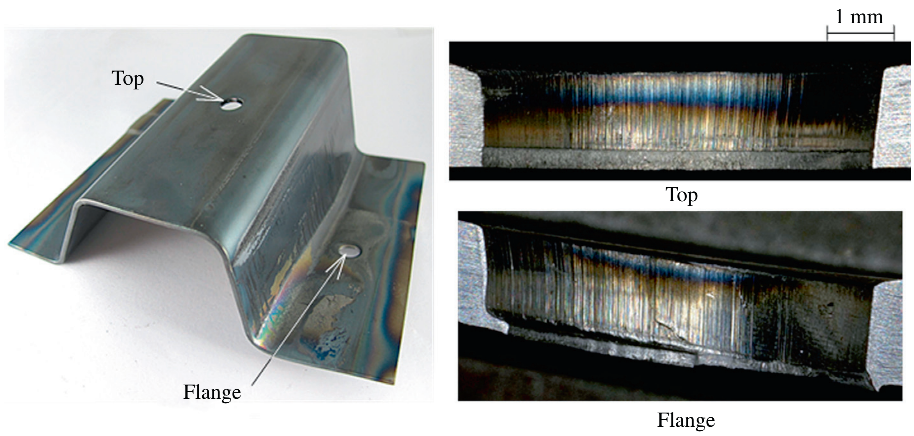


Figure 14. Cross-sections and surfaces of bottom and flange holes after cold scrap removing.

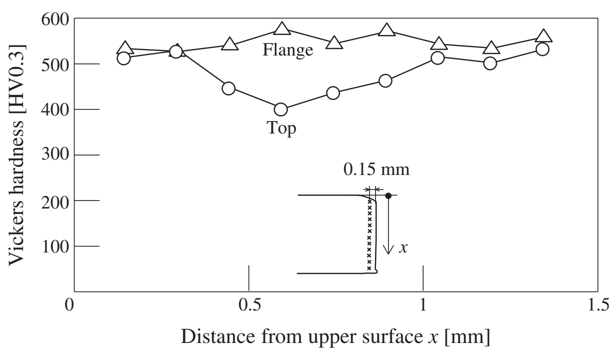


Figure 15. Distributions of Vickers hardness in thickness direction around edges of top and flange holes.

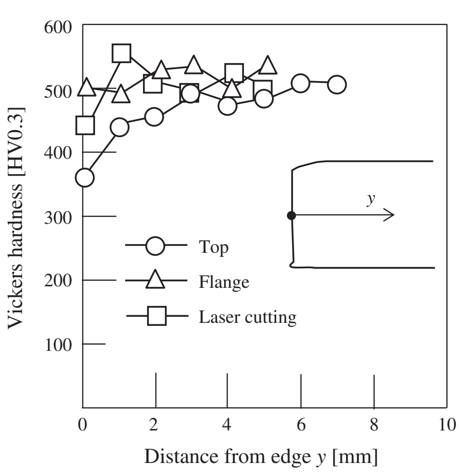


Figure 16. Distributions of Vickers hardness at middle of thickness from edges of top and flange holes.

The distributions of Vickers hardness in the thickness direction around the edges of the top and flange holes are shown in Figure 15. The hardness for the top hole decreased in the middle of the thickness, because the hole edge was detached from the punch by the thermal shrinkage during die quenching and the cooling speed was low.

The distributions of Vickers hardness at the middle of the thickness from the edges of the top and flange holes are shown in Figure 16. Although the hardness around 500 HV0.3 for laser cutting is close to the hole edge, that for the top hole is above 3 mm from the edge. In semi-punching, the hardness around the hole edge is influenced by the contact with the punch.

5. Conclusions

Although the use of hot stamping processes of ultra-high strength steel parts considerably increases, punching and trimming of stamped parts are still a bottleneck due to low productivity of laser cutting. Hot punching and trimming included in hot stamping processes are attractive for reducing the production cost, whereas the design of hot stamping processes becomes complex due the addition of shearing operations in the one-shot process. The hot punching process is more complicated than the hot trimming process, because tools are positioned inside and many holes are made. The hot semi-punching process is simpler than the hot full punching one because of no treatment of punching scraps.

Hot punching and trimming have some problems for the application to actual hot stamping operations. Tool materials and coating effective in hot punching and trimming are necessary because tools undergo large shearing force at high temperatures. The design of the stamping process for including punching and trimming tools is significantly important. The timing of punching and trimming operations is also adjusted, e.g. the punches are not taken from holes by thermal shrinkage after die quenching. The productivity and production cost of hot stamping operations are improved by hot punching and trimming, and the hot semi-punching and cold scrap removing processes are a realistic approach.

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