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ORIGINAL ARTICLE

Steel sheets partnered with quenchable sheet in hot stamping of tailor-welded blanks and its application to separation prevention of fractured components

Ken-ichiro Mori [1] · Yasutaka Suzuki [2] · Daisuke Yokoo [1] · Michiya Nishikata [1] · Yohei Abe [1]

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Abstract
The phase transformation and mechanical properties of non-quenchable steels partnered with the quenchable boron steel in hot stamping of tailor-welded blanks were evaluated to produce tailored components with partially balanced strength and ductility. The effect of the forming start temperature after natural air cooling on the phase transformation and mechanical properties for 270 MPa mild steel, non-quenchable steel, 440 MPa high strength steel, and 22MnB5 steel sheets was examined, and the 270 MPa and non-quenchable sheets had enough ductility after hot stamping. Tailored components having a hardness of about 500 HV1 in the high strength zone and a total elongation of about 30% in the high ductility zone were hot-stamped from a tailor-welded blank composed of 22MnB5 and 270 MPa sheets. It was found that the 270 MPa mild steel sheet is sufficient as a partner sheet of tailor-welded blanks. In addition, the safety of hot-stamped components was heightened by welding a 22MnB5 main blank with a 270 MPa steel patch. Even if the main blank is fractured by a collision, the hot-stamped component is not separated by the 270 MPa patch having high ductility.

Keywords Hot stamping · Tailor-welded blank · Partner steel sheet · Ductility · Component separation

1 Introduction

To heighten the crash safety of automobiles without weight increase, ultra-high strength steel components of body-in-white have been increasingly produced by hot stamping. In hot stamping, heated quenchable steel sheets are formed and then are quenched by being held with cold dies at the bottom dead centre of a press [1]. The high strength of the components is gained by means of microstructure control through both austenite and martensite transformations, and the heat treatments are included in stamping operations. Die quenching leads to another advantage of small springback of hot-stamped components due to plastic deformation induced by volume expansion of the martensitic transformation during holding at the bottom dead centre [2]. Most of steel sheets used for hot stamping are manganese-boron steel 22MnB5, and the tensile strength of the formed components is about 1.5 GPa. The superiority of the high strength for hot stamping is being lowered by the development of new 1.5 GPa ultra-high strength steel sheets used for cold stamping [3], because cold stamping has the advantages of high productivity, conventional and cheaper equipment, no oxidation prevention treatment, etc. It is desirable to generate additional advantages of hot stamping.

Although the strength of steels generally decreases with increasing ductility, the crash safety of automobile components such as A and B-pillars is improved by partially increasing the ductility because of the rise in energy absorption [4]. Hot stamping is suitable for producing tailored components with partially balanced strength and ductility. Merklein et al. [5] gave a detailed review of tailored hot stamping processes, and Mori el al. [6] classified these processes into heat treatments and tailored blanks. Since both austenite and martensite transformations are required to attain high strength of components, the formed components are not hardened by preventing one of the two transformations, and the ductility becomes high. In tailoring using the heat treatments, the austenite or martensite transformation is partially prevented in components. By partially heating sheets above

✉ Ken-ichiro Mori
mori@plast.me.tut.ac.jp

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

[2] TOA Industries Co., Ltd., 26-1 Nishishin-machi, Oota 373-0847, Japan

and below the austenitisation temperature, the stamped components have both high strength and high ductility zones. In 22MnB5 quenchable steel sheets commonly employed for hot stamping, the austenitisation temperature is about 800 °C. Wilsius et al. [7] partially covered steel sheets with heat shields in a heating furnace to prevent the austenite transformation. Landgrebe et al. [8] partially heated sheets by sandwiching between heating plates having a temperature distribution. Mori et al. [9] partially heated sheets with bypass resistance heating in which zones in contact with copper bypasses having a low resistance and large cross-sectional area were not heated due to the passage of most of current though the bypasses. Maikranz-Valentin et al. [10] pre-heated steel sheets below the austenitisation temperature, and then partially inductive-heated these sheets above the austenitisation temperature for die quenching.

The martensite transformation is partially prevented by decreasing the cooling rate of the high ductility zone in the heated sheet during die quenching. Tailored tempering is the most typical process of the partial martensitisation. Dies used for hot stamping are generally water-cooled to attain a high cooling rate; conversely, dies are partially heated in order to drop the cooling rate for tailored tempering, and both heating and cooling regions exist in the die. For the 22MnB5 boron steel sheets, the martensite transformation does not occur below 30 °C/s in cooling rate, and softer ferrite and bainite appear. Fernandez et al. [11] exhibited strategies of the tailored tempering. Tang et al. [12] predicted microstructure of hot-stamped components produced by tailored tempering for various heating temperatures of dies. Bardelcik et al. [13] examined the mechanical properties, microstructure, and damage of tailored components. Omer et al. [14] examined the crush behaviour of a component produced by tailored tempering from an experiment and FEM simulation. Nakagawa et al. [15] developed tailored tempering processes without heating of dies.

Tailored blanks having optimal differences in thickness and material are increasingly applied for automobile components [16]. The flexibilities in product design, formability, structural stiffness, crash safety, etc., are improved by means of tailor-welded blanks. The tailored blanks are mainly produced by laser butt welding of several sheets. Min et al. [17] evaluated the weldability and formability of tailor-welded blanks for automobile clutch parts. Kinsey et al. [18] applied force to welds of a tailor-welded blank during stamping to increase the formability. Chan et al. [19] evaluated the formability of tailor-welded blanks having different thicknesses. Padmanabhan et al. [20] optimised the blankholder force in square cup drawing of a tailor-welded blank to improve the drawability.

The tailor-welded blanks are mostly employed for cold stamping, and the application to hot stamping processes also increases. Although the formability in cold stamping of tailor-welded blanks is greatly influenced by low ductility near the welds, its ductility is improved by heating in hot stamping. Tailored hot stamping using the tailor-welded blanks is more flexible than that using the heat treatments because of partial different thickness and no die heating, whereas the cost of the blank is higher due to laser welding. Tailored components having partially balanced strength and ductility can be hot-stamped from tailor-welded blanks consisting of quenchable and non-quenchable steel sheets. Choi et al. [21] examined the hot stretch flangeability of tailor-welded blanks composed of quenchable boron and non-quenchable 340 MPa steel sheets. The hot formability of the quenchable steel sheet at elevated temperatures is similar to that of the non-quenchable sheets. Choi et al. [22] simulated deformation behaviour and phase transformation in hot stamping of a tailor-welded blank and in hot stamping using tailored tempering. Kang et al. [23] examined the effects of welding

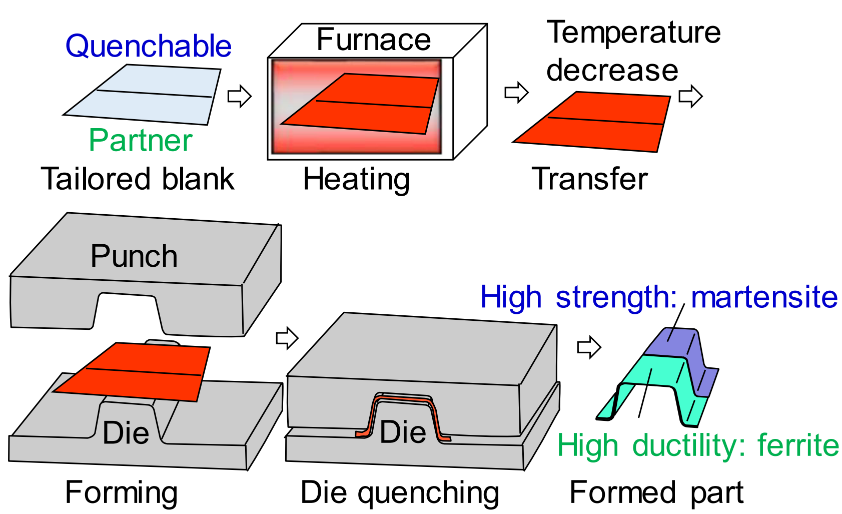


Fig. 1 Phase transformation in hot stamping of tailored components having partially high strength and ductility from tailor-welded blank

Table 1 Chemical composition of steel sheets used for experiment

Steel		Chemical composition (wt%)			
		C	Mn	B	Si
Partner	Non-quenchable	0.064	0.75	0.0003	0.191
	270 MPa	0.05	0.22	-	0.01
	440 MPa	0.17	0.68	-	0.01
High strength	22MnB5	0.21	1.22	0.003	0.26

and heating conditions on the microstructure near the weld in hot stamping of a tailor-welded blank. Tang et al. [24] examined the effect of weld seam locations on deformation behaviour in hot stamping of tailor-welded blanks from the finite element simulation.

For non-quenchable steels partnered with the quenchable boron steel in hot stamping of a tailor-welded blank, it is required to have appropriate ductility and strength after the same heating, forming and die quenching operations as the boron steel. Tang et al. [25] evaluated the mechanical properties of partner steels in hot stamping of tailor-welded blanks. Kong et al. [26] developed one-step quenching and partitioning treatment of a tailor-welded blank composed of boron and TRIP steels. Ductibor® [27] is commonly employed in industry as a partner steel, whereas this steel is costly and the suppliers are limited. It is desirable in industry to investigate anti-quenchability of partner steels in hot stamping of tailor-welded blanks.

In the present paper, the applicability of the conventional steel sheets used for cold stamping as partner sheets in hot stamping of tailor-welded blanks was evaluated. The phase transformation and mechanical properties of partner steel sheets in hot stamping of tailor-welded blanks were examined. The phase transformation of the steel sheets for heating and cooling histories of hot stamping operations was measured, and the ductility and strength of the quenched sheets were evaluated. In addition, an approach for improving the safety of hot-stamped components using a 270 MPa sheet having high ductility after die quenching is proposed.

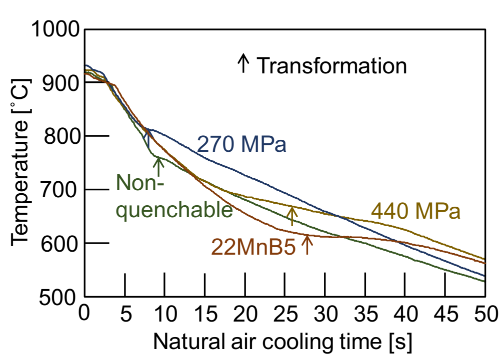


Fig. 2 Variation in temperature and phase transformation of 4 steel specimens in natural air cooling

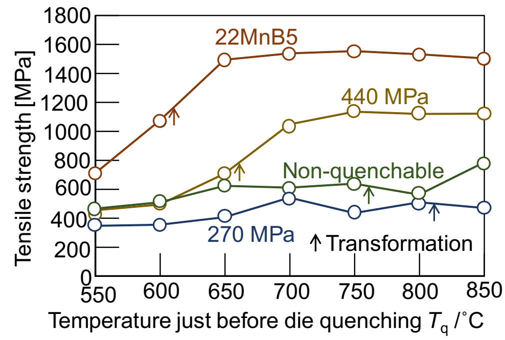


Fig. 3 Relationship between tensile strength and temperature just before die quenching for 4 sheets

2 Phase transformation and mechanical properties of partner steel sheets without forming

2.1 Partially high strength and ductility in hot stamping of tailor-welded blank

In hot stamping of tailored components having partially high strength and ductility from tailor-welded blanks, welded quenchable and partner steel sheets are heated, transferred, formed, and die-quenched under the same temperature history, as shown in Fig. 1. Both quenchable and partner steel sheets are transformed into austenite by heating. During the transfer from the furnace to the dies, the temperature of the blank decreases due to natural air cooling. When the transfer time is long, the quenchable steel sheet is transformed into ferrite during the transfer and is not hardened without the martensite transformation even for die quenching anymore. On the other hand, a long transfer time is desirable for the partner steel sheet to obtain high ductility by the ferrite transformation during the transfer. It is required that the transformation during the transfer is prevented for the quenchable steel sheet and is caused for the partner steel sheet. Since the forming start temperature is changed by the transfer time, the effect of the forming start temperature on the phase transformation, the strength, and ductility of the quenchable and partner steel sheets is examined.

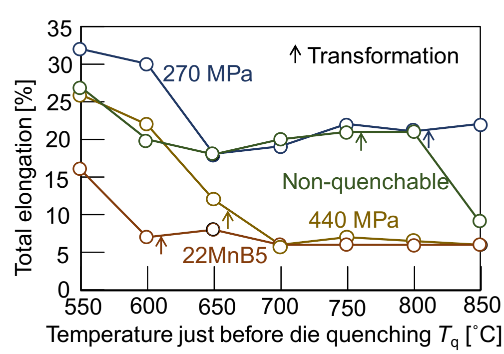


Fig. 4 Relationship between total elongation and temperature just before die quenching for 4 sheets

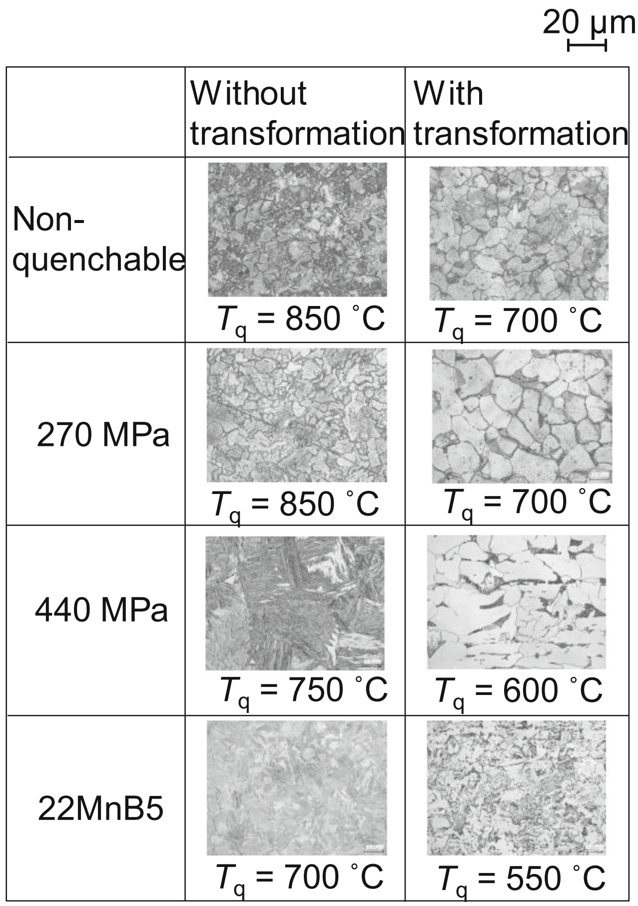


Fig. 5 Microstructures of die-quenched sheets without and with phase transformation during natural air cooling

2.2 Experimental procedure and natural air cooling

The quenchable steel sheet of the tailor-welded blank was an Al-Si coated 22MnB5 steel generally used for hot stamping, and the partner steel sheets were a non-quenchable steel, 270 MPa mild steel, and 440 MPa high strength steel, where the non-quenchable steel sheet is commonly employed for as a partner sheet of the tailor-welded blank and 270 MPa and 440 MPa steel sheets are conventional steel sheets used for cold stamping. The thickness of all the sheets was 1.6 mm. The chemical composition of the steel sheets used for the experiment is given in Table 1.

A tensile specimen with a width of 25 mm and a gauge length of 50 mm was heated to 910 °C for 330 s in an electric furnace to be transformed into austenite. The heated specimen was naturally air-cooled after taking out of the furnace. The temperature of the specimen was measured by a thermocouple at the surface of the middle of the gauge section.

The phase transformation of the 4 steel sheets under natural air cooling was measured. In hot stamping, the temperature during the transfer from a furnace to dies is decreased by natural air cooling, and the cooling rate during this period is low. The variation in temperature and the phase transformation of the 4 steel specimens in natural air cooling are shown in Fig. 2. When the slop of the temperature curve becomes small, the latent heat appears, and the phase transformation occurs. Once the ferrite transformation appears for the 22MnB5 sheet, the martensite transformation does not occur even for rapid cooling, and thus, high strength is not attained. The time up to the transformation of the 22MnB5 sheet is a limit of natural air cooling for hot stamping. On the other hand, for the partner sheets, the transformation during natural air cooling leads to the high ductility, and the 270 MPa and non-quenchable steel are early transformed. The ferrite transformation of the 22MnB5 sheet is prevented by this early transformation.

2.3 Effect of forming start temperature

In hot stamping, heated steel sheets are formed after natural air cooling during transfer to dies, and the forming start temperature has a great effect on the phase transformation and mechanical properties. This effect was evaluated from quenching with cold flat dies without forming. The tensile specimens were naturally air-cooled after taking out of the furnace, as shown in Fig. 2, and were quenched from a temperature between 850 and 550 °C.

The relationship between the tensile strength and the temperature just before die quenching, T_q, for the 4 sheets was shown in Fig. 3, where this temperature is equivalent to the forming start temperature because of no forming. The higher the temperature just before die quenching, the larger the effect of quenching becomes. The 22MnB5 and 440 MPa sheets are quenched above 650 and 700 °C, respectively, and the tensile strength is greatly changed around the phase transformation.

Table 2 Levels of tensile strength and total elongation of die-quenched steel sheets without and with phase transformation during natural air cooling

	Transformation during natural air cooling	Non-quenchable	270 MPa	440 MPa	22MnB5
Level of tensile strength	Without	Low, 600 MPa	Low, 500 MPa	Middle, 1100 MPa	High, 1500 MPa
	With	Low, 400 MPa	Low, 300 MPa	Low, 500 MPa	Low, 700 MPa
Level of total elongation	Without	High, 20%	High, 20%	Low, 5%	Low, 5%
	With	High, 25%	High, 30%	High, 25%	Middle, 15%

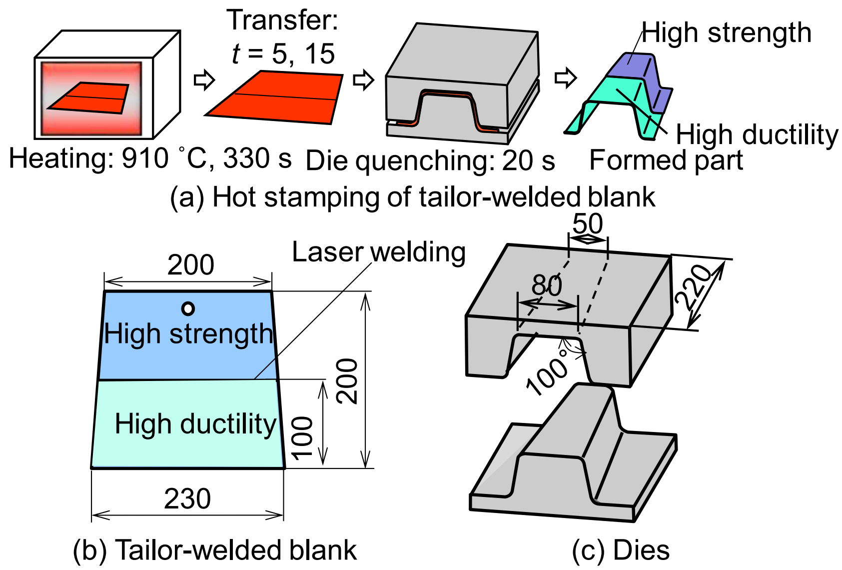


Fig. 6 Procedure of hot stamping experiment of tailor-welded blanks into hat shape

The strengths for the 270 MPa and non-quenchable sheets are almost constant, and the strength for the quenched 270 MPa sheet is lower than that for the quenched non-quenchable sheet.

The relationship between the total elongation and the temperature just before die quenching for the 4 sheets was given in Fig. 4. Although the elongations for the 270 MPa and non-quenchable sheets are large even at high temperatures just before die quenching, that at 850 °C for the non-quenchable sheet drops and the tensile strength shown in Fig. 3 also increases.

The microstructures of the die-quenched sheets without and with the phase transformation during natural air cooling are shown in Fig. 5. For the quenched 22MnB5 and 440 MPa sheets, the microstructures without the transformation during natural air cooling are martensite, and those with the transformation are pearlite and ferrite, respectively. On the other hand, the microstructures without and with the transformation during natural air cooling for the 270 MPa and non-quenchable sheets are ferrite, whereas those without the transformation during natural air cooling are finer.

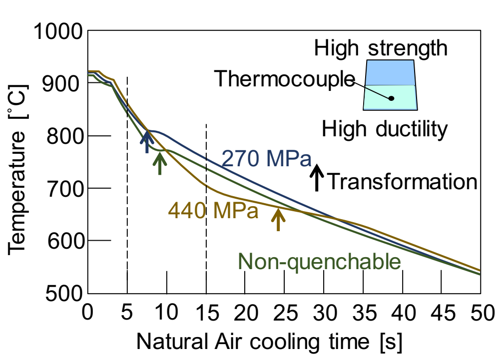


Fig. 7 Variation in temperature and phase transformation of partner sheets of tailor-welded blanks in natural air cooling

The levels of the tensile strength and total elongation of the die-quenched steel sheets with and without the phase transformation during natural air cooling are summarised in Table 2. The 270 MPa and non-quenchable sheets are available as partner sheets having high ductility, whereas the 440 MPa sheet is insufficient as a partner sheet.

3 Hot stamping of tailored parts having high strength and ductility zones using tailor-welded blanks

3.1 Procedure of hot stamping

The 22MnB5 sheet was laser-welded with the non-quenchable, 270 MPa and 440 MPa sheets as partner sheets, and the three tailor-welded blanks were hot-stamped into a hat shape. The 22MnB5 sheet was formed into a high strength zone, and the rest of the three sheets were formed into a high ductility zone. The procedure of a hot stamping experiment of

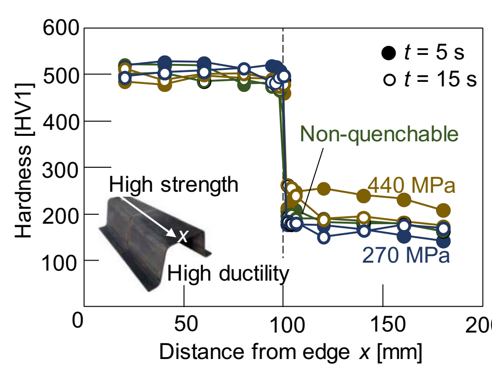


Fig. 8 Distributions of Vickers hardness in hat-shaped parts for $t = 5$ and 15 s

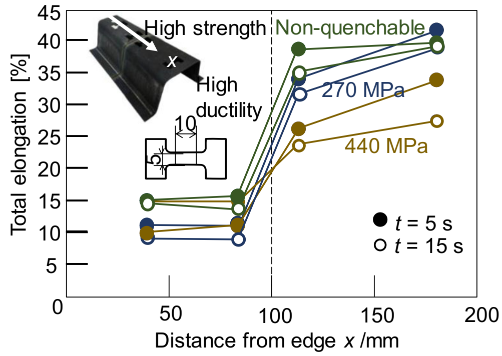


Fig. 9 Distributions of total elongation in hat-shaped parts for $t = 5$ and 15 s

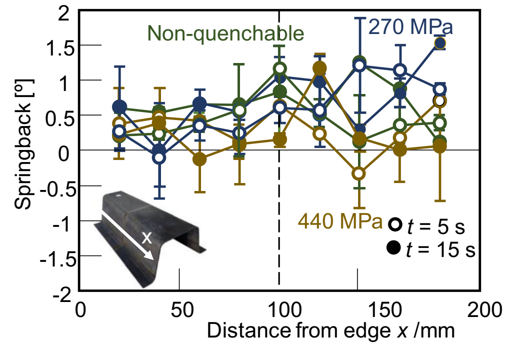


Fig. 11 Distributions of springback of sidewall of hat-shaped parts

the tailor-welded blanks is illustrated in Fig. 6. The blank was heated to 910 °C for 330 s in the electric furnace, and the transfer time from the furnace to the dies were $t = 5$ and 15 s, because the common transfer time in practical hot stamping operations is between 5 and 15 s. The heated blanks were bend into a hat shape, and then was fully die-quenched by a holding time of 20 s at the bottom dead centre of a press. No cracking occurred around the welds of all the formed parts.

The variation in temperature and the phase transformation of the partner sheets of the tailor-welded blanks in natural air cooling are shown in Fig. 7. For $t = 5$ s, all the partner sheets are die-quenched before the phase transformation, whereas the 270 MPa and non-quenchable sheets are die-quenched after the transformation for $t = 15$ s.

3.2 Results of hot stamping

The distributions of the Vickers hardness in the hat-shaped parts for $t = 5$ and 15 s are illustrated in Fig. 8. The hardness in the high strength zone is about 500 HV1, and those in the high ductility are below 200 HV1 except for $t = 5$ s of the 440 MPa sheet.

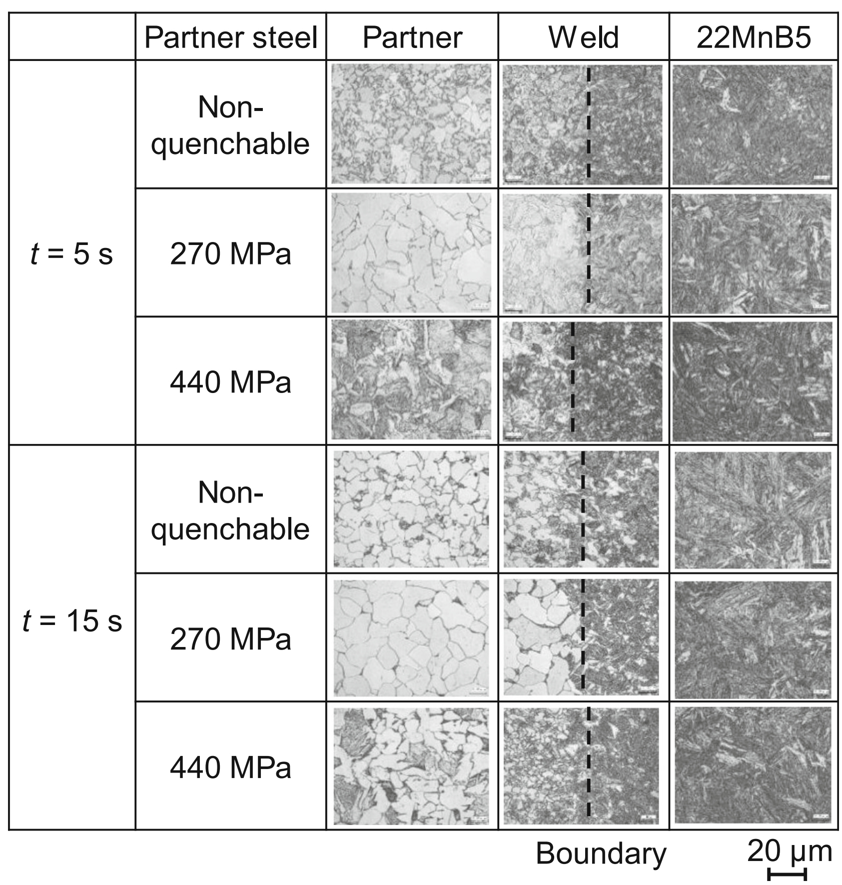


Fig. 10 Microstructures of hat-shaped parts for $t = 5$ and 15 s

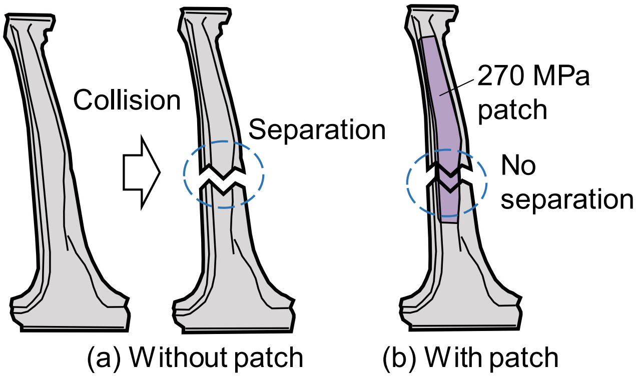


Fig. 12 Prevention of separation of hot-stamped components using 270 MPa patch having high ductility for safety improvement

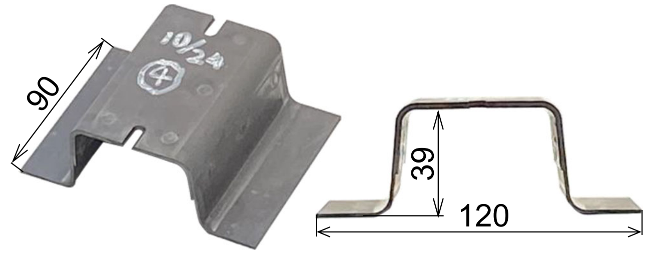


Fig. 14 Hot-stamped patchwork blank composed of 22MnB5 main blank and 270 MPa patch

The distributions of the total elongation in the hat-shaped parts for t = 5 and 15 s are shown in Fig. 9, where small tensile specimens were cut from the hat-shaped parts by wire electrical-discharge machining. Due to the small specimen, the elongation shown in Fig. 9 is larger than that in Fig. 4. The elongations for the 270 MPa and non-quenchable sheets are large, and that for the 440 MPa is lower. It was found that the 270 MPa sheet has similar ductility and strength to the non-quenchable sheet.

The microstructures of the hat-shaped parts for t = 5 and 15 s are given in Fig. 10. All the high strength zones composed of the 22MnB5 sheet are transformed into martensite. The microstructures of the 270 MPa sheet for t = 5 and 15 s are ferrite, and the microstructure for t = 5 s of the non-quenchable sheet is finer. The microstructure of the 440 MPa sheets for t = 5 s is martensite, and thus, the 440 MPa sheet is not suitable for a short transfer time to dies.

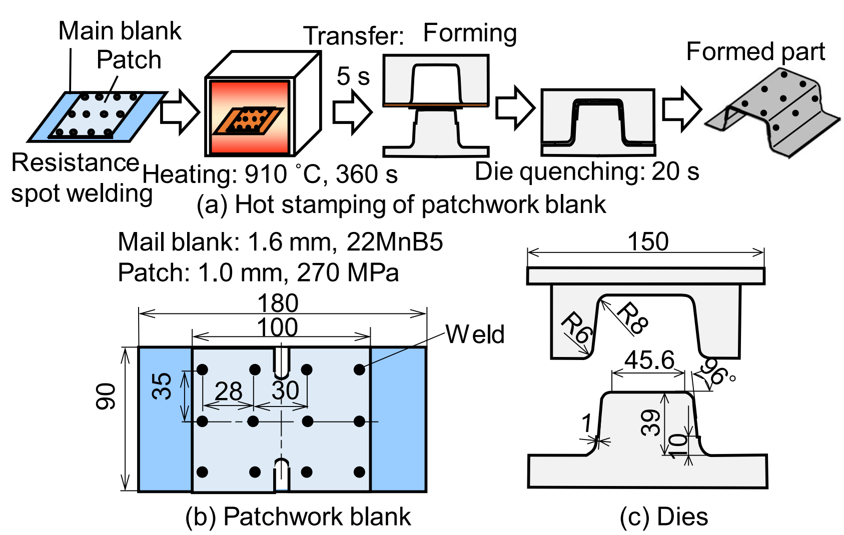
The distributions of the springback of the sidewall of the hat-shaped parts are shown in Fig. 11. Although the springback of all the three tailored blanks is relatively small, the springback of the high ductility zone tends to be larger than that of the high strength zone. This is due to no martensite transformation at low temperatures [2].

4 Application of 270 MPa mild steel sheet to improvement of safety of hot-stamped components

4.1 Prevention of separation of fractured components using 270 MPa patch

As another application, an approach for improving the safety of hot-stamped components using the 270 MPa sheet having high ductility after die quenching is proposed. Although hot-stamped components having high strength hardly deform, the components are fractured by a small displacement because of low ductility. When the component is fractured by a collision of automobiles,

Fig. 13 Procedure of hot stamping experiment of patchwork blank composed of 22MnB5 main blank and 270 MPa patch



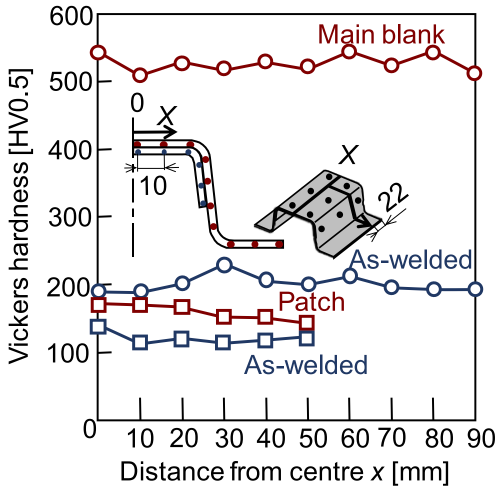


Fig. 15 Distributions of Vickers hardness of main blank and patch before and after hot stamping

separated pieces fly at a high speed due to rapid release of collision energy, and this is very dangerous [28]. This separation is prevented by welding with a 270 MPa mild steel patch having high ductility even after hot stamping. A patchwork blank is produced by welding a 22MnB5 main blank with the 270 MPa patch, and the patchwork blank is hot-stamped. Even if the hot-stamped main blank is fractured by the collision, the fractured pieces are not separated by the 270 MPa patch having high ductility, as shown in Fig. 12.

The hot stamping process of the patchwork blank is illustrated in Fig. 13. A 22MnB5 main blank and 270 MPa patch were resistance-spot-welded, the patchwork blank was heated to 910 °C for 360 s in the electric furnace, and then was hot-stamped into a hat shape. The thicknesses of the main blank and patch were 1.6 and 1.0 mm, respectively. As a

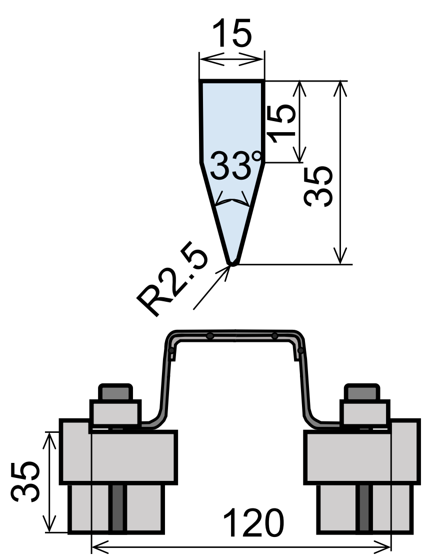


Fig. 16 Collapse test of hot-stamped patchwork blank

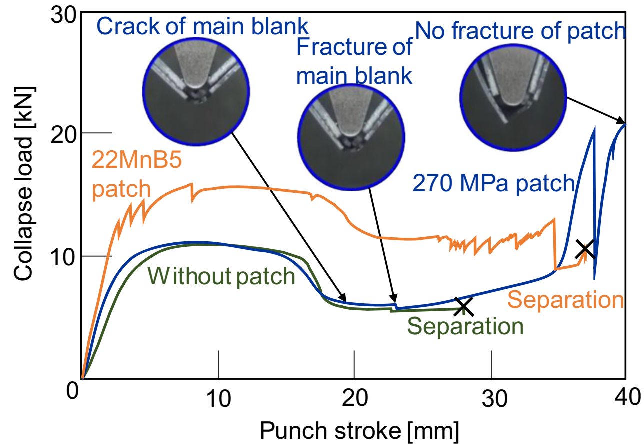


Fig. 17 Collapse load-punch stroke curve for hot-stamped patchwork blank

comparison, a patchwork blank with a 22MnB5 patch was hot-stamped. Since the patch is only to prevent the separation, a thinner and smaller patch is used because of less increase in weight.

4.2 Results of hot stamping

The hot-stamped patchwork blank composed of the 22MnB5 main blank and 270 MPa patch is given in Fig. 14. The springback of the formed blank is small.

The distributions of Vickers hardness in the main blank and patch before and after hot stamping are shown in Fig. 15. Although the 22MnB5 main blank is sufficiently die-quenched, the 270 MPa patch is not hardened.

4.3 Results of collapse test

The collapse test of the hot-stamped patchwork blank is illustrated in Fig. 16. The centre of the top of the formed blank is pushed with the sharp punch under fixing both flanges. The punch speed was 10 mm/min, and the test was finished when the main blank separated or the punch stroke attained 40 mm.

The collapse load-punch stroke curve for the hot-stamped patchwork blank is illustrated in Fig. 17. The collapse load fluctuates for cracking of the welds. The blank without a patch and the patchwork blank with the 22MnB5 patch separate at punch strokes of 28 and 37 mm, respectively, and the 270 MPa patch does not fracture up to a stroke of 40 mm even for the fracture of the main blank. The loads for the hot-stamped patchwork blank with the 270 MPa patch and without a patch are similar because of the thin and soft patch.

The hot-stamped parts after the collapse test are shown in Fig. 18. Although the hot-stamped blank without a patch and the hot-stamped patchwork blank with the 22MnB5 patch separate, the hot-stamped patchwork blank with the 270 MPa patch does not separate. Even if the

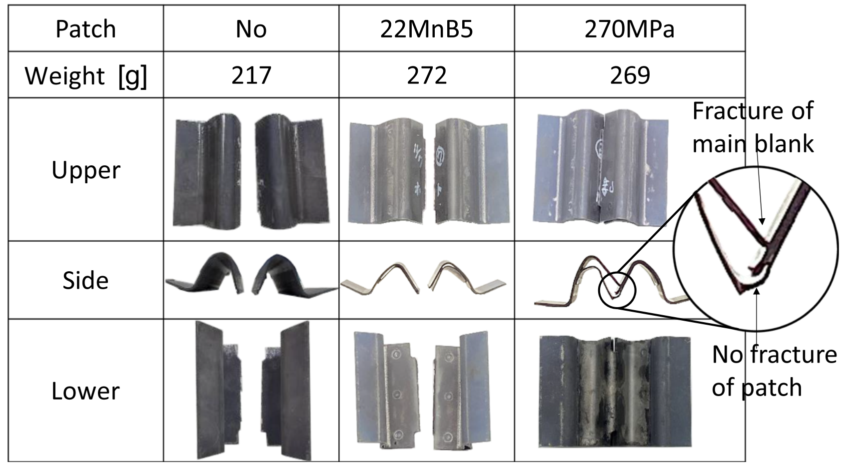


Fig. 18 Hot-stamped parts after the collapse test

main blank fractures, the 270 MPa patch does not fracture. It was found the 270 MPa patch is useful to prevent the separation of fractured components. Although the large patch was employed in this experiment, it is sufficient that portions having a comparatively high risk of fracture are locally patched.

5 Conclusions

Hot stamping of tailor-welded blanks is increasingly applied to production of automobile tailored components to heighten the flexibility in design. In hot stamping of tailored components having partially high strength and ductility from tailor-welded blanks, the phase transformation and mechanical properties of three partner steel sheets for the quenchable 22MnB5 steel sheets were examined. The partner steel sheets were a non-quenchable steel, 270 MPa mild steel, and 440 MPa high strength steel. In addition, an approach for improving the safety of hot-stamped components using the 270 MPa sheet having high ductility after die quenching was proposed. The obtained results are summarised as follows:

(1) The early transformation during the transfer to dies for the non-quenchable and 270 MPa mild steel sheets was appropriate for transforming the 22MnB5 steel sheet into martensite.
(2) The 270 MPa sheet was available as a partner sheet having high ductility after die quenching as well as the non-quenchable sheet, whereas the 440 MPa sheet is insufficient.
(3) Tailored components having a hardness of about 500 HV1 in the high strength zone and a total elongation of about 30% in the high ductility zone were successfully hot-stamped from a tailor-welded blank composed of 22MnB5 and 270 MPa sheets.
(4) The safety of hot-stamped components was improved by preventing the separation of fractured components using a 270 MPa steel patch.

The 270 MPa mild steel sheet keeps a ferrite structure after die quenching and has similar high ductility to the non-quench steel sheet. The 22MnB5 sheet is superior as a quenchable steel sheet due to late ferrite transformation. The use of the low-cost conventional mild steel sheet for a partner sheet in hot stamping of tailor-welded blanks is effective.

Although the hot-stamped components have high strength, fractured components are very dangerous due to flying of separated pieces. The separation is prevented by welding a 22MnB5 main blank with a 270 MPa patch. Even if the main blank fractures, the patchwork component is not separated by the 270 MPa patch having high ductility. The increase in weight of the patchwork blank is not very large, because the 270 MPa patch is thin and partial. It is effective that portions having a comparatively high risk of fracture are welded with the 270 MPa patches. The safety of hot-stamped components is increasingly heightened by the 270 MPa patch.

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Data availability The data that support the findings of this study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Competing interest The authors declare that they have no competing interest.

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