Int J Adv Manuf Technol (2018) 95:459–467
https://doi.org/10.1007/s00170-017-1203-3

ORIGINAL ARTICLE

Springback-free mechanism in hot stamping of ultra-high-strength steel parts and deformation behaviour and quenchability for thin sheet

Yuki Nakagawa [1] · Ken-ichiro Mori [1] · Tomoyoshi Maeno [2]

Received: 27 July 2017 / Accepted: 6 October 2017 / Published online: 25 October 2017

Abstract The springback-free mechanism in hot stamping of ultra-high-strength steel parts was clarified by the mechanical, thermal and transformation viewpoints. In hot stamping, the effects of elastic recovery during unloading and thermal shrinkage on the springback are comparatively small, but the effect of the phase transformation is critical. Volume expansion occurs primarily upon the start of the martensitic transformation, and plastic deformation is induced by the volume expansion during holding at the bottom dead centre, causing the springback including the post-stamping deformation to disappear. It was observed from well-organised experiments that holding at the bottom dead centre until the martensite finish temperature prevents the springback, and the springback-free mechanism in hot stamping of ultra-high-strength steel parts was clarified from the observation. The springback behaviour in hot stamping of a thin steel sheet with 0.6 mm thickness was explained from the above mechanism, and the deformation behaviour and quenchability for the thin sheet were examined. A sufficient holding time at the bottom dead centre was more closely associated with the prevention of springback rather than sufficient hardening. Additionally, local thinning around the bottom corner of a bent thin sheet was prevented by optimising the transfer time from the furnace.

✉ Yuki Nakagawa
nakagawa@plast.me.tut.ac.jp

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

[2] Division of Materials Science and Chemical Engineering, Faculty of Engineering, Yokohama National University, Yokohama, Kanagawa 240-8501, Japan

Keywords Hot stamping · Springback-free · Thin sheet · Local thinning

1 Introduction

For weight reduction and crash safety improvement of automobiles, ultra-high-strength steel sheets with a tensile stress above 1 GPa are beneficial. Cold stamping of these sheets becomes difficult because of the large amount of springback, a high level of tool damage and a narrow range of formability. To address these problems, cold stamping processes are frequently replaced with hot stamping processes of quenchable steel sheets. Ultra-high-strength steel parts with approximately 1.5 GPa in tensile strength can be produced under a small stamping load [1]. The hot-stamped parts are hardened by the martensitic transformation during die quenching. Moreover, the springback of the stamped parts is almost negligible, and thus the shape accuracy of the stamped parts becomes high. Even if the ductility of ultra-high-strength steel sheets at room temperature is increased by the development of new steel, a considerably large springback is caused by high forming load for cold stamping, and thus hot stamping would remain advantageous because of the springback-free characteristic [2].

The hot stamping processes have the superior advantages of not only high strength of 1.5 GPa but also small springback. In cold stamping, the springback is caused by the elastic recovery of the formed parts during unloading, while springback behaviour for hot stamping is more complicated than that for cold stamping because of thermal effects. In hot stamping, the flow stress and elastic modulus of the sheets are small due to the high temperature. The residual stress is decreased by the high temperatures during die quenching, and thermal shrinkage and expansion during the phase

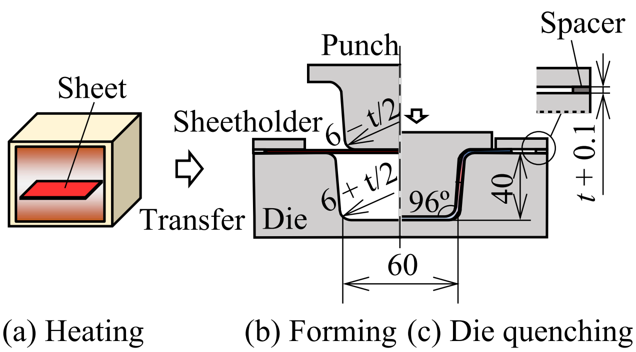


Fig. 1 Conditions of hot hat-shaped bending

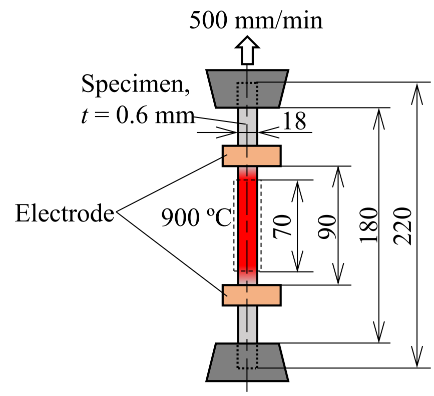


Fig. 2 Conditions for the tensile test of the heated specimen

transformation from austenite to martensite occur. Mori et al. [3] examined the effect of heating temperature on the springback in warm and hot stamping of various steel sheets and indicated that springback disappeared above 700 °C. Yanagimoto and Oyamada [4] measured the springback in V-shaped and hat-shaped bending of steel sheets for different forming temperatures. Yanagimoto and Oyamada [5] explained that the springback-free phenomenon results from high-temperature transient creep deformation. However, the expansion caused by the martensitic transformation during hot stamping was not considered. Kusumi et al. [6] investigated the effect of the martensitic transformation on springback behaviour and concluded that the residual stress induced by hot stamping is reduced by the martensitic transformation. Senuma et al. [7] indicated that springback disappears by holding for several seconds at the bottom dead centre of a press for die quenching. However, the springback-free mechanism in hot stamping has been not clarified yet.

The finite element method was applied to simulate the springback behaviour in hot stamping processes. Xing et al. [8] calculated the effects of the blankholder force, the clearance between a punch and die and the corner radius of the die on the springback in hat-shaped bending. Lee et al. [9] compared the amounts of springback calculated by finite element simulations with and without the transformation plasticity. Bao et al. [10] investigated the effect of the difference between the internal and external cooling rates caused by contact with dies during die quenching on the springback. Bok et al. [11] calculated the springback in hot stamping of tailor-welded blanks. The accuracy of the calculated results by the simulation of hot stamping still is not high, because it is not easy to measure the material constants such as the flow stress, the coefficient of friction and the heat transfer coefficient and the constants used for prediction of phase transformation, etc.

Although the thickness of steel sheets used for hot stamping is generally between 1.0 and 2.2 mm, it is desirable to manufacture thinner hot-stamped parts to enable automobile weight reduction. Since thin sheets tend to cool rapidly during transfer from the furnace to the dies, deformation and quenching behaviours in hot stamping are different from those of the thicker conventional sheets. Lee et al. [12] investigated the formability in hot deep drawing of a 0.6-mm thick sheet. Georgiadis et al. [13] simulated a temperature distribution during hot stamping of a 0.5-mm thick sheet by the finite element method. Nakagawa et al. [14] indicated that a thin 22 MnB5 sheet with a thickness of 0.6 mm is roughly quenched even by natural air cooling, resulting in a hardness of 380 HV1. Die quenching in hot stamping of thin sheets is relatively easy to achieve. Georgiadis et al. [15] evaluated the influence of sheet thickness on the forming limits under both isothermal and non-isothermal conditions. Naturally, the springback behaviour of the thin sheet is influenced by the rapid temperature drop.

In the present study, the springback-free mechanism in hot stamping of ultra-high-strength steel parts was clarified by the

Table 1 Conditions for hot hat-shaped bending experiment

Thickness of sheet (t)	0.6, 1.0, 1.6 mm
Length of sheet	180 mm
Width of sheet	90 mm
Transfer time (T_t)	7–20 s
Forming speed	85 mm/s
Holding time at bottom dead centre (T_h)	0–10 s

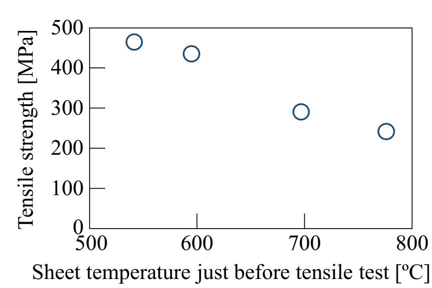


Fig. 3 Relationship between tensile strength and sheet temperature just before tensile test for $t = 0.6$ mm

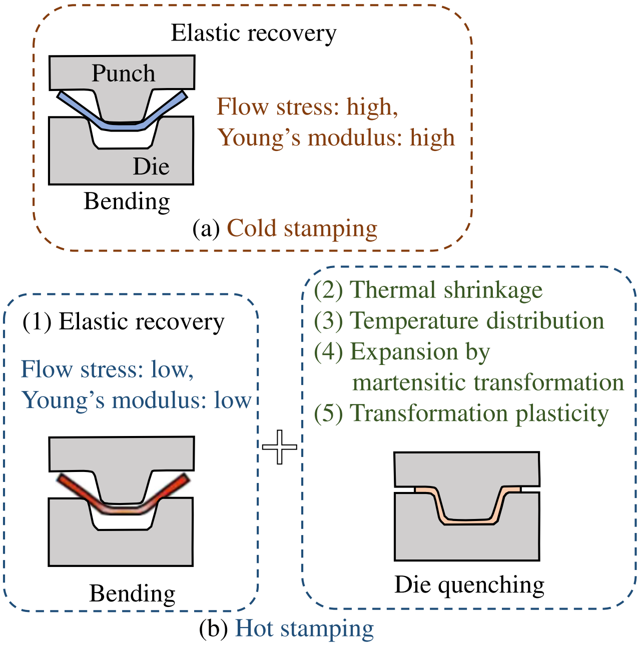


Fig. 4 Factors affecting springback behaviour in cold and hot stamping operations

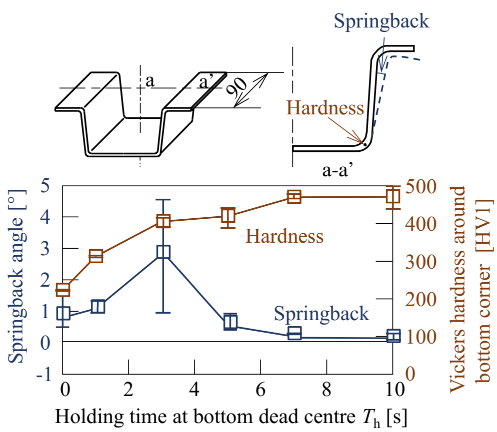


Fig. 5 Effect of holding time at the bottom dead centre on the springback angle and Vickers hardness around the bottom corner of the bent sheet

mechanical, thermal and transformation viewpoints. In addition, the deformation behaviour including springback and the quenching behaviour in hot stamping of a thin sheet with 0.6 mm thickness were examined.

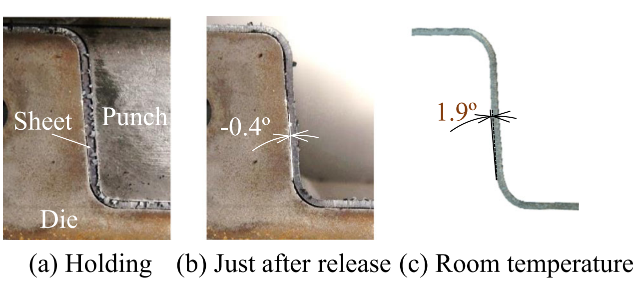


Fig. 6 Shape variation of the bent sheet after hot stamping for T_h = 3 s

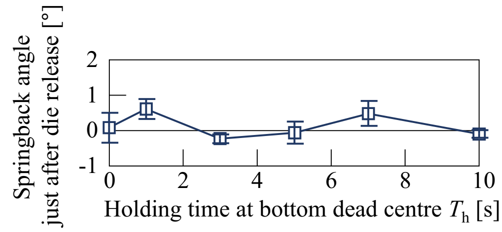


Fig. 7 Relationship between the springback angle just after die release and the holding time at the bottom dead centre

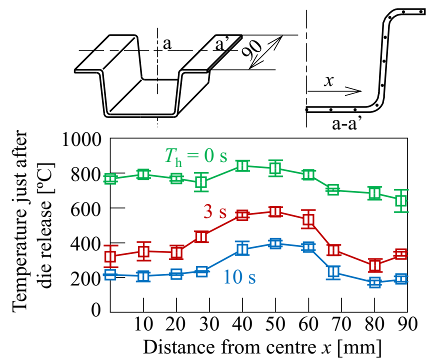


Fig. 8 Temperature distribution in bent sheet just after die release for T = 900 °C

2 Hot bending procedure

2.1 Hot hat-shaped bending

To examine the deformation and quenching behaviours of a steel sheet during hot stamping, a hot hat-shaped bending experiment was performed, as shown in Fig. 1. The sheets

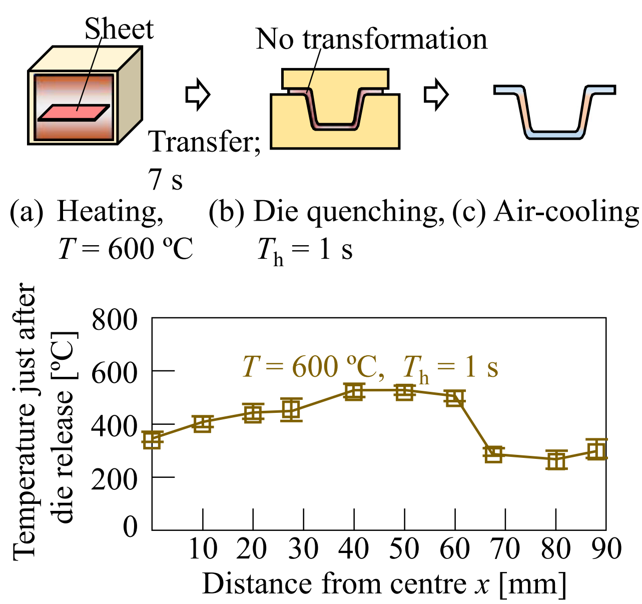


Fig. 9 Temperature distribution in the bent sheet just after die release for T = 600 °C

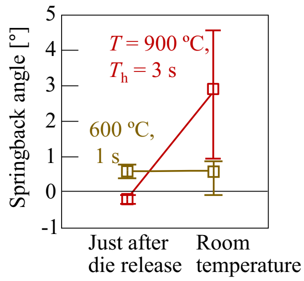


Fig. 10 Effects of thermal shrinkage and temperature distribution on springback

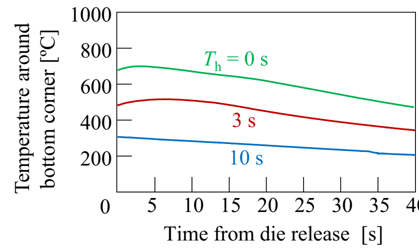


Fig. 12 Temperature variation around the bottom corner after die release

were heated to $T = 900$ °C and held for 120 s in an electrical furnace to generate the intermetallic layer for protecting oxidation at high temperatures on the surface sufficiently. The heated sheets were manually transferred from the furnace to the die with a steel tong and later hot-stamped into the hat shape. Although the sheet bent elastically during the transfer, the sheet returned to a flat shape after positioning on the die. The temperature distribution in the sheet was measured using an infrared thermograph. A mechanical servo press with a maximum load of 1500 kN was used in this experiment.

Aluminium-coated quenchable 22 MnB5 steel sheets (C 0.23; Mn 1.22; Si 0.27; and B 0.0032 mass%) with thicknesses of $t = 0.6$, 1.0 and 1.6 mm were used in this experiment. The conditions for the hot hat-shaped bending experiment are given in Table 1. The transfer time from the furnace to the die was between $T_t = 7$ and 20 s. The forming speed was 85 mm/s, and the holding time at the bottom dead centre for die quenching was between $T_h = 0$ and 10 s. Since the sheet was in loose contact with the blankholder and the die due to the thicker spacers than the sheet shown in Fig. 1c, the temperature drop of the flange during forming was comparatively small.

2.2 Tensile strength

To examine the effect of temperature on deformation behaviours, the tensile strength at various temperatures was measured by a tensile test, as shown in Fig. 2. The tensile strength was measured to evaluate the deformation behaviour of the heated sheet. A universal testing instrument with a maximum load of 250 kN was used in the tensile test. The testing zone of the tensile specimen between the two electrodes was resistance-heated to 900 °C for 30 s and was then stretched at 500 mm/min after attaining the desired temperature under natural air cooling. Merklein et al. [16] developed a tensile test using resistance heating and compressed air cooling for measuring the flow stress of a steel sheet used for hot stamping. For a 90-mm testing zone, the central region of approximately 70 mm had a uniform temperature distribution just before the tension was applied, and the central region of approximately 50 mm underwent uniform deformation until the maximum load was applied. Since it was not easy to measure the displacement of the central region of approximately 50 mm at high temperatures, only the tensile strength was obtained to express the temperature sensitivity of flow stress.

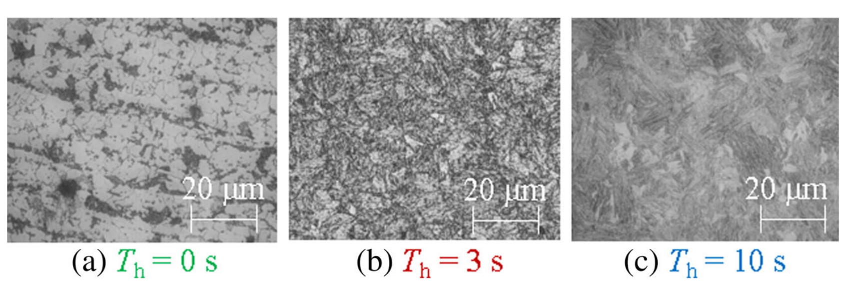
The relationship between the tensile strength and the sheet temperature just before the tensile test for $t = 0.6$ mm is shown in Fig. 3. As the temperature of the sheet increases, the tensile strength decreases. The stress just before unloading in hot stamping is small, and consequently the residual stress after unloading is also small.

3 Springback-free mechanism in hot stamping

3.1 Factors affecting springback

The factors affecting springback behaviour in cold and hot stamping operations are illustrated in Fig. 4. In cold stamping, the springback is caused by the elastic recovery of the sheets during unloading. In cold stamping, the amount of springback is increased by a high flow stress but decreased by a high Young's modulus. These tendencies for the hot stamping are reversed. In addition, the die quenching operation affects the springback behaviour, i.e. the thermal shrinkage is affected by a drop and distribution of temperature, and the expansion is

Fig. 11 Microstructures around the bottom corner of the bent sheet



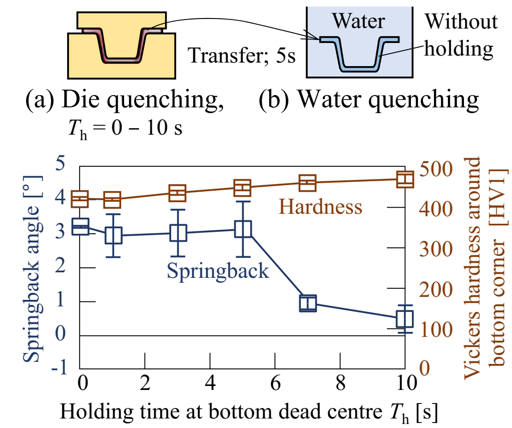


Fig. 13 Relationship between the springback angle after water quenching and the holding time at the bottom dead centre and Vickers hardness

caused by the martensitic transformation. Moreover, transformation plasticity and other factors play a role.

To investigate the springback-free mechanism in hot stamping of quenchable sheets, the martensitic transformation and the temperature and hardness distributions were examined during hot hat-shaped bending. This study used a sheet with t = 1.6 mm thickness, a common thickness used in hot stamping, and the transfer time from the furnace to the die was fixed at T_t = 7 s. The parameter which varied in this experiment was the holding time at the bottom dead centre for die quenching.

3.2 Effects of elastic recovery

The effect of the holding time at the bottom dead centre on the springback angle and the Vickers hardness around the bottom corner of the bent sheet is shown in Fig. 5. All the bent sheets were naturally air-cooled in the air after die release. Above T_h = 7 s, the springback is almost zero and the hardness is approximately 450 HV1 due to the martensitic transformation.

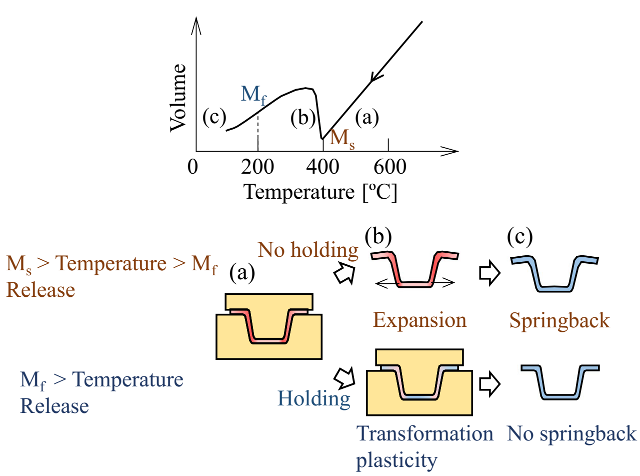


Fig. 14 Springback-free mechanism in hot stamping

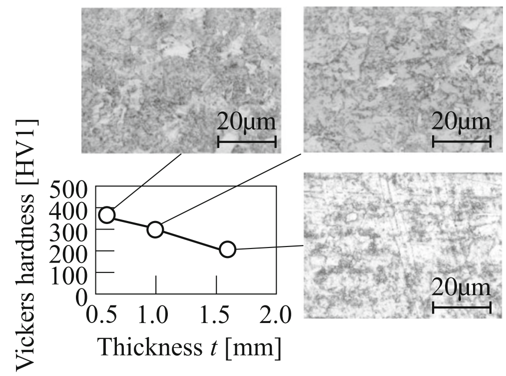


Fig. 15 Relationship between the Vickers hardness of naturally air-cooled sheet without forming and the sheet thickness and microstructures

For T_h = 0 s without holding, the springback is comparatively small and the hardness is considerably lower. The springback angle for cold stamping was between 8° and 10°. In contrast, for T_h = 3 s, the springback and its variation are large, and the martensitic transformation partially occurs, indicated by the 400 HV1 hardness value. Around T_h = 3 s, a phenomenon occurs which increases the springback.

The shape variation of the bent sheet after hot stamping for T_h = 3 s is shown in Fig. 6. The springback just after die release is considerably small, but becomes large during natural air-cooling.

The relationship between the springback angle just after die release and the holding time at the bottom dead centre is shown in Fig. 7. The springback angle just after die release is small for all holding times, i.e. the effect of elastic recovery during unloading on the springback for hot stamping is small. The large springback for T_h = 3 s shown in Fig. 5 which occurred after die release.

3.3 Effects of thermal shrinkage and temperature distribution

The temperature distribution in the bent sheet just after die release is shown in Fig. 8. The bent sheet for T_h = 10 s was cooled considerably, while the temperature for T_h = 0 s without holding remained high. In addition, the temperature

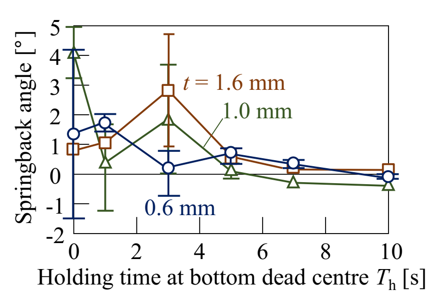


Fig. 16 Relationship between the springback angle of bent sheet and the holding time at the bottom dead centre for T_t = 7 s

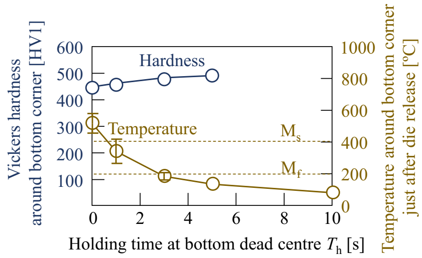


Fig. 17 Relationships between the Vickers hardness and the holding time at the bottom dead centre and between the temperature of the bent sheet around the bottom corner just after die release and the holding time for $t = 0.6$ mm and $T_t = 7$ s

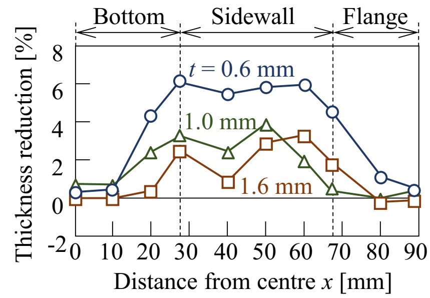


Fig. 19 Distribution of thickness reduction in the bent sheet for $T_t = 7$ s and $T_h = 5$ s

distribution became non-uniform because the sidewall was in loose contact with the dies.

To examine the effects of thermal shrinkage and temperature distribution on the springback after die release, the sheet was heated to $T = 600$ °C, transferred from the furnace to the die, bent with the dies, die-quenched for $T_h = 1$ s and naturally air-cooled. Heating to $T = 600$ °C means that no martensitic transformation occurs because of no austenitic transformation. The temperature distribution in the bent sheet just after die release is shown in Fig. 9. For $T = 600$ °C and $T_h = 1$ s, the temperature distribution was similar to that for $T = 900$ °C and $T_h = 3$ s, shown in Fig. 8. The operation for $T = 600$ °C is warm forming without the transformation and that for $T = 900$ °C is hot forming with the transformation.

The effects of the thermal shrinkage and temperature distribution on the springback are shown in Fig. 10. Since the springback for $T = 600$ °C without the transformation is small, the effects of the thermal shrinkage and the temperature distribution are small. On the other hand, the springback for $T = 900$ °C with the transformation is large, and thus the effect of the martensitic transformation is crucial.

3.4 Effect of martensitic transformation

The microstructures around the bottom corner of the bent sheet are shown in Fig. 11. The microstructure for $T_h = 0$ s without holding is ferrite due to the low cooling rate, whereas partial and full martensitic transformations occur for $T_h = 3$ and 10 s, respectively.

The temperature variation around the bottom corner after die release is shown in Fig. 12. For $T_h = 0$ and 3 s, the temperature increases just after die release. These increases are due to the latent heats of the ferrite transformation for $T_h = 0$ s and the partial martensite transformation for $T_h = 3$ s. For $T_h = 0$ and 3 s, the phase transformation occurred after die release.

To examine the effect of the martensitic transformation on the springback, all bent sheets were transformed into martensite by water quenching without holding just after die release. The relationship between the springback angle after water quenching and the holding time at the bottom dead centre is shown in Fig. 13. For all bent sheets, the hardness is above 420 HV1, indicating the martensitic transformation occurred. In comparison with Fig. 5, the springback is large below $T_h = 5$ s, indicating the springback is increased by the martensitic transformation without holding.

3.5 Springback-free mechanism

From the results of Figs. 7, 10 and 13, the springback-free mechanism in hot stamping of ultra-high-strength steel parts is explained as shown in Fig. 14, where M_s and M_f are the martensite start and finish temperatures, respectively. In hot stamping, the transformation from austenite to martensite occurs during cooling just after forming, and the volume of the sheet is changed by the transformation. When the martensitic transformation starts at M_s during cooling, the volume of the sheet sharply increases just after this temperature [17], and

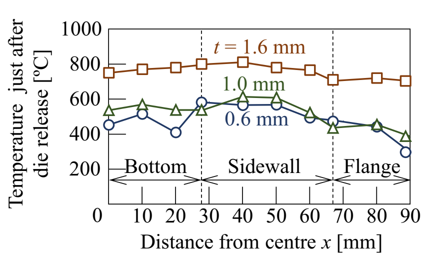


Fig. 18 Temperature distribution in the bent sheet just after die release for $T_t = 7$ s and $T_h = 0$ s

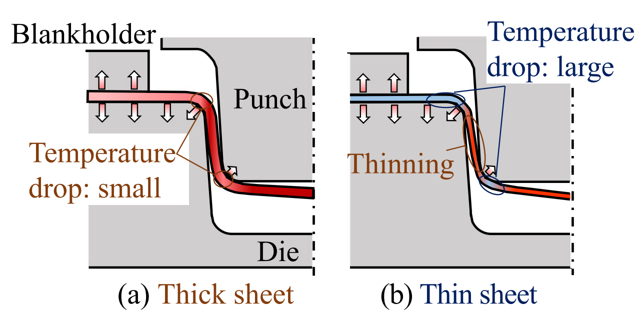


Fig. 20 Mechanism of local thinning for thin sheet

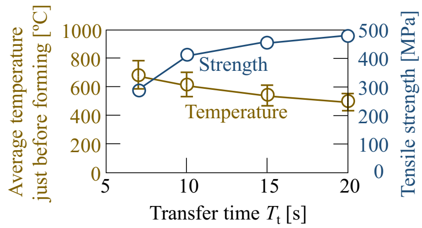


Fig. 21 Relationship between the average temperature in sheets just before forming and the transfer time for $t = 0.6$ mm

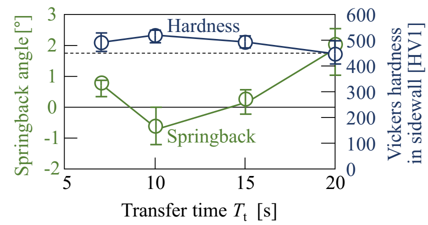


Fig. 23 Effect of the transfer time from the furnace on the springback angle and Vickers hardness in the sidewall for $t = 0.6$ mm and $T_h = 5$ s

transformation plasticity often occurs [18]. When die release occurs between M_s > temperature > M_f, the springback is caused by this expansion without holding at the bottom dead centre, i.e. there is no constraint for the expansion. Conversely, plastic deformation is induced by constraining the expansion under holding until M_f before release, causing the springback to disappear. For $T_h = 3$ s in Fig. 5, the martensitic transformation occurred without holding, and thus the springback and its variability increased. It was found that the springback including the post-stamping deformation can be prevented by holding at the bottom dead centre up to the martensite finish temperature. Sufficient holding at the bottom dead centre is required for both hardening and springback prevention.

4 Deformation and quenching behaviours for thin sheet

To enable weight reduction for body-in-white parts, the thickness of quenchable steel sheets used for hot stamping tends to decrease. The temperature drop of the heated sheet after removing from the furnace becomes larger with decreasing thickness [14]. The relationships between the Vickers hardness of a naturally air-cooled sheet without forming and the sheet thickness and microstructures are presented in Fig. 15. The ferrite transformation occurred for $t = 1.0$ and 1.6 mm, whereas the martensitic transformation partially occurred for $t = 0.6$ mm due to the high cooling rate, indicated by a Vickers hardness of 380 HV1. In the thin sheet, the springback behaviour is different from that of the conventional thickness

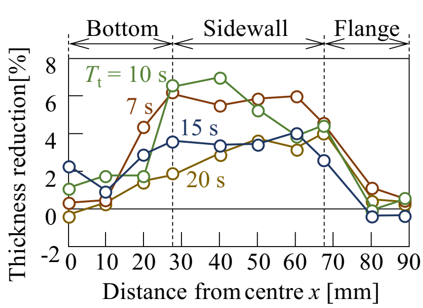


Fig. 22 Thickness reduction distribution in the bent sheet for $t = 0.6$ mm and $T_h = 5$ s

because the effect of the martensitic transformation on the springback is large.

The relationship between the springback angle of the bent sheet and the holding time at the bottom dead centre for $T_t = 7$ s is shown in Fig. 16. For holding times below $T_h = 5$ s, the springback angle and its variation are large.

The relationships between the Vickers hardness around the bottom corner and the holding time at the bottom dead centre and between the temperature of the bent sheet around the bottom corner just after die release and the holding time for $t = 0.6$ mm and $T_t = 7$ s are shown in Fig. 17. Because the thin sheet is rapidly cooled after die release, the hardness achieved without holding is sufficient, but the springback and its variation are large, as shown in Fig. 16. These results are due to the martensitic transformation without holding after the die release, as explained in "Sect. 3.5".

5 Prevention of local thinning for thin sheet

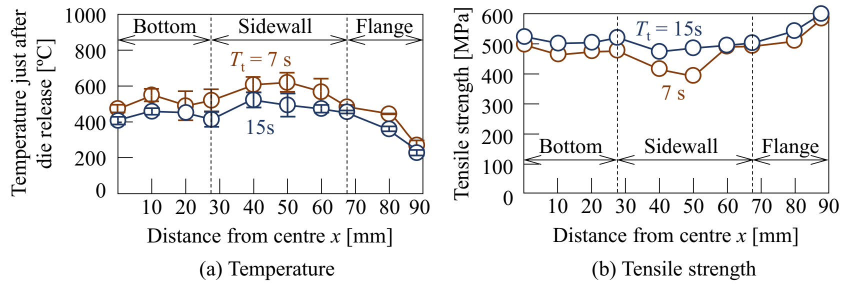
5.1 Local thinning of thin sheet

The temperature distribution in the bent sheet just after die release for $T_t = 7$ s and $T_h = 0$ s is shown in Fig. 18. Since the temperature drop caused by contact with the tools during forming is large for $t = 0.6$ mm, the temperature distribution tends to become non-uniform.

The distribution of thickness reduction in the bent sheet for $T_t = 7$ s and $T_h = 5$ s is shown in Fig. 19. The thickness is reduced by drawing around the bottom corner, and the reduction for $t = 0.6$ mm is fairly large. Mori et al. [19] showed that the reduction in thickness for draw-type tools is larger than that for form-type tools.

The large thickness reduction around the bottom corner for $t = 0.6$ mm results from the non-uniform temperature distribution in the sheet during forming. For the thin sheet, the temperature drops during forming largely due to the contact with the dies, as shown in Fig. 20. As explained by Maeno et al. [20], the temperature in portions not in contact with the dies is high, and the deformation concentrates in those portions due to the low flow stress. The concentration of deformation brings about local thinning. For a thin sheet, a marked temperature distribution results (Fig. 18).

Fig. 24 **a** Temperature and **b** tensile strength distribution in the bent sheet just after die release without holding for $t = 0.6$ mm, $T_t = 7$ and 15 s



5.2 Prevention of local thinning by transfer time optimisation from the furnace

As the transfer time from the furnace increases, the temperature in the sheet decreases, and the tensile strength increases, as shown in Fig. 21. This tensile strength was calculated using the temperature from Fig. 3 and was extrapolated to 501 °C for T_t = 20 s. The change in the tensile strength decreases with increasing transfer time, and the flow stress distribution in the sheet becomes uniform. Local thinning is prevented by optimising the transfer time.

The thickness reduction distribution in the bent sheet for $t = 0.6$ mm and $T_h = 5$ s is shown in Fig. 22. For transfer times higher than T_t = 15 s, the distribution of thickness reduction becomes uniform, and the thickness reduction around the bottom corner decreases with increasing transfer time.

The effect of the transfer time from the furnace on the springback angle and the Vickers hardness in the sidewall for $t = 0.6$ mm and $T_h = 5$ s is shown in Fig. 23. The hardness for transfer times below T_t = 15 s is above 450 HV1, but for $T_t = 20$ s the hardness is insufficient due to the low cooling rate during the transfer. A transfer time of T_t = 15 s is optimum because it results in no springback, sufficient hardness and a small thickness reduction.

The temperature distribution in the bent sheet just after die release without holding for t = 0.6 mm, T_t = 7 and 15 s is shown in Fig. 24. Using this distribution, the distribution of tensile strength was calculated from Fig. 3. As the transfer time increases, the temperature decreases and the distribution of tensile strength becomes uniform, thereby preventing local thinning.

6 Conclusions

Hot stamping is an advantageous forming process for producing high-strength parts without springback. In cold stamping of high-strength steel sheets, the springback is generated by elastic recovery during unloading, while the cause of springback for hot stamping is considerably different because of the addition of thermal phenomena, including post-stamping deformation. In hot stamping, the effects of elastic recovery and thermal shrinkage on the springback are comparatively small, but the effect of the phase transformation is critical. The phase transformation is associated with a volume change and latent heat. Although thin sheets and water-quenched sheets attain high strength after hot stamping, the springback is not negligible. A sufficient holding time at the bottom dead centre until the martensite finish temperature of about 200 °C is required for both hardening and springback prevention.

The deformation and quenching behaviours in hot stamping of thin sheets are different from those of conventional-thickness sheets. Although the quenchability is improved by the high cooling rate, local thinning tends to occur due to the non-uniform distribution of flow stress. The optimisation of the transfer time from the furnace to the dies is effective in preventing local thinning, e.g. 15 s for a thickness of 0.6 mm. Although a short transfer time in hot stamping is conventionally employed to prevent temperature drop, the optimisation of the transfer time may lead to other advantages, such as the prevention of local thinning.

Funding information This work was supported in part by the Grant-supported Researches in Amada Foundation (AF-2015001).

References

1. Åkerström P, Oldenburg M (2006) Austenite decomposition during press hardening of a boron steel—computer simulation and test. J Mater Process Technol 174(1–3):399–406
2. Mori K, Bariani PF, Behrens BA, Brosius A, Bruschi S, Maeno T, Merklein M, Yanagimoto J (2017) Hot stamping of ultra-high strength steel parts. CIRP Ann Manuf Technol 66(2):755–777
3. Mori K, Maki S, Tanaka Y (2005) Warm and hot stamping of ultra high tensile strength steel sheets using resistance heating. CIRP Ann Manuf Technol 54(1):209–212
4. Yanagimoto J, Oyamada K (2005) Springback of high-strength steel after hot and warm sheet formings. CIRP Ann Manuf Technol 54(1):213–216
5. Yanagimoto J, Oyamada K (2007) Mechanism of springback-free bending of high-strength steel sheets under warm forming conditions. CIRP Ann Manuf Technol 56(1):265–268
6. Kusumi K, Yamamoto S, Takeshita T, Abe M (2008) The effect of martensite transformation on shape fixability in the hot stamping process. Steel Res Int 79:71–76
7. Senuma T, Magome H, Tanabe A, Takemoto Y (2009) New hot stamping technology characterized by its high productivity. Proc of

2nd Int Conf on Hot Sheet Metal Forming of High-Performance Steel, Lulea, pp. 221–228

8. Xing ZW, Bao J, Yang YY (2009) Numerical simulation of hot stamping of quenchable boron steel. Mater Sci Eng A 499(1–2): 28–31
9. Lee MG, Kim SJ, Han HN (2009) Finite element investigations for the role of transformation plasticity on springback in hot press forming process. Comput Mater Sci 47(2):556–567
10. Bao J, Liu H, Xing Z, Song B, Yang Y (2013) Springback of hot stamping and die quenching with ultra-high-strength boron steel. Eng Rev 33(3):151–156
11. Bok HH, Choi JW, Suh DW, Lee MG, Barlat F (2015) Stress development and shape change during press-hardening process using phase-transformation-based finite element analysis. Int J Plast 73: 142–170
12. Lee M, Baeck S, Kang CG (2012) Investigation of thin boron steel sheet formability in hot deep-drawing processes according to process parameters. Proc Inst Mech Eng B J Eng Manuf 226(5):898–908
13. Georgiadis G, Tekkaya AE, Weigert P, Weiher J, Kurz H (2014) Investigations on the manufacturability of thin press hardened steel components. Procedia CIRP 18:74–79
14. Nakagawa Y, Maeno T, Mori K (2015) Forming and quenching behaviours in hot stamping of thin quenchable sheets. MATEC Web Conf 21(05002):1–7
15. Georgiadis G, Tekkaya A E, Weigert P, Horneber S, Kuhnle P A (2017) Formability analysis of thin press hardening steel sheets under isothermal and non-isothermal conditions. Int J Mater Form In press
16. Merklein M, Lechler J, Geiger M (2006) Characterisation of the flow properties of the quenchenable ultra high strength steel 22MnB5. CIRP Ann Manuf Technol 55(1):229–232
17. Bok HH, Kim SN, Suh DW, Barlat F, Lee MG (2015) Non-isothermal kinetics model to predict accurate phase transformation and hardness of 22MnB5 boron steel. Mater Sci Eng A 626(25): 67–73
18. Billur E, Porzner H, Lorenz D, Holecek M, Vrojlik M, Hoss M, Damenha B, Friberg J, Koroschetz C, Skrikerud M (2015) From part design to part production – virtual hot forming engineering illustrated – focus material modelling. Proc of 5th Int Conf on Hot Sheet Metal Forming of High-Performance Steel, Toronto, pp. 463–470
19. Mori K, Maeno T, Yanagita Y (2016) Deep drawability and bendability in hot stamping of ultra-high strength steel parts. Key Eng Mater 716:262–269
20. Maeno T, Mori K, Nagai T (2014) Improvement in formability by control of temperature in hot stamping of ultra-high strength steel parts. CIRP Ann Manuf Technol 63(1):301–304