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Hot local compression and die quench ausforming of quenchable steel sheet

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Abstract. Characteristics of hot local compression were investigated to apply hot stamping to a plate forging process. A heated quenchable steel sheet was locally compressed in a thickness direction and held with a punch at the bottom dead centre for die quenching. The effect of a forming temperature on reduction ratio and hardness was examined. Holding at the bottom dead centre improved the compression ratio due to plastic deformation during martensite transformation. Additionally, the quenched hardness of the locally compressed portion increased due to ausformig.

Introduction

The cold forging from plates produces functional and small parts with complex shapes. It is called plate forging [1] or sheet-bulk forming [2]. The plate forging produces small functional parts such as gear, cam, plate with pin, stepped plate, etc. Although drawing, bending and shearing are the main deformations in the stamping of the thin sheets, local compression in a thickness direction, backward extrusion and semi-shearing are often used in plate forging [1]. The productivity and material yield of plate forging is higher than that of machining and bulk forging. However, the compression in the thickness direction for local thinning significantly increases the forming load due to friction [3, 4]. When the required hardness of the product is high, batch or continuous heat treatment is performed. Therefore, there is no flexibility in production plans.

On the other hand, hot stamping produces high-strength panel parts for automobiles. The forming load is remarkably reduced by heating the steel sheets, and springback is prevented. Moreover, the stamped parts are hardened by quenching with dies; thus, ultra-high strength steel parts with a tensile strength of approximately 1.5 GPa are obtained [5]. Furthermore, the production control is flexible because the die quenching as heat treatment in hot stamping is processed individually.

The combination of plate forging and hot stamping is attractive for reducing the forming load and omitting the heat treatment process after forming [6]. In plate forging, the degree of material deformation is greater than that of sheet metal forming. In addition, the required shape accuracy in plate forging is also severe. It is necessary to understand the deformation and die quench characteristics under compression in the thickness direction, which are the main factors in plate forging.

In the present study, hot local compression and die quenching of a quenchable thick steel sheet were performed to investigate the feasibility of hot plate forging. The compression and die-quenching behaviour were investigated. The effect of a forming temperature on reduction ratio and hardness was examined. Furthermore, a mechanism of improvement in hardness at the compressed portion was discussed.

Hot local compression of quenchable thick steel sheet

Fig. 1 shows the concept of hot plate forging. For hot plate forging with die quenching, Complex shape forming by progressive stamping in plate forging and individual heat treatment in hot stamping are combined to achieve one-piece flow manufacturing. In addition, since the material is heated and softened, the high-forming load in compression in the thickness direction will be reduced.

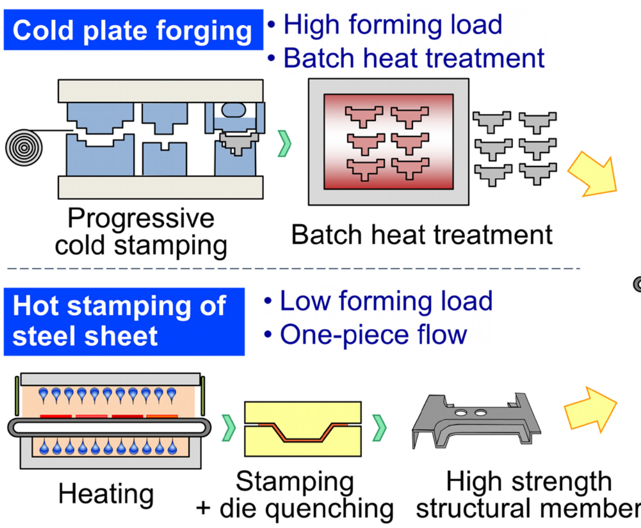

Fig. 1. Flexible production control by hot plate forging with die quenching.

Hot local compression with die-quenching of a quenchable thick steel sheet is illustrated in Fig. 2. A boron steel sheet of N22CB with a thickness of 4 mm is cut into 100×120 and used for local compression. The chemical composition of the N22CB quenchable steel sheet is shown in Table 1. This sheet is similar to a 22MnB5 commonly used in hot stamping. The blank sheet is heated in an electric furnace at 950°C for 7 minutes and then transferred to the die. The centre of the heated sheet is compressed with a cylindrical punch after natural cooling to a forming start temperature T_f. The punch is held at the bottom dead centre for t_h seconds for die quenching. The diameter of the punch is 15 mm, and a gap of 2.5 mm is provided around the punch between it and the sheet holder. Compression is performed without lubrication. An 800 kN Mechanical servo press is used, the average press speed during compression is 30 mm/s, and the time from contact between the sheet and punch to the bottom dead centre is 0.1 s at a nominal compression ratio r = 75%. The temperature of the heated sheet is measured by a radiation thermometer calibrated with a thermocouple.

Table 2 shows the conditions used in the experiment. The penetration ratio of the punch to the initial plate thickness under no load was assumed as the nominal compression rate r. The sheet material used transforms into a ferrite phase at 670°C during air cooling, so under the condition of T_f = 650°C, transformation occurs before compression and is not hardened. For comparison, cold compression without heating was also performed.

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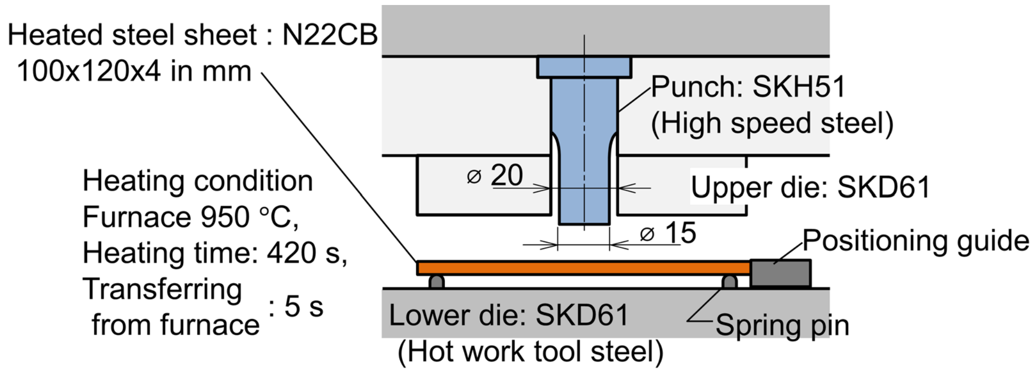


Fig. 2. Hot local compression and die-quenching of quenchable thick steel sheet.

Table 1. Chemical composition of N22CB quenchable steel sheet

C	Si	Mn	B
0.22	0.15	0.45	35 ppm

Table 2. Used condition for hot local compression and die-quenching.

Nominal compression ratio r [%]	Temperature at compression T_f [°C]	Holding time for die-quenching t_h [s]
25,50,75	room, 650, 750, 840	0, 1.5, 5.5, 20

Results of Hot local compression in thickness direction of quenchable thick steel sheet

The cross sections of the compressed portion obtained at different compression temperatures for r = 50%, t_h = 20 s are shown in Fig. 3. A protrusion is observed around the compressed portion for heated conditions. On the other hand, the underside of the compressed portion is curved for the cold and at T_f = 650°C. Because the punch and sheet holder descend together, the sheet is bent and then returned to a flat by sandwiching the sheet holder. However, for cold and at 650°C as under transformation temperature, springback occurred, and the sheet was not flat.

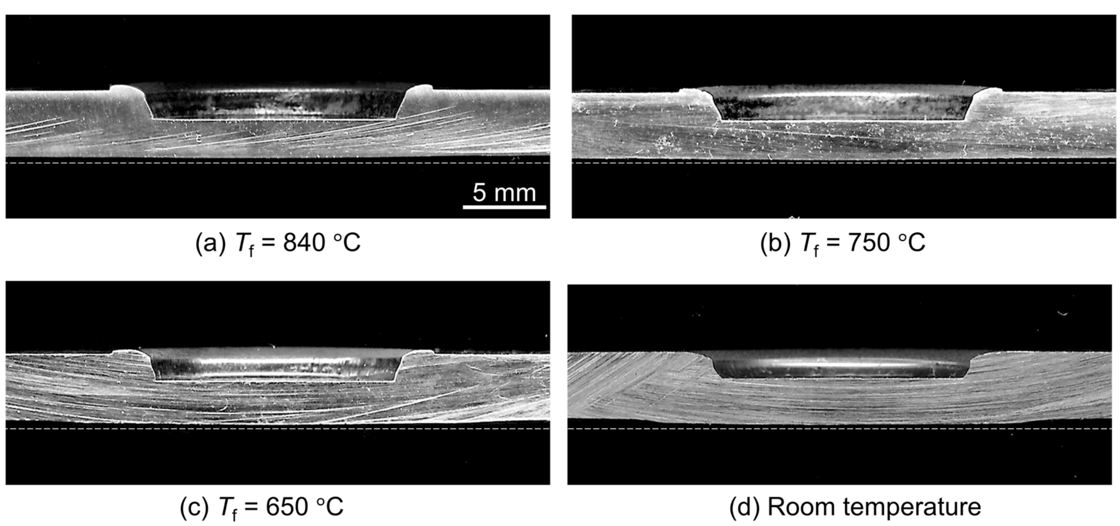


Fig. 3. Cross sections of compressed portion obtained at different compression temperature for r = 50%, t_h = 20s.

The relationships between a maximum load and obtained compression ratio in hot local compression for T_f = 840°C without sheet holder are shown in Fig. 4. The sheet holder was removed to evaluate the forming load because the load increased rapidly when the sheet holder interacted with it. When obtaining the same reduction, the maximum load at T_f = 840°C was approximately 40% lower than that of cold compression. In addition, the obtained compression ratio was close to the nominal one due to a decrease in the elastic deformation of the punch.

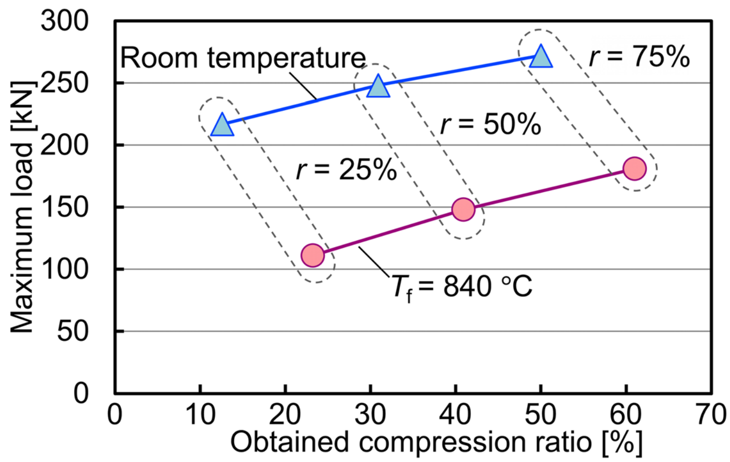


Fig. 4. Relationship between maximum load and obtained compression ratio in hot local compression for T_f = 840°C without sheet holder.

The effect of holding time on the obtained compression ratio for hot local compression for T_f = 650°C and 840°C are shown in Fig. 5. For T_f = 840°C, an increase in compression is observed in the early stages of holding time at the bottom dead centre. In contrast, it does not occur for T_f = 650°C.

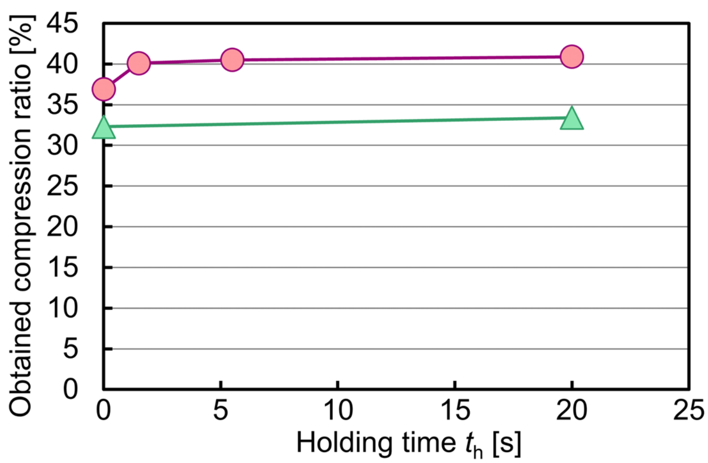


Fig. 5. Effect of holding time on obtained compression ratio for hot local compression for T_f = 650°C and 840°C.

Mechanism of increasing in compression ratio by holding at bottom dead centre

The mechanism of increase in compression ratio by holding at the bottom dead centre for T_f = 840°C was investigated. The relationship between sheet temperature at the compressed portion after 0.5 s from compression and holding time for T_f = 840°C r = 50 % is shown in Fig.6. For reference, the Ms point and Mf point of a 22MnB5 steel sheet with a similar composition are also shown. The Martensite start (M_s) and finish (M_f) temperature of a 22MnB5 steel sheet with a similar composition are also referenced in Fig 6. The Martensitic transformation has not started because the temperature is maintained at 700°C at t_h = 0 s. At t_h = 1.5 s, the temperature is below 400°C, and martensitic transformation begins, and the transformation appears to be ongoing until t_h = 5-10 s.

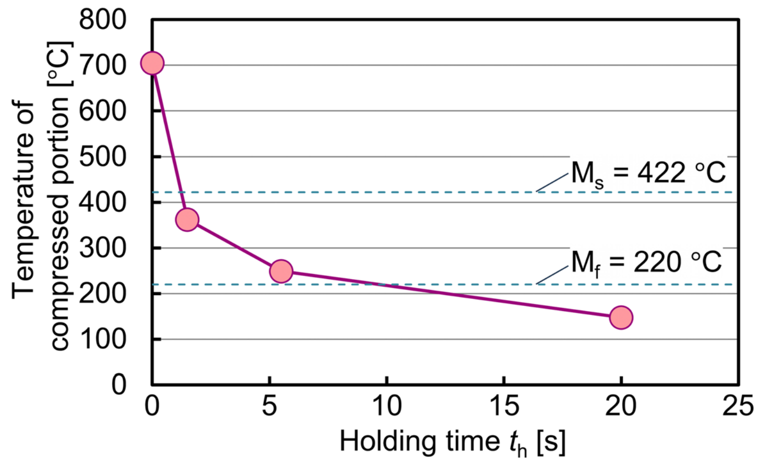


Fig. 6. Relationship between temperature at compressed portion after 0.5 s from compression and holding time for T_f = 840 °C r = 50 %.

The compression load-time curves during holding at the bottom dead centre for r = 50% are given in Fig. 7. The step noise at 10 s is due to the specifications of the servo press and can be ignored. The load decreases monotonically for the cold an T_f = 650°C as under transformation temperature. It is thought that the holding load decreased monotonically due to creep deformation and thermal shrinking of the sheet. On the other hand, for T_f = 750°C and 840°C, the load decreases until 1.5 s and then increases from 1.5 to 5 s. After that, the load shows a gradual decrease again.

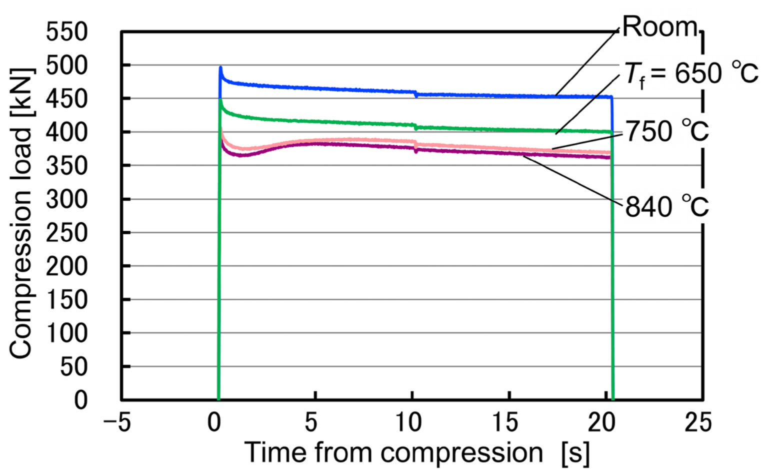


Fig. 7. Compression load-time curves during holding at bottom dead centre for r = 50%.

The mechanism of improvement of compression ratio by holding at a bottom dead centre in local hot compression is illustrated in Fig. 8. When without holding at the bottom dead centre, volume expansion by face transition from fcc to bcc or bct structures occurs without tool restraint. Hence, volume expansion occurs in isotropic, and naturally, the thickness of the compressed part increases. On the other hand, for holding at the bottom dead centre, the die fixes the expansion in a thickness direction during a martensitic transformation of the compressed portion. As a result, the compressed portion is plastically deformed in the radial direction, and the reduction ratio is improved during holding at the bottom dead centre.

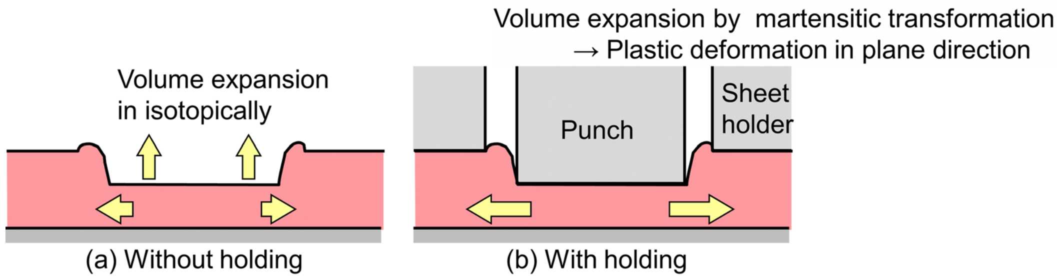


Fig. 8. Mechanism of improvement of compression ratio by holding at bottom dead centre in local hot compression.

Effect of local compression on die-quenched hardness

The hardness distributions of the compressed portion for T_f = 840°C are shown in Fig. 9. The hardness of water-quenching without compression is also shown for reference. The hardness peripheral to the compressed portion, i.e., the non-compressed portion, is slightly lower than water-quenching due to auto-tempering with the low cooling rate. Meanwhile, for the compressed part, the hardness increases as the compression ratio increases, exceeding 600HV at r = 75%.

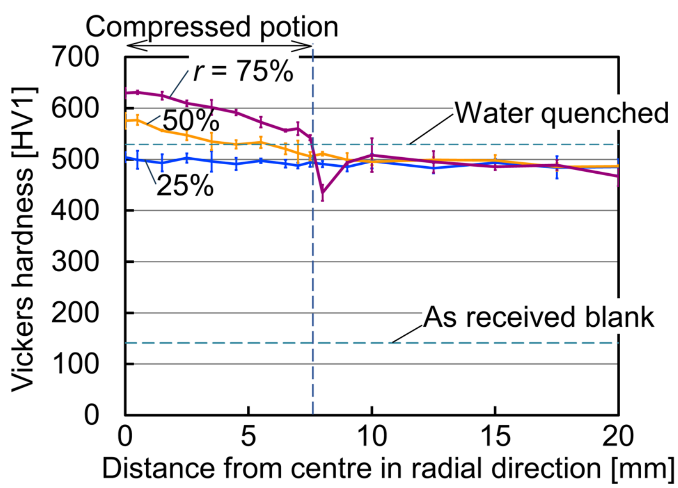
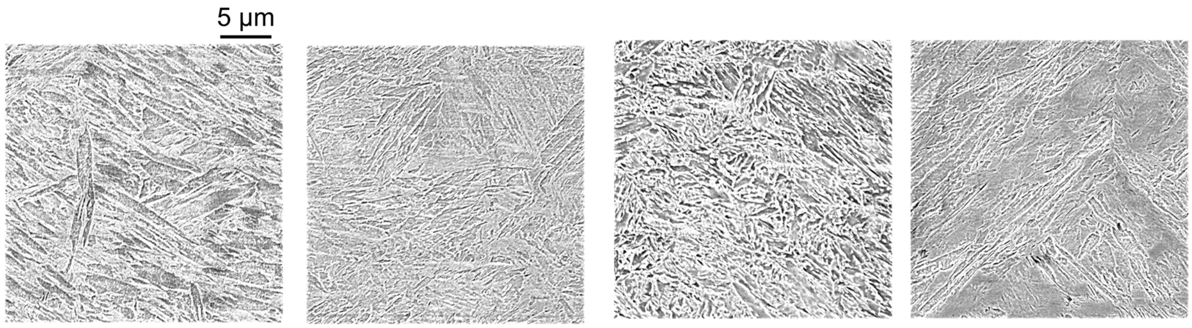


Fig. 9. Hardness distributions of compressed portion for T_f = 840°C.

The microstructures of a cross-section at the centre of a hot local compressed portion after die quenching for T_f = 840°C and t_h = 20 s are shown in Fig. 10. The microstructure was obtained by scanning electron microscopy after etching with Nital. The microstructure of water quenched without compression is also shown for comparison. All microstructures show the martensite. In addition, the appearance becomes finer as the compression ratio increases, and the structure at r = 75% is noticeably finer than that of r = 25% and water-cooling. The increase in hardness in the compressed portion shown in Fig. 9 is thought to be due to the refinement of the martensitic structure. This hardness increase by compression is similar to ausforming, which is composed of rapid cooling, plastic deformation, and quenching [7]. As shown in Fig. 6, the compression was performed at 840°C-700°C. Hence, it can be said to be modified ausforming [8]. In this process, a compressed portion is quenched by punch holding immediately after local compression without transferring to the next stage. Since the plastically deformed austenite is die-quenched without recrystallization, modified ausforming has been achieved. Ausforming has little practical use because it is difficult to control the forming temperature and timing of quenching it before recrystallization. In plate forging hot stamping, which combines large plastic deformation and die-quenching, the application of ausforming is highly feasible. It is expected to increase not only hardness but also toughness by Ausforming [9].



(a) T_f = 840 °C, r = 25% (b) T_f = 840 °C, r = 50% (c) T_f=840 °C r = 75% (d) Water quenching without compression

Fig. 10. Microstructure of cross-section at centre of hot local compressed portion after die quenching for T_f = 840°C and t_h = 20 s.

A required holding time for die quenching tends to be extended in hot plate forging due to the high heat capacity of a thick steel sheet. This is a bottleneck in the production line. Direct water cooling is applied to hot stamping to reduce the holding time [10]. However, although applying only water quenching omits a holding, the improvement in compression ratio by holding will be lost. Furthermore, ausforming may not be achieved due to recrystallisation caused by a cooling delay in the transfer for water cooling. Therefore, direct water cooling was applied after short holding at the bottom dead centre. The transferring time between holding and water cooling is 8 s.

The effect of a holding time and water-cooling on a hardness distribution for r = 50% and T_f = 840°C is shown in Fig. 11. At T_h = 1.5, the sheet was transferred to a water bath from the tool during martensitic transformation, resulting in insufficient quenching. For water cooling after holding T_h = 5.5 s as that martensite transformation finished, a hardness distribution similar to that of T_h = 20 s was obtained.

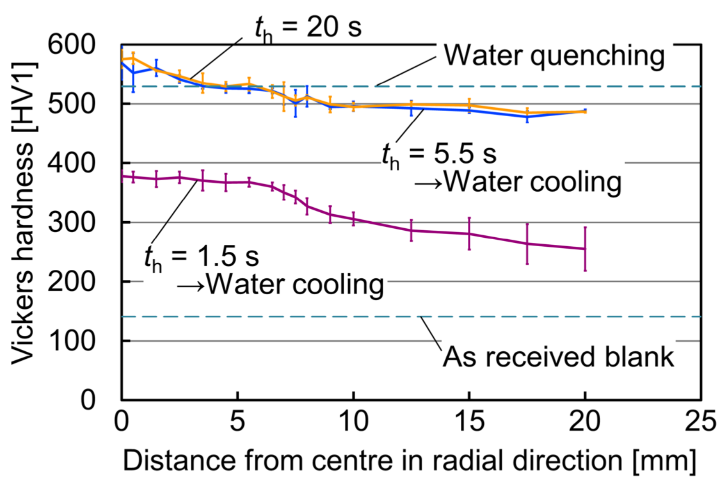


Fig. 11. Effect of holding time and water-cooling on hardness distribution for r = 50% and T_f = 840°C.

Conclusion

In this study, hot local compression of a quenchable thick steel sheet was performed to apply hot stamping having die quenching to plate forging. The following results were obtained. The forming load for hot local compression is significantly low compared to cold forming, and it is advantageous in plate forging, which often uses compression in the thickness direction.

- Holding at the bottom dead centre provides a die quenching and improves the compression ratio. The mechanism is plastic deformation induced by volume expansion during martensitic transformation under holding with the punch tool.
- The die-quenched hardness after local compression is increased by ausforming. The microstructure of that became finer.
- The holding time at the bottom dead centre was reduced using water cooling and die quenching together. Provided the holding was kept until the completion of martensitic transformation, the improvement in compression ratio by holding and hardening by ausforming was obtained even for water cooling.

Hot plate forging is a multi-step forming process similar to progressive stamping. Since there is a temperature drop at each forming stage, an appropriate order of forming stages, such as bending, shearing, etc., should be discussed. In addition, the required cooling rate and the relationship between the strain and the hardness after quenching should be examined in ausforming using die quenching.

References

[1] K. Mori, T. Nakano, State-of-the-art of plate forging in Japan, Prod. Eng. Res. Devel. 10 (2016) 81–91. https://doi.org/10.1007/s11740-015-0648-1

[2] D. Gröbel, R. Schulte, P. Hildenbrand, M. Lechner, U. Engel, P. Sieczkarek, S. Wernicke, S. Gies, A.E. Tekkaya, B.A. Behrens, S. Hübner, M. Vucetic, S. Koch, M. Merklein, Manufacturing of functional elements by sheet-bulk metal forming processes, Prod. Eng. Res. Devel. 10 (2016) 63–80. https://doi.org/10.1007/s11740-016-0662-y

[3] T. Maeno, K. Osakada, K. Mori, Reduction of friction in compression of plates by load pulsation, Int. J. Mach. Tool. Manuf. 51 (2011) 612–617. http://dx.doi.org/10.1016/j.ijmachtools.2011.03.007

[4] T. Maeno, K. Mori, A. Hori, Application of load pulsation using servo press to plate forging of stainless steel parts, J. Mater. Proc. Tech. 214 (2014) 1379–1387. https://doi.org/10.1016/j.jmatprotec.2014.01.018

[5] K. Mori, P.F. Bariani, B.-A. Behrens, A. Brosius, S. Bruschi, T. Maeno, M. Merklein, J. Yanagimoto, Hot stamping of ultra-high strength steel parts, CIRP Annals 66 (2017) 755–777. https://doi.org/10.1016/j.cirp.2017.05.007

[6] K Mori, T Maeno, M. Tsuchiya, T. Nanya, Inclusion of hot stamping operations in progressive-die plate forging of tailored high strength gear part, Int. J. Adv. Manuf. Technol., 90 (2017) 3585–3594. DOI: 10.1007/s00170-016-9705-y

[7] A. Tekkaya, J. Allwood, P. Bariani, S. Bruschi, J. Cao, S. Gramlich, P. Groche, G. Hirt, T. Ishikawa, C. Löbbe, J. Lueg-Althoff, M. Merklein, W.Z. Misiolek, M. Pietrzyk, R. Shivpuri, J. Yanagimoto, Metal forming beyond shaping: Predicting and setting product properties, CIRP Ann. Manuf. Technol. 64 (2015) 629–653. https://doi.org/10.1016/j.cirp.2015.05.001

[8] C.M. Yen, C.A. Stickels, Lamellate fracture in 5150 steel processed by modified ausforming, Metall. Trans. 1 (1970) 3037–3047. https://doi.org/10.1007/BF03038417

[9] M.W. Vaughan, P. Samimi, S.L. Gibbons, R.A. Abrahams, R.C. Harris, R.E. Barber, I. Karaman, Exploring performance limits of a new martensitic high strength steel by ausforming via equal channel angular pressing, Scr. Mater. 184 (2020) 63–69. https://doi.org/10.1016/j.scriptamat.2020.03.011

[10] T. Maeno, K. Mori, M. Fujimoto, Improvements in productivity and formability by water and die quenching in hot stamping of ultra-high strength steel parts, CIRP Ann. Manuf. Technol. 64 (2015) 281–284. https://doi.org/10.1016/j.cirp.2015.04.128