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Investigation of Die Quench Properties of Hot Stamping Steel 15B22

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Hot stamping technology can be used to increase the formability of ultra-high-strength steel sheet. In addition to sheet metal parts with high strength and high dimensional accuracy, this technology can avoid the spring-back problems of high-strength steels for cold forming to achieve weight reduction. For the process applications of hot stamping steel, 15B22 was employed at the different sheet strengths from different parameters, to help the downstream customers in process development and applications of hot stamping products. This investigation might speed up the establishment of a domestic hot stamping technology and product development, which might fill the technology gap in the automobile industry supply chain. The results showed that, when 15B22 (t = 2mm) was heated to 930°C and die quenched, the temperature dropped below 200°C in about 15 seconds. The average cooling rate was about 48°C/s when the temperature was reduced from 800°C to 400°C. By proper control of the hot stamping process conditions, the tensile strength of 15B22 steel could be promoted to more than 1520MPa.

Keywords：Hot stamping, Forming, Die quench

1. INTRODUCTION

In response to the increasingly serious global warming and the depletion of oil reserves and energy sources, energy saving and carbon reduction requirements have become more stringent in countries all over the world, forcing the auto industry to develop lightweight cars. The auto parts are made of high strength steel which can reduce the vehicle weight and achieve the purposes of energy saving, exhaust reduction, and vehicle safety improvements. However, steel formability decreases with increasing strength as shown in Fig.1[1]. In cold stamping, the following problems often occur as high strength steels (HSS, AHSS and UHSS) are used:

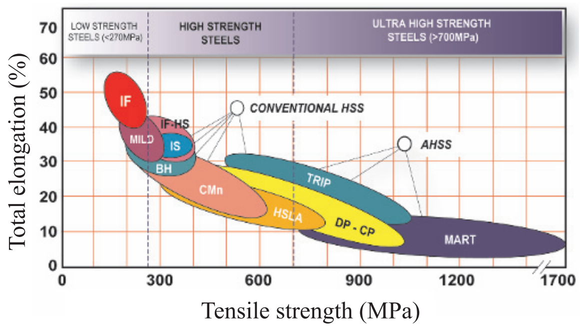

Fig.1. The elongation vs strength of different steel materials[1].

(1) Poor formability - easy to break;
(2) Poor forming accuracy and greater spring-back problems - easy to produce a variety of surface defects;
(3) Equipment with high pressure required;
(4) Difficulty in manufacturing ultra-high-strength steels; and
(5) Difficulty or even impossibility in stamping ultra -high-strength steels.

Therefore, the traditional cold stamping method has become unsuitable for ultra-high-strength steel forming. To overcome the technological bottlenecks of high-strength steel forming, sheet stamping industries are actively developing hot stamping technologies. Hot stamping is a new forming method. It can significantly improve the formability of high strength steel. In addition to high strength and high dimensional accuracy of steel sheet formed, it can also avoid cold stamping spring-back problem for high-strength steel and achieve the purpose of weight reduction as shown in Fig.2[1].

Currently, the utilization of hot stamping parts in automotive body structures is proportionately increasing year by year. Taking the example of Volkswagen, the utilization of hot stamping parts in the series models is generally more than 10%, and the parts in a car are

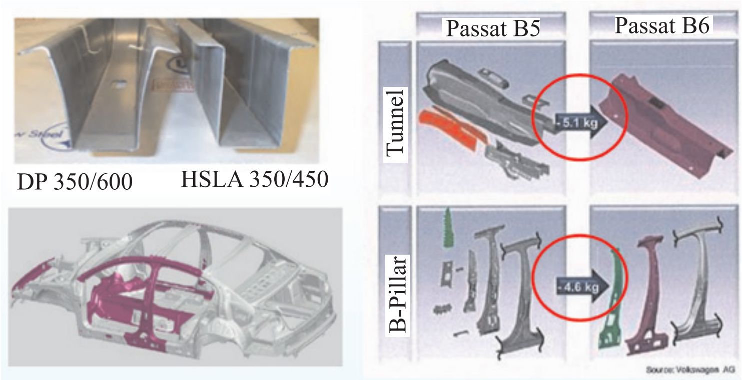

Fig.2. High strength steels in vehicles with improved safety and light weight[1].

shown in the middle side pieces in Fig.3[2,3]. Others, such as Fiat, also have a plan to apply more than 16% hot stamping parts in subsequent new models. Volvo also intends to use more than 35% hot stamping parts in their new models. From 2008 to 2010 EuroCarbody collected related information. Hot stamping auto parts were used in a proportion of 4 to 15% generally. A typically representative part is the B-pillar in automobiles.

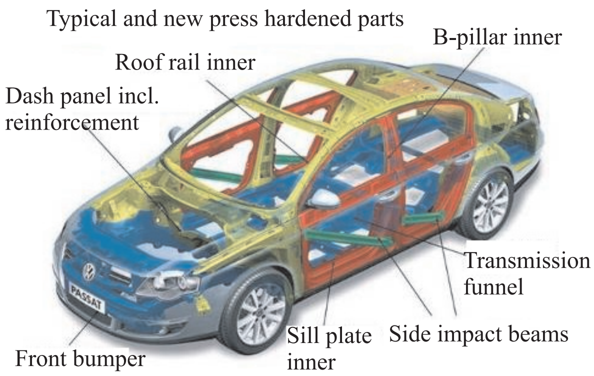

Fig.3. Hot stamping parts for automotive applications in a car[2,3].

In 2009 the worldwide market demand for hot stamping parts was about 115 million units. Schuler predicted that it would reach 450 million units in 2013. The occurrence that the supply is unable to meet the demand started in 2012 as shown in Fig.4[4], and the gap is increasing annually. If this technology is established before any further increase in the gap, there will be a good commercial opportunity for China Steel (CSC) in the future. Currently there are about 140 hot stamping production lines in the world. The main equipment suppliers and their market shares are Schuler (50%) in Germany, AP & T (30%) in Sweden, and Loire Safe (20%) in Spain. In China there are also 30 hot stamping production lines. The three main foreign companies are Bentler, Cosma, GeStamp, and Baosteel which supply the hot stamping parts market throughout China.

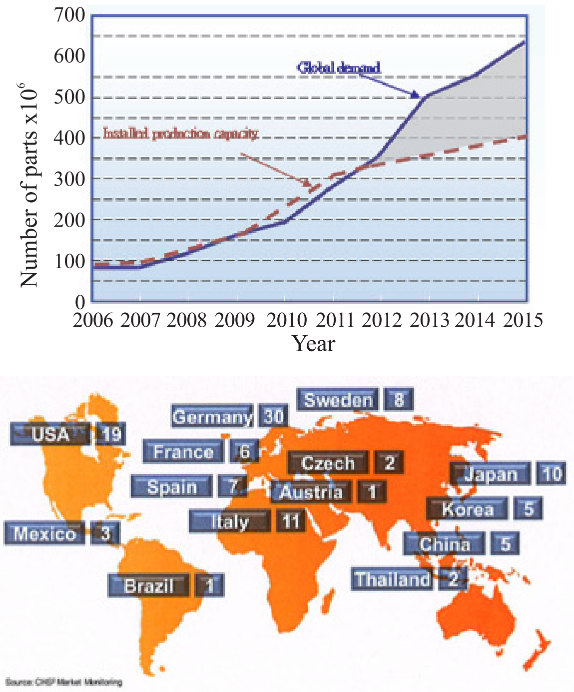

Fig.4. Global hot stamping production capacity and the parts market demand trend[4].

A typical hot stamping production line is in the Swedish AP & T Company as shown in Fig.5[5]. The appearance of the whole production line as a continuous contour can be observed. The length of the furnace accounts for a large part of the line. With the typical cycle time of 15 seconds and the distance between the furnace billet 1.5 m as well as the heating time of 6 minutes (360 seconds), the entire production line is estimated to be about 36 m. If the production

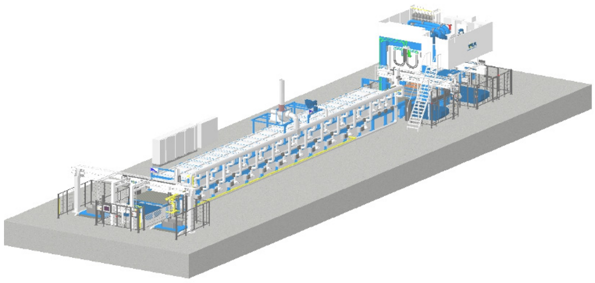

Fig.5. Typical hot stamping production line (AP&T Company)[(5)].

speed is faster and the heating time is longer, the length of the furnace will be increased. The key technologies of the hot stamping process are as follows:

(1) Hot stamping steel (including coating, welding and painting techniques);
(2) Hot stamping simulation finite element analysis techniques;
(3) Die design technology (including die cooling system technology);
(4) Heating equipment; and
(5) Stamping equipment and automated conveyor systems.

This study was to investigate the different sheet strengths from different parameters, to help the downstream customers in process development and the applications for hot stamping products. It should speed up the establishment of the domestic hot stamping technology and product development which could fill the technology gap in the automobile industry.

2. EXPERIMENTAL METHODS

For the simulation of the hot stamping process in this study, a hot stamping flat die was used to test the hot stamping steel specimens. The specimens were heated up to a high temperature state. After a uniform temperature was attained, the test pieces were conveyed with different times into the die quench. At the same time, the die was pressurized to different pressures. After a certain period of time under pressure, the test pieces were removed to test the hardness and strength. The microstructure was also analysed. In addition, image analysis technology was employed to calculate the percentage of specimen martensite after the die quench. The chemical composition of the 15B22 hot stamping steel is shown in Table 1. Because the steel used was bare without any high temperature oxidation resistant coating, it was necessary to protect the surface by nitrogen gas to reduce surface oxidation and decarburization. However, when the high temperature steel sheet was transferred from the furnace to the die, some oxidation still occurred due to the direct contact with the atmosphere. The hot stamping test conditions are shown in Table 2.

Table 1 Chemical composition of 15B22

Steel	C	Si	Mn	P	S	B
15B22 (wt%)	0.22	0.23	1.2	0.015	0.004	0.002

Fe：balance

Table 2 Hot stamping test conditions of die quench

Material of sheet	15B22 (t = 2mm)
Specimen size (mm)	100×280
Heating temperature (°C)	830、880、930、980
Soaking time (min)	5
Shielding gas	Nitrogen
Die pressure (ton)	15、20、25
Transfer time (s)	5、10、15、20
Material of die	SKD61 (H13)
Die cooling agent	Water
Water temperature (°C)	25

3. RESULTS AND DISCUSSION

The results and discussion in this study included the temperature variation of the die quench, and the hardness and strength of the hot stamping steel after die quench. Both of the latter two characteristics were also microanalyzed.

3.1 Temperature variation of die quench

In order to avoid thermal stress from the hot stamping spring-back deformation of sheet metal parts, we kept the die after forming steel sheet parts under pressure for a certain period until the steel sheet temperature was reduced to below 200°C. Therefore, the temperature in die quench process was measured to estimate the time for the hot stamping under pressure. Figure 6 shows two curves, one of which is heating 15B22 of thickness 2 mm to 930°C in approximately 180 seconds. The other one is that, afterwards, the specimen was held for 5 seconds and sent to the die to quench under 25 tons of pressure. From the temperature variation data, the time from sorting out the die clamping of 15B22 to 200°C was about 15 seconds.

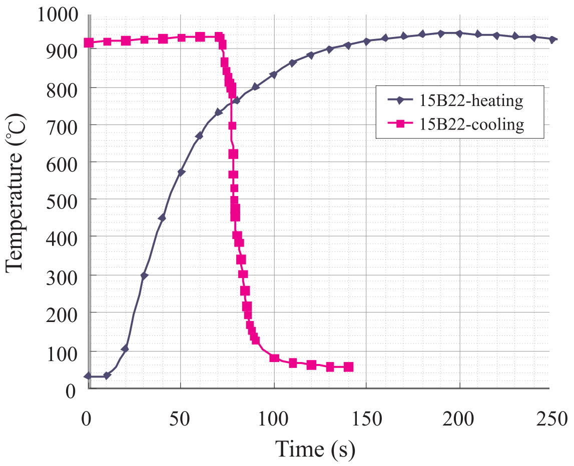

Fig.6. Curves of heating hot stamping steel of 15B22 (t = 2mm) to 930^{o}C and that of cooling after die quench.

Figure 7 shows the curves of heating and cooling temperature as well as the instantaneous rate of 15B22 after heating to 930^{o}C followed by cooling after being transferred to the die quench. The temperature curve of 15B22 after die quench was almost vertical. The maximum instantaneous cooling rate after die quench was at 550^{o}C/s. The average cooling rate from 800 to 400^{o}C was 48^{o}C/s, which was higher than the 25^{o}C/s in literature as shown in Fig.8[(6)]. The cooling curve in this study did not touch the CCT curve in the austenite and bainite dual-phase region. The initial die quench temperature was about 820^{o}C, which was higher than the phase transformation temperature. Theoretically, the die quench steel sheet microstructure in this condition would be almost all martensite, which should give the product a very high strength.

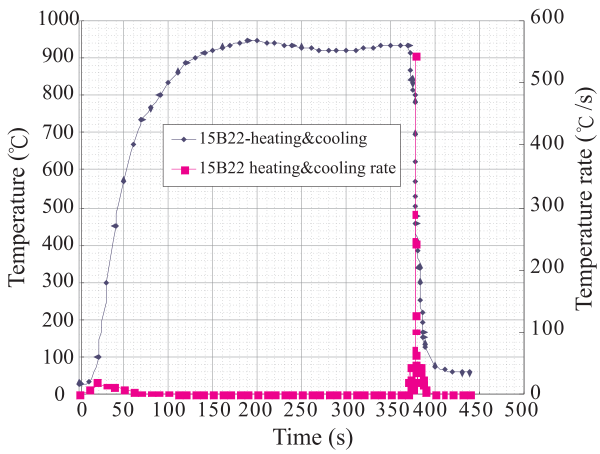

Fig.7. Curves of heating and cooling temperature as well as instantaneous rate of 15B22 as heating to 930^{o}C followed by cooling after transferral to die quench.

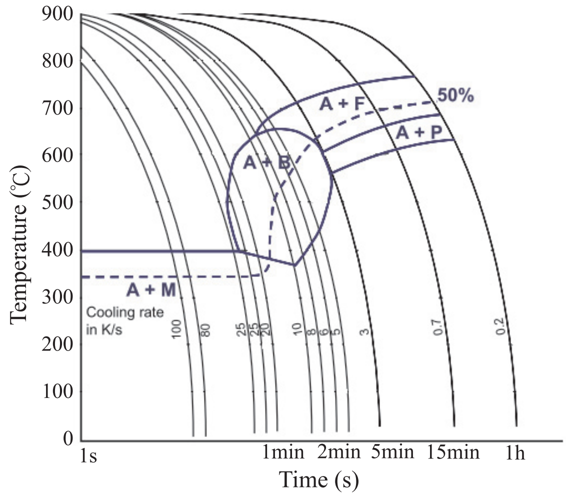

Fig.8. CCT curves of hot stamping process temperature vs. time with various cooling rates[(6)].

Based on the above measurements of the heating and cooling of hot stamping steel after die quench, it takes about three minutes to reach the preset temperature for 15B22 of thickness 2 mm. The air cooling temperature and time of hot stamping steel are different for different steel sheet thickness. Based on the relationship between air cooling temperature and time, the quench temperature within the die could be found from the time for the test piece to be transferred from the furnace to the die. It took approximately 15 seconds for hot stamping steel 15B22 (t = 2 mm) in a die quench to cool from 930^{o}C to below 200^{o}C. 15B22 was heated to 930^{o}C and sent to the die quench in 5 seconds. The thermal history revealed that the instantaneous cooling rate of die quench was up to 550^{o}C/s, and the average cooling rate from 800 to 400^{o}C was about 48^{o}C/s, which met the high cooling rate requirement of the hot stamping process.

3.2 Hardness and microanalysis of hot stamping steel at die quench

Table 3 shows the die quench HRC hardness test results of 15B22 under different test conditions (different temperatures, transfer times, and pressures). The analysis data revealed that the factors affecting the hardness were the heating temperature and the test piece transfer time from furnace to die, especially the latter. In the case of test pieces of 15B22 being heated to 830^{o}C with transfer times of 15 and 20 seconds, the maximum hardness of 15B22 after die quench was only HRC 29. As shown in Fig.9, the microstructure in this experimental condition clearly revealed precipitated ferrite (white), indicating that the reduction of hardness resulted from the too low die quench temperature. The quench temperature curve contacted with CCT curve and entered into the dual phase area. If the heating

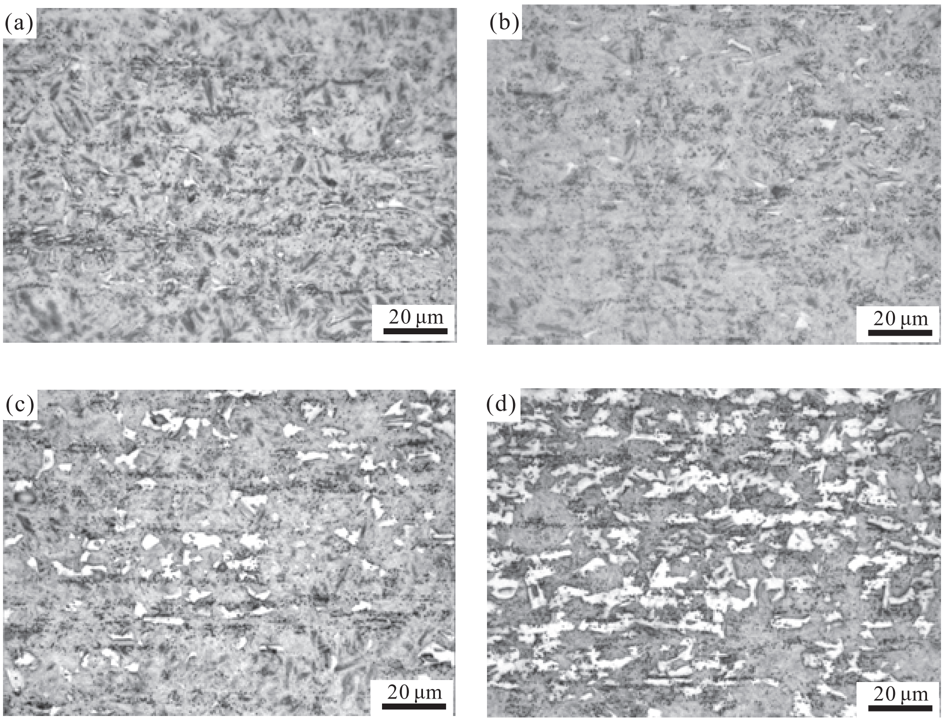

Fig.9. The microstructure of 15B22 after heating to 830°C and sending to the mold under 15 tons pressure at different times (a) 5s; (b) 10s; (c) 15s and (d) 20s.

Table 3 The hardness of 15B22 from different heating temperatures, transfer times, and die quench pressure conditions (HRC)

Material \ Hardness(HRC)			Transfer time (s)			
			5	10	15	20
15B22	830℃	25T	44.0	43.3	36.9	37.5
		20T	44.4	43.5	36.9	34.8
		15T	43.9	43.8	43.9	36.3
	880℃	25T	44.5	43.5	43.4	43.5
		20T	44.3	44.2	43.3	43.8
		15T	44.3	43.9	44.6	43.9
	930℃	25T	43.3	43.3	42.8	43.6
		20T	43.5	43.1	42.8	43.5
		15T	43.5	42.9	43.0	42.9
	980℃	25T	43.1	42.8	43.0	41.2
		20T	41.5	42.5	42.7	42.5
		15T	42.8	42.9	42.7	42.4

temperature was raised to 880°C under the same transfer time conditions, the 15B22 surface hardness was significantly improved to HRC 42~43 after die quench.

Figure 10 shows the microstructure of 15B22 after heating to 830°C followed by sending the specimens to the mold under 25 tons pressure die quench with different transfer times. The martensite percentages after transfer times 5 and 10 seconds were 95.5 and 92.5%, respectively, both of which were over 90%.

In addition, micro-Hv hardness analysis was employed to obtain the specimen hardness distribution throughout the cross-section after die quench. 15B22 was heated to 830°C followed by sending the specimens to the die in five seconds under 15 tons pressure in the die quench conditions. The hardness test results in Fig.11 show that the specimen cross-sectional micro-Hv hardness distribution was uniform, i.e. the specimen was fully hardened. There was no internal softening phenomenon. The average HRC hardness translated from the micro-Hv was HRC 44.6 which was very close to the direct measured surface hardness HRC 43.9.

Figure 12 shows the micro-Hv hardness measurement results for 15B22 at different transfer times andpressures. It revealed that the test piece transfer time affected the hardness after die quench significantly. A shorter time of sending the specimen to the die resulted in a higher hardness after die quench.

3.3 Strength and microanalysis of hot stamping steel at die quench

Hot stamping steel strength after die quench is one of the most important mechanical properties of hot stamping materials. Table 4 shows the test results for

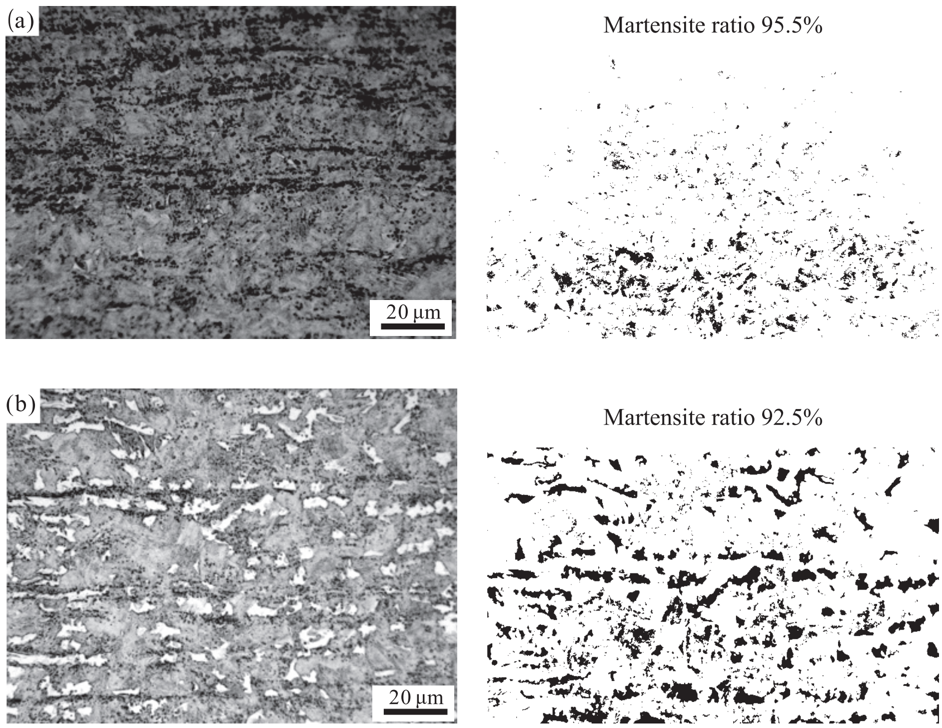

Fig.10. The microstructure of 15B22 after heating to 830^{o}C followed by sending the specimens to the mold under 25 tons pressure die quench in transfer times (a) 5s; (b) 10s.

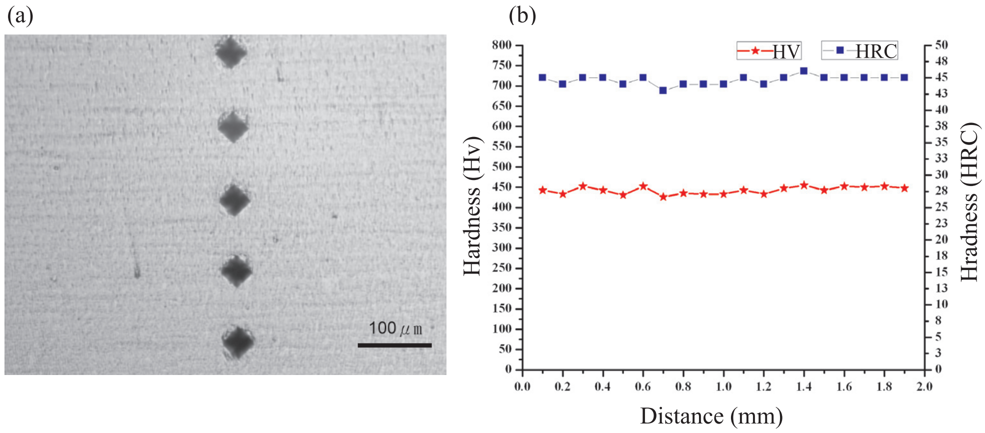

Fig.11. The hardness of 15B22: (a) indentations on the specimens; and (b) variation of the micro-hardness (Hv) and the Rockwell hardness (HRC). Test conditions of hardness: loads of 500 g (Hv); 15B22 heating to 830^{o}C; and a 5 second transferral to die quench under 15 tons pressure.

the mechanical properties (TS, YS and EL) of 15B22 under different test conditions. The table shows the effect of different heating conditions. 15B22 heating to a temperature of 880°C had a greater strength than heating to other temperatures after die quench. TS was higher than 1500 Mpa, provided that the transfer time was from 5 to 10 seconds. The ranges of TS and YS were about 1518~1539 and 1059~1095 MPa, respectively, while that of EL was about 9~10%. As 15B22 was heated to 830°C and the transfer time was prolonged from 15 to 20 seconds, its strength became lower (TS about 1210~1354 MPa, YS about 614~807 MPa), while EL was increased to about 10.1~11.1%.

Figure 13 shows the strength and elongation for 15B22 (t = 2 mm) at different temperatures and transfer times under 25 tons pressure. It is evident that, no matter how long the transfer time, the tensile strength varied with the heating temperature and a maximum optimum existed at 880°C after die quench. Figure 14 shows the SEM analyses of cross-sectional tensile specimens of 15B22 after die quench. Most areas were Dimple patterns, and only some of the local small regions revealed transgranular fracture patterns. Figure 15 shows the microstructure of 15B22 after heating to 880°C followed by sending the specimen to the mold under 25 tons pressure die quench in different times.

Figure 16 shows the microstructure of 15B22 after heating to 880°C and sending the specimen to the mold in 20 seconds after die quench. The microstructure had a very high proportion of martensite with the martensite

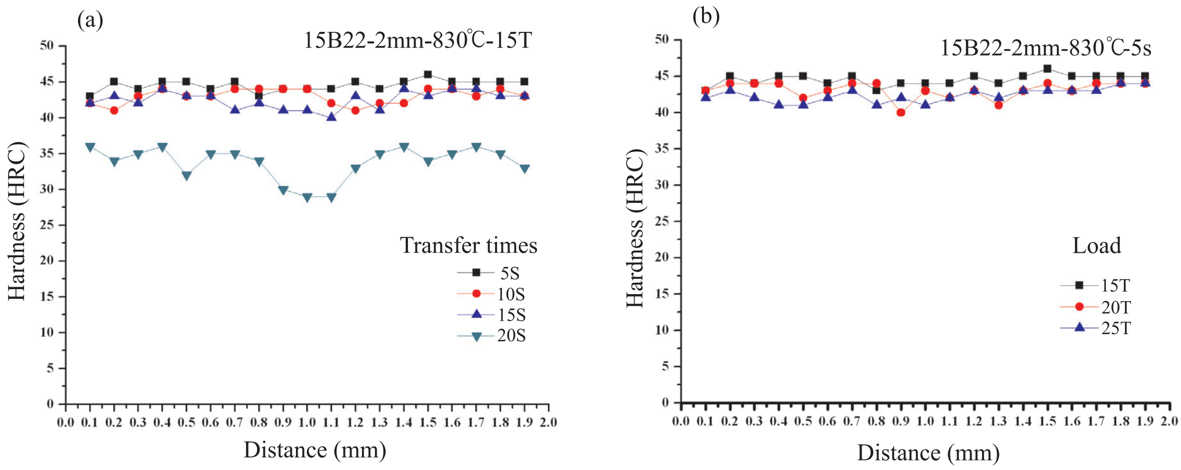

Fig.12. Hardness of 15B22: (a) for different transfer times; and (b) under different pressures.

Table 4 Mechanical properties of 15B22 under different hot stamping conditions

Material		TS(YS/EL)	Transfer time (s) 5	10	15	20
15B22	830℃	25T	1485(1030/9.40)	1454(975/10.1)	1281(684/11.1)	1354(807//10.6)
		20T	1526(1078/6.9*)	1416(890/10.1)	1248(692/6.7*)	1210(614/10.1)
		15T	1432(948/10.3)	1446(982/9.5)	1497(1037/9.5)	1268(671/11.0)
	880℃	25T	1532(1078/9.2)	1523(1071/10)	1519(1071/9.8)	1518(1070/9.0)
		20T	1523(1089/9.3)	1521(1075/9.3)	1523(1086/9.8)	1521(1059/9.2)
		15T	1534(1091/9.1)	1523(1096/7.8)	1539(1095/9.4)	1523(1077/8.9)
	930℃	25T	1481(1052/8.8)	1479(1047/9.3)	1489(1052/9.7)	1471(1035/7.7)
		20T	1486(1038/9.9)	1477(1043/9.3)	1486(1040/9.3)	1478(1057/8.4)
		15T	1487(1052/9.6)	1494(1058/9.1)	1486(1062/8.0)	1480(1050/9.1)
	980℃	25T	1470(1027/8.3)	1473(1037/9.2)	1464(1031/9.6)	1447(1015/4.9*)
		20T	1455(1031/8.4)	1465(1031/9.5)	1464(1037/8.9)	1464(1037/8.8)
		15T	1469(1041/7.8*)	1463(1026/9.1)	1467(1035/10.3)	1477(1044/9.6)

Note: TS(MPa), YS(MPa), EL(%), * Elongation at break outside in GL.

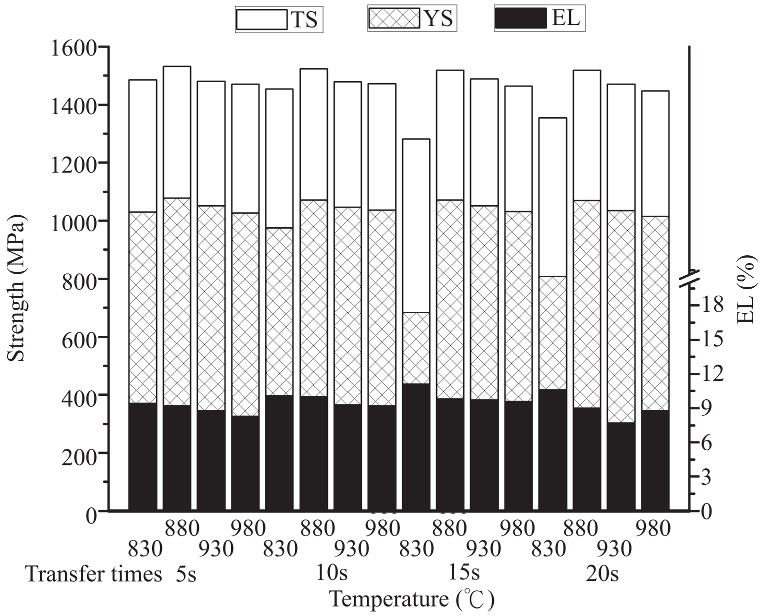

Fig.13. Strength and elongation for 15B22 (t = 2 mm) at different temperatures and transfer times under 25 tons pressure.

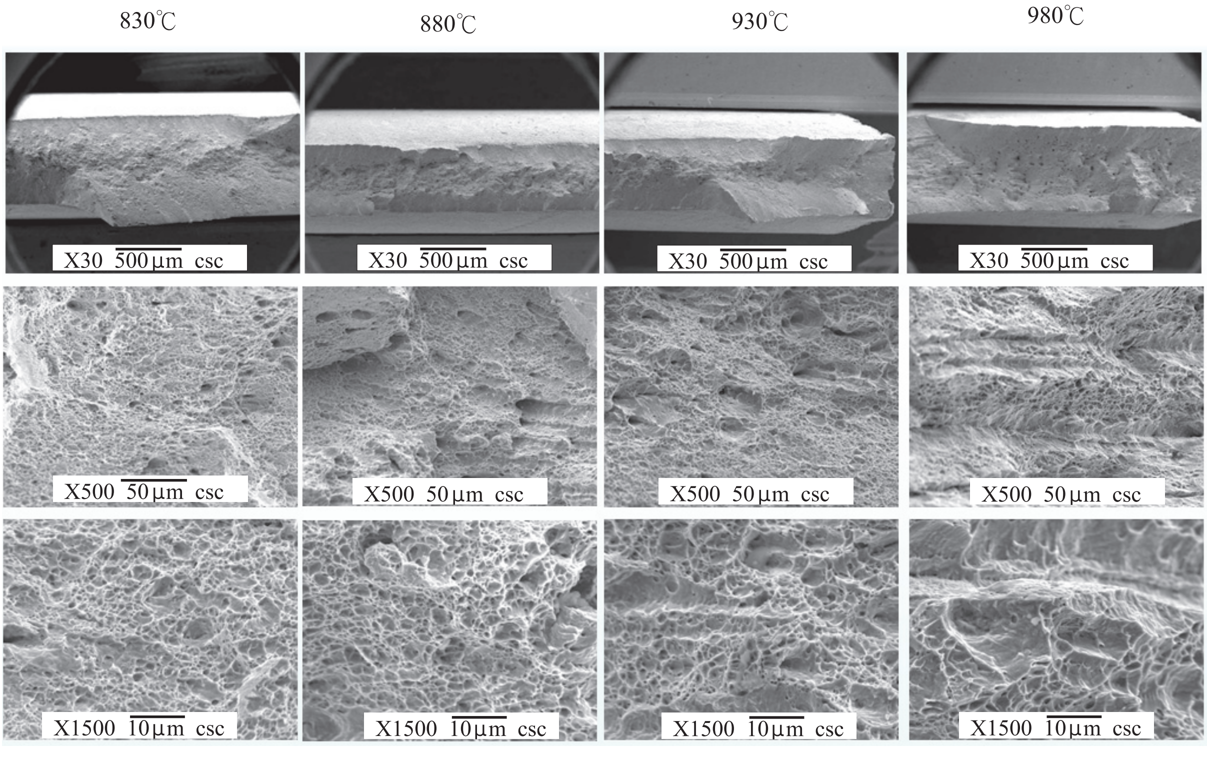

Fig.14. SEM analyses of cross-sectional tensile specimens of 15B22 after die quench.

percentage estimated to be about 98.5%. However, above 880^{o}C the die quench strength of 15B22 decreased with any increase in heating temperature. Figure 17 shows the microstructure of 15B22 after die quench from different prior heating temperatures. It is evident that the martensite after die quench became coarsened as the heating temperature was raised above 880^{o}C. This is due to the austenite grain growth of 15B22 at high heating temperatures, leading to coarse martensite after die quench and the tensile strength being reduced.

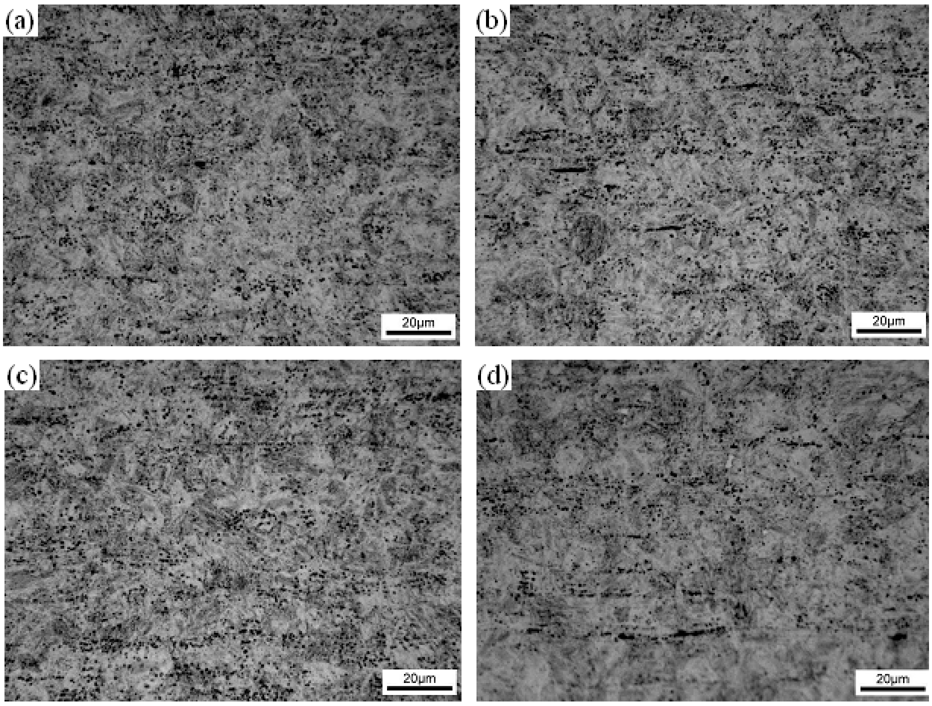

Fig.15. The microstructure of 15B22 after heating to 880°C followed by sending the specimen to the mold under 25 tons pressure die quench in time: (a) 5s; (b) 10s; (c) 15s and (d) 20s

Martensite percentage 98.5%

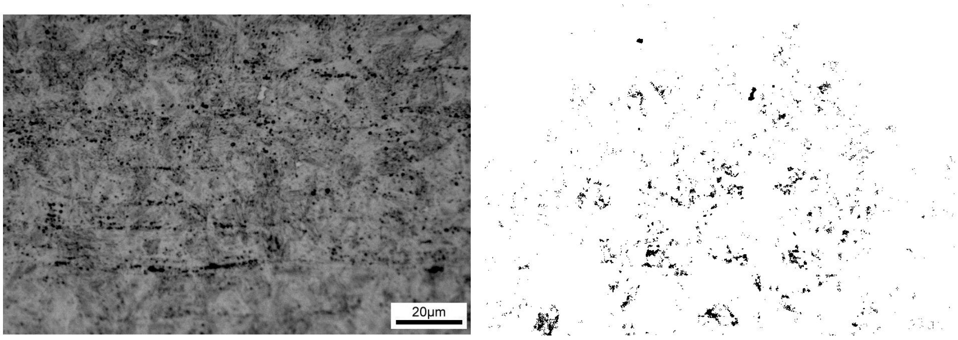

Fig.16. The microstructure of 15B22 heating to 880°C and sending to the mold in 20 seconds after die quench.

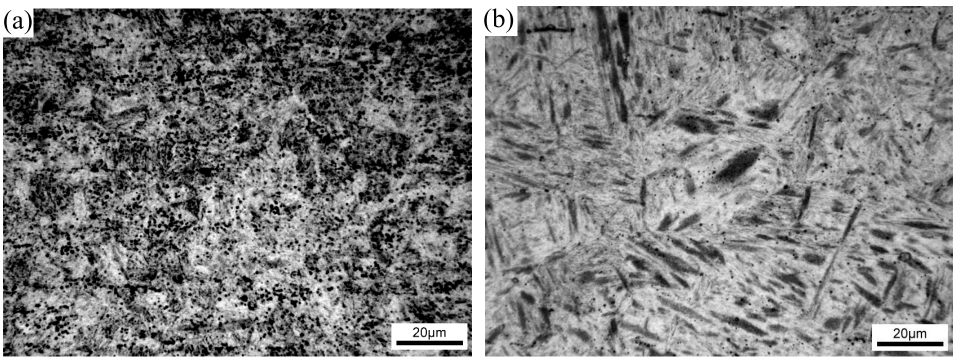

Fig.17. The microstructure of 15B22 after die quench from prior heating temperatures (a) 880°C and (b) 930°C.

Figure 18 shows the relationship of hardness and strength for hot stamping steel after die quench. By regression analysis, the relationship can be obtained as follows.

$$y = 28.273x + 265.19$$

$$x : \text{hardness(HRC)}$$

$$y : \text{tensile strength(MPa)}$$

This formula is based on the experimental data. The formula is expected to correspond to a more realistic steel strength after die quench. A change of one HRC in hardness corresponds to a change of about 28 MPa in tensile strength. If the steel hardness is HRC 43, the tensile strength TS is about 1480 MPa.

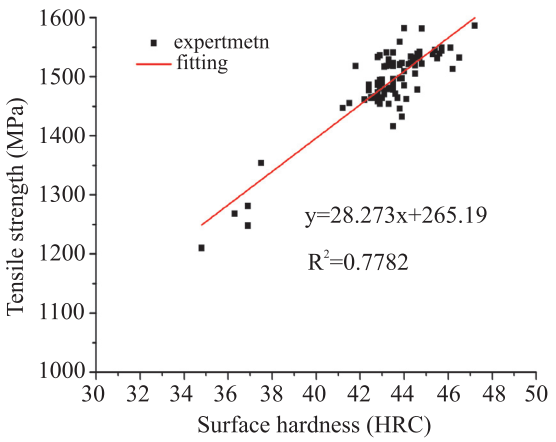

Fig.18. Relationship of hardness and strength for hot stamping steel after die quench.

3.CONCLUSIONS

From the different die quench experimental conditions, strength, hardness, and microstructure analysis of 15B22, the conclusions of this study are the following.

Hot stamping steel 15B22 of thickness 2 mm can reach a preset temperature in about 3 minutes after being sent to a high temperature furnace. From the relationship of air cooling temperature and time, together with the transfer time from a high-temperature furnace to die, quenching temperature inside the die could be obtained. 15B22 was heated to 930°C and sent to the die in 5 seconds followed by quenching. The average cooling rate from 800 to 400°C was about 48°C/s. Micro-Hv hardness measurements from the surface to the interior demonstrated that a 15B22 die quench specimen was fully hardened and the effect of transfer time on the hardness was more obvious. Heating 15B22 to 880°C was the best condition from this research. The steel sheet strength was promoted to 1520 MPa or more. In the conditions of transfer time rising from 5 to 10 seconds, the ranges of TS and YS were 1518~1539 and 1059~1095 MPa, respectively, while that of EL was 9~10%. Furthermore, the strength of the steel sheet 15B22 was lower when it was heated to 930 and 980°C. Because of the high temperature austenitic grain growth, the martensite after die quench became coarsened, leading to a reduction in steel strength. How to suppress austenite grain growth in hot stamping steel will be a worthy direction for further study in the future.

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