Study on Strengthening Mechanism and Application Performance of the High Toughness 2 GPa Hot Forming Steel

B. Chen(✉), Z. W. Liang, S. C. Yin, L. P. Liu, J. G. Zhang, C. Y. Zhai, and T. Liu

Tangshan Iron and Steel Group Co., Ltd., Tangshan, Hebei, China
chenbo312@163.com
https://www.tangsteel.com.cn

Abstract. The high toughness 2 GPa hot forming steel of Tangsteel achieved the strength of 2 GPa after hot stamping through the composite strengthening mechanism of composition design, martensitic strengthening, fine grain strengthening and precipitation strengthening. The carbon content in martensite was reduced by the precipitation of nano-VC, and the formation of brittle twin martensite was physically inhibited. The strength was improved while the toughness and ductility were obtained, and the comprehensive mechanical properties were excellent. Moreover, the irreversible hydrogen trap with high binding energy of V element in the steel improves the anti-hydrogen brittleness of the material and greatly reduces the risk of delayed cracking in the service environment after hot forming. The hot stamping process of 2 GPa hot forming steel with high toughness was studied, and the recommended process is heating temperature 910–930 °C, heating time 240–300 s, holding time 7–15 s. The key application properties of 2 GPa hot formed steel with high toughness, such as spot-welding performance, bending performance, high speed tensile performance, anti-delayed fracture performance and coating anti-corrosion performance were studied. All of them met or were better than the requirements of relevant standards, indicating that the 2 GPa hot formed steel with high toughness of Tangsteel has good application performance.

Keywords: 2 GPa · Hot forming steel · High toughness · Strengthening mechanism · Application performance

1 Foreword

Due to the advantages of high strength and significant lightweight effect, hot forming steel is widely used in manufacturing automotive key structural parts and safety parts [1]. At present, 22MnB5, including non-coating and aluminum-silicon coating, as the first generation of 1.5 GPa high strength hot-formed steel is widely used to manufacture automotive safety components in the world. The tensile strength of the components after hot stamping can reach 1.5 GPa. With the increasingly stringent requirements of automotive on safety, lightweight and environmental protection, the research and application of hot forming steel has turned to the second-generation of 2 GPa high

Y. Zhang and M. Ma (Eds.): ICHSU 2022, AHMST 2, pp. 5–18, 2023.
https://doi.org/10.2991/978-94-6463-114-2_2

strength hot forming steel with higher strength in recent years, and the tensile strength of automotive components produced by this material can reach 2 GPa [2]. With the tensile strength increasing from 1.5 GPa to 2 GPa, the thickness of automotive components can be reduced by 20%, further realizing the lightweight of automotive.

Tangsteel developing the high toughness 2 GPa grade hot forming steel is to solve the first generation of hot forming steel cannot meet the urgent requirement of automotive lightweight, safety, energy conservation and environmental protection, and Tangsteel can produce and supply two kinds of products of the uncoated CR1300/2000HS and AlSi coated CR1300/2000HS+AS. Through composition design and production process optimization, the 2 GPa hot forming steel of Tangsteel has obtained good toughness and ductility while improving strength and excellent comprehensive mechanical properties. The material is controlled by alloying elements to greatly reduce the risk of delayed cracking in service environment after hot forming. This paper introduces the composition design and strengthening mechanism of the high toughness 2 GPa hot forming steel, studies the key application performance of hot stamping process, the spot-welding performance, bending performance, hydrogen induced delayed fracture resistance and coating anticorrosion performance, in order to better promote and applicate the material in automotive industry. At present, the high toughness 2 GPa hot formed steel of Tangsteel has been applied in batches in many domestic OEMs.

2 Composition Design and Strengthening Mechanism

The composition design of Tangsteel high toughness 2 GPa hot forming steel is by means of optimizing C element and microalloy additions elements such as V, combined with hot forming technology to realize grain refinement, and through the nano vanadium carbide (VC) precipitation reduce the carbon content of martensite, physically inhibiting the production of brittle twin martensite, fundamentally improve the toughness and plastic of the material, and the strength of the material after hot stamping exceeded 2 GPa through the composite strengthening mechanism of martensitic transformation strengthening, fine grain strengthening and precipitation strengthening.

As can be seen from Table 1, the high toughness 2 GPa hot forming steel of Tangsteel has a higher C content than that of the traditional 1.5 GPa hot forming steel. As a solution strengthening element and austenite stabilizing element, element C can reduce Ac3 temperature and the hot stamping heat temperature. Element C plays the role of interstitial solution strengthening in martensite, and its effect on martensite strengthening is far greater than that of alloy element strengthening with replacement solution. At the same time, the elements C and V combine to produce VC, which improved the strength and plasticity of the material because of VC precipitation strengthening and

Table 1. Chemical composition design of high toughness 2 GPa hot forming steel (mass fraction, %).

C	Mn	Cr	Si	Ti+V	B
0.29–0.40	≤2.50	≤0.80	≤0.55	≥0.25	≤0.0050

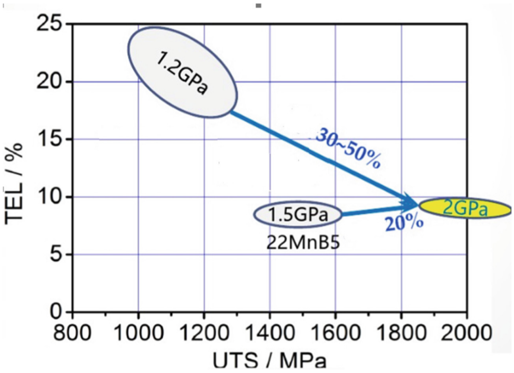


Fig. 1. Heat treatment process in laboratory.

Table 2. Set parameters for hot stamping process.

Process No.	Heating temperature/°C	Heating time/s	Pressure/kN	holding time/s
1	910	300	7000	10
2	930	300	7000	10
3	950	300	7000	10

fine grain strengthening. The combination of element V and C can reduce the content of C in martensite, inhibit the emergence of twin martensite, improve the plasticity and toughness of the material, and the solid solution of element V improves the hardenability of the material. Moreover, the irreversible hydrogen trap with high binding energy contained in the steel made by element V improves the hydrogen brittleness resistance of the 2 GPa hot forming steel [3] (Fig. 1).

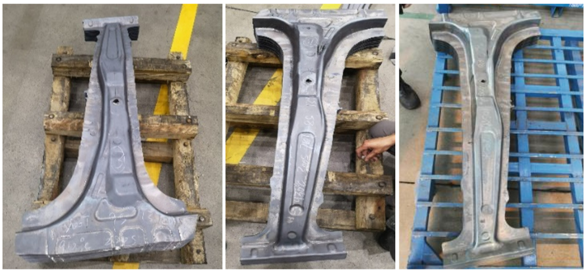
3 Research on Hot Stamping Process

The bare plates of Tangsteel high toughness 2 GPa hot forming steel was used as the test material, and different hot stamping processes were tested by manufacturing the part of B-pillar in a hot stamping parts manufacturing enterprises to study the hot stamping process and key parameters for the high toughness 2 GPa hot forming steel [4, 5].

3.1 Process Parameter Setting and Parts Trial Production

Refer to the hot stamping process of 1.5 GPa hot forming steel produced by the plant and other hot stamping parts manufacturing enterprises, three hot stamping process of 2 GPa hot forming steel were designed. The key hot stamping process parameters were set as shown in Table 2.

10 pieces of B-pillar were produced for every process of process 1, 2 and 3, and the parts were formed normally without cracking or wrinkling (as shown in Fig. 2). The



(a) 910°C (b) 930°C (c) 950°C

Fig. 2. Parts produced by different processes.

Fig. 3. Sampling and testing locations of the parts.

dimension accuracy of the parts met the standard requirements. Comparing the surface quality of the parts produced by the three kinds of process, there is a little scale on the parts for process 1 and 2, which can meet the requirements of surface quality, but for process 3, there is a lot of scale on the parts, which cannot meet the requirements of surface quality and it is not recommend selecting the process for 2 GPa hot forming parts production.

3.2 Tensile Properties and Metallographic Structure Testing

Tensile properties, Vickers hardness, metallographic structure and decarburization layer depth were tested with the parts produced by the three hot stamping process at room temperature. The sampling locations of the parts were shown in Fig. 3, and the test results were shown in Table 3.

It can be seen from Table 3 that all of the tensile properties tested values of the parts produced by the three hot stamping processes meet the standard requirements.

It can be seen from Table 4 that all of the Vickers hardness tested values of the parts produced by the three hot stamping processes meet the standard requirements.

The metallographic structure of the parts produced by the three hot stamping processes is shown in Fig. 4, which all meet the standard requirements of martensite content $\geq 95\%$.

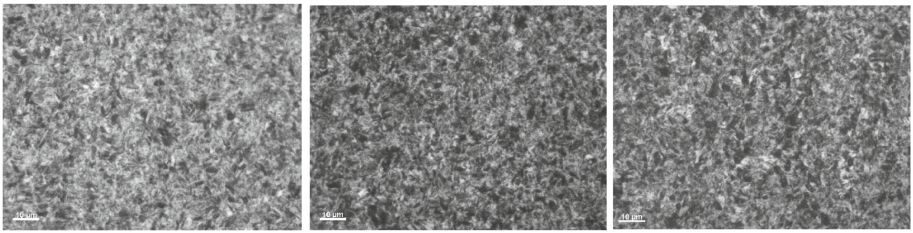
Due to the large amount of scale on the surface of the parts produced by process 3 and some shedding, this process was directly abandoned, and the depth of decarburization

Table 3. Test results of tensile properties.

Heating temperature/°C	Tensile strength/MPa	yield strength/MPa	Elongation/%	Judgment
910 °C	1985	1297	5.5	qualified
930 °C	2003	1370	6.0	qualified
950 °C	2018	1330	6.0	qualified
Standard values	1800–2200	1200–1600	A50 ≥ 5%	

Table 4. Vickers hardness test results.

Heating temperature/°C	Location 1	Location 2	Location 3	Judgment
910 °C	591	602	585	qualified
930 °C	579	584	586	qualified
950 °C	592	601	600	qualified
Standard values	HV10 ≥ 500			



(a) 10 °C (b) 930 °C (c) 950 °C

Fig. 4. Metallographic photographs of parts produced by the three processes.

layer was not detected for the parts produced by this process. According to the tested values of process 1 and process 2, the decarbonization layer depth of the two processes both meet the standard requirements (Table 5).

AS the above research and analysis for the parts, it can be seen that the mechanical properties, Vickers hardness and microstructure of the parts produced by Tangsteel 2 GPa hot forming steel with the three processed can meet the standard requirements, while the parts produced with process 3 has a lot of scale, the process 3 is not recommended for the industrial production of 2 GPa hot forming steel. All the test values of process 1 and process 2 can meet the standard requirements. Combined with the common hot stamping process of 1.5 GPa hot forming steel and the equipment characteristics of hot stamping enterprises, the recommended hot stamping process of 2 GPa hot forming steel is as below, heating temperature 910–930 °C, heating time 240–300 s, holding time 7–15 s.

Table 5. Test results of decarburization layer depth (μm).

Heating temperature/°C	Measured value 1	Measured value 2	Measured value 3	Measured value 4	Measured value 5	Average value	Judgment
910 °C	12.8	14.5	12.9	13.9	14.2	15.5	qualified
930 °C	17.3	15.2	13.6	16.0	15.3	16.2	qualified
950 °C	Not tested						
Standard values	Average depth of decarburization layer ≤ 50 μm						

4 Research on Application Performance

In order to better apply and promote 2 GPa hot formed steel, the welding properties, bending properties, high speed tensile hydrogen induced delayed fracture resistance and coating corrosion resistance of the material after flat die quenching were studied.

4.1 Research on Welding Performance

According to GWS-5A standard of General Motors, the welding properties and welding joint life of 1.2 mm thickness uncoated CR1300/2000HS after flat die quenching were studied. Welding parameters are set as shown in Table 6. The unit of welding time is CYC (1 CYC = 0.02 s). In the test, the welding time is minimum 7 CYC, medium 9 CYC and maximum 11 CYC, and the minimum welding spot diameter is required to be no less than 4.4 mm. The standard φ 16 mm × 23 mm electrode head was used as the welding tool in the test. The diameter of the electrode head was designed as φ 6 mm. Welding equipment includes Panasonic single-phase AC resistance welding machine (model YR-500SB2HVE), pressure measuring equipment SP-255-FU10KN, tensile equipment Zwick Roell/Z100, metallurgical equipment STEMI2000-C, microhardness measuring equipment Tukon2500 Minuteman. Welding performance test includes drawing welding process window, shear tensile test, cross tensile test, metallographic test and microhardness test.

The welding process parameters are shown in Table 6, and the welding process window is shown in Fig. 7. Under the selected three welding times, the current range is greater than the 1.0 kA requirement in GWS-5A. The solder joint metallography is shown in Fig. 8, the solder joint thinning is not more than 30%, and the microhardness is shown in Fig. 9. The electrode head life test results showed that 500 solder joints met the requirements, and no solder core size was less than 4.4 mm (as shown in Table 7). Figure 10 shows the change of solder joint nucleation diameter during the test (Figs. 5 and 6).

The above analysis shows that the welding performance and the service life of the electrode head of Tangsteel hot forming steel CR1300/2000HS meet the requirements of GWS-5A.

Table 6. Welding parameter for CR1300/2000HS steel specimens.

Test electrode	Electrode pressure/kN	Welding time/CYC	Hold time /CYC	Minimum welding current/kA	Maximum welding current/kA
Φ16 × 23	2.6	7	2	A/5.0	B/7.0
		9		C/4.8	D/7.0
		11		E/4.7	F/6.8

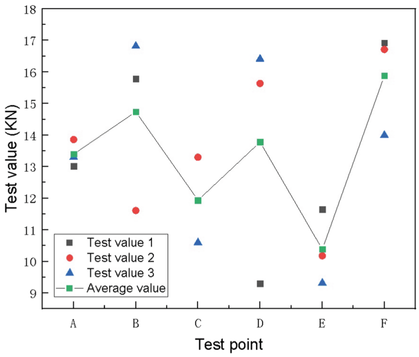


Fig. 5. Shear tensile test results of CR1300/2000HS.

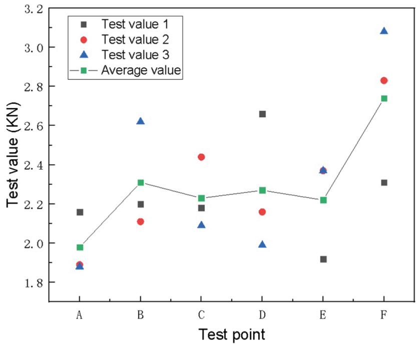


Fig. 6. Cross stretching test results of CR1300/2000HS.

4.2 Research on Bending Properties

According to the two standards of VDA238 and BMW AA-0520, the design of the test fixture refers to the content of the test device in the two standards. The bending test device and schematic diagram are shown in Fig. 11. The diameter D of the rollers on both sides of the fixture is 30 mm, L is the gap between the two rollers, the value is twice the plate thickness plus 0.5 mm, S is the displacement of the pressure head. The setting

Table 7. Test results of molten core diameter by the electrode lifetime metallography method.

Material	CR1300/2000HS	Thickness/mm	1.2	Electrode voltage/kN	2.6
Welding current /kA	6.8	Welding time/CYC	9	Hold time/CYC	2
Number of welding		Molten core diameter/mm		Whether it meets the requirements (Y/N)	
50		4.96		Y	
100		4.84		Y	
150		4.74		Y	
200		4.70		Y	
250		4.51		Y	
300		4.72		Y	
350		4.68		Y	
400		4.74		Y	
450		4.70		Y	
500		4.77		Y	

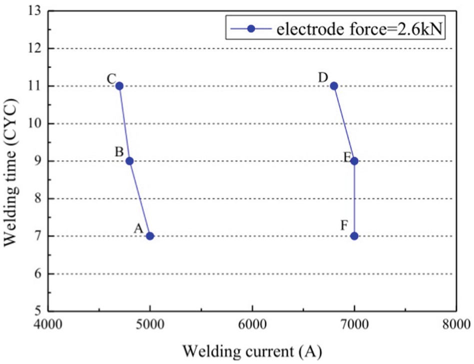
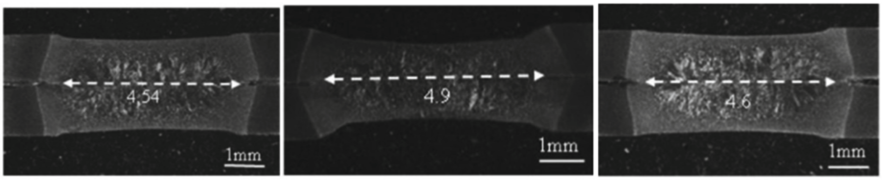


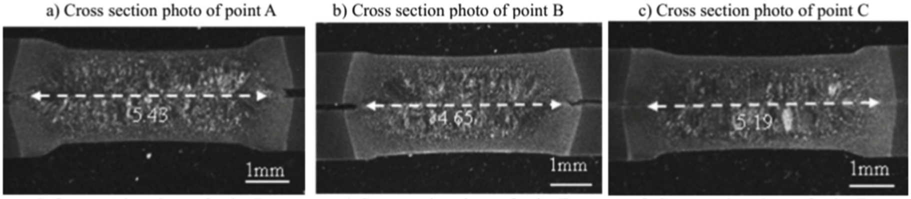
Fig. 7. Welding process window for CR1300/2000HS steel specimens.

parameter of the test refers to two standards, preload 30 N, test speed 20 mm/min, and load drop 60 N as the termination condition of theoretical test.

By testing CR1300/2000HS (flat die quenching with heating temperature 910 °C, 930 °C, 950 °C), two directions (0°, 90°) bending test, total of 18 tests. It can be seen from the test results that 90° has a larger maximum bending load and bending angle than that of 0°, while the maximum bending load and bending angle of specimens heated temperature 930 °C are greater than those of specimens heated temperature 910 °C and 950 °C. The test results are shown in Table 8 (Fig. 12).



a) Cross section photo of point A b) Cross section photo of point B c) Cross section photo of point C



d) Cross section photo of point D e) Cross section photo of point E f) Cross section photo of point F

Fig. 8. Cross-sectional photos of solder joints at different points of CR1300/2000HS steel specimens.

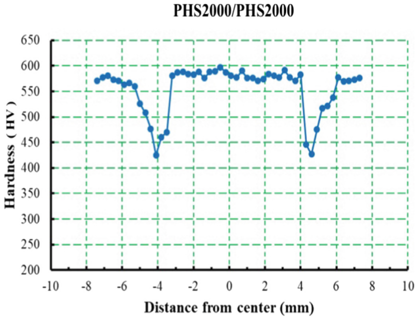


Fig. 9. Solder joint microhardness tested status.

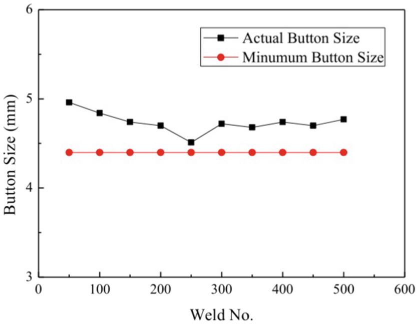


Fig. 10. Change of welding spot nucleation diameter during testing.

4.3 Research on Resistance to Delayed Fracture

The possibility of hydrogen-induced delayed fracture of 2 GPa hot stamping steel non-coated and aluminum-silicon coated plates under plane strain state which is close to

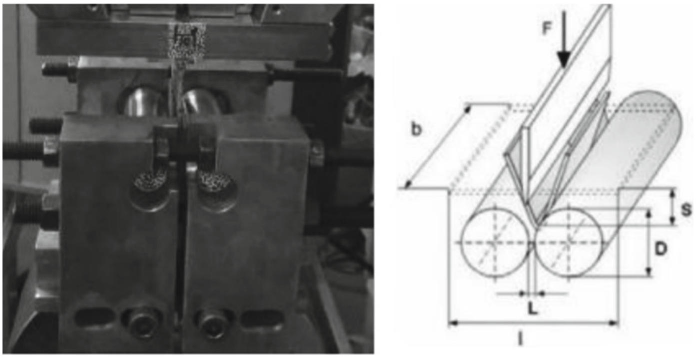


Fig. 11. Bending test device and schematic diagram.

Table 8. Maximum bending load and bending angle tested by CR1300/2000HS steel specimens.

Sample number	Average maximum load/N	Mean bending Angle/°
910 °C–0°	9862.4	52.5
910 °C–90°	9816.0	51.5
930 °C–0°	10139.2	51.5
930 °C–90°	10563.5	57.4
950 °C–0°	9649.6	46.8
950 °C–90°	9961.3	50.4

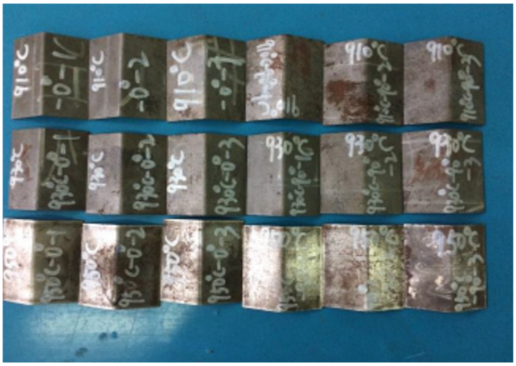


Fig. 12. Photo of specimen after three-point bending test of CR1300/2000HS steel specimens.

parts forming and collision service conditions, and simulated corrosion environment was studied the delayed fracture by u-shaped curved beam test method [6, 7]. Before the test, the standard samples of the uncoated and AlSi coated 2 GPa steel were prepared, and the samples placed in a special mould for u-shaped bending forming, using the

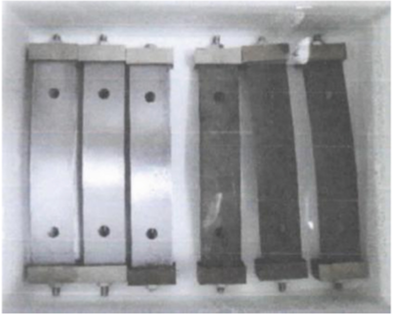


Fig. 13. Specimen photos before soaking.

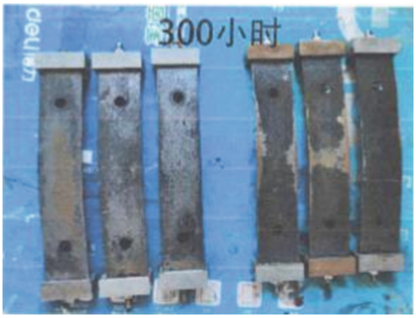
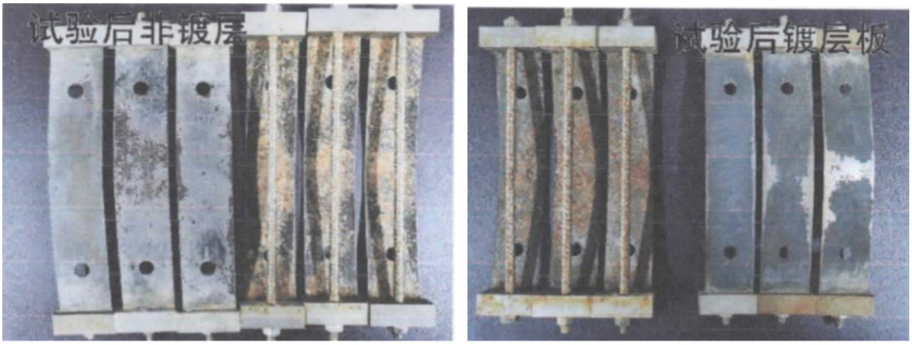


Fig. 14. Photos of bent over-yielding specimens soaked for 300 h.

special loading equipment to bend the samples until their angles meet requirements and use fixture fastening them, as shown in Fig. 13, the uncoated samples are on the left and the AlSi coated samples are on the right. Then, the samples were placed in 0.1 mol/L hydrochloric acid solution for soaking treatment, and the samples were observed whether there were fractures or not within 300 h. The photos of the samples after 300 h test in 0.1 mol/L hydrochloric acid solution are shown in Fig. 14, and the photos of the samples after the test are shown in Fig. 15. The test results show that the uncoated and AlSi coated 2 GPa hot forming steel samples bended at a specific angle and soaked in 0.1 mol/L hydrochloric acid solution for 300 h, all the samples have no cracks, which indicates that 2 GPa hot forming steel of Tangsteel has good anti-delayed fracture performance.

4.4 Research on Corrosion Resistance

The specimens were taken from the hot-formed parts produced by a hot stamping enterprise with Tangsteel 1.4 mm thickness uncoated and AlSi coated CR1300/2000HS and CR1300/2000HS+AS. The corrosion tests were carried out according to the OEM standards. Neutral salt spray test was conducted for uncoated CR1300/2000HS specimens for 1000 h, and cyclic corrosion test was conducted on AlSi coated CR130/2000HS+AS specimens included 30 cycles and 60 cycles, the test results are shown in Table 9 and Table 10.



(a) Uncoated specimens (b) AlSi coating specimens

Fig. 15. Specimens photos after the soaking test.

Table 9. Neutral salt spray test for CR1300/2000HS steel specimens.

Item	Standard requirement	Corrosion width test for single side			Test results
		Sample 1	Sample 2	Sample 3	
Neutral salt spray experiment	single side corrosion width ≤2 mm	1.6	1.4	1.4	qualified

Table 10. Cyclic corrosion test for CR1300/2000HS+AS steel specimens.

Cyclic corrosion test	Standard requirement	Corrosion width test for single side			Test results
		Sample 1	Sample 2	Sample 3	
30 cycles	① There is no blister or rust on the surface of the test plate except the scratch area; ② single side corrosion width ≤1.5 mm.	1.4	1.1	1.2	qualified
60 cycles	① There is no blister or rust on the surface of the test plate except the scratch area; ② single side corrosion width ≤2.5 mm.	2.1	2.2	2.0	qualified

The corrosion resistance of Tangsteel uncoated and AlSi coated 2 GPa hot forming steel CR1300/2000HS and CR1300/2000HS+AS meet the requirement of OEM's standard, which shows that the uncoated and AlSi coated 2 GPa hot forming steel of Tangsteel have good coating anticorrosion properties.

5 Conclusion

(1) The high toughness 2 GPa hot forming steel of Tangsteel can achieve 2000 MPa tensile strength after hot stamping through the composite strengthening mechanism of composition design, martensite transformation strengthening, fine grain strengthening and precipitation strengthening. The carbon content in martensite is reduced by precipitation of nano VC, and the formation of brittle twin martensite is physically inhibited. While the strength is improved, good toughness and ductility are obtained and the comprehensive mechanical properties are excellent.
(2) The recommended hot stamping process for Tangsteel high toughness uncoated 2 GPa hot forming steel is heating temperature 910–930 °C, heating time 240–300 s, holding time 7–15 s.
(3) The quenched 2 GPa hot forming steel CR1300/2000HS has good spot-welding performance, and the welding performance and the service life of the electrode head can meet the requirements of General Motors GWS-5A standard.
(4) The bending test results show that the bending properties of the quenched 2 GPa non-coating material at 90° are better than those at 0°, and the bending properties of the quenched material heated at 930 °C are better than those at heated 910 °C and 950 °C.
(5) The delayed fracture resistance of uncoated and AlSi coated 2 GPa steel plate of Tangsteel was studied by u-shaped curved beam test method. No cracks appeared in the samples of the two kinds of material after 300 h of testing with 0.1 mol/L hydrochloric acid solution, indicating that the uncoated and AlSi coated 2 GPa hot forming steel of Tangsteel have excellent resistance to delayed cracking caused by hydrogen.

Acknowledgments. This work is supported by Technical Center of Tangsteel Company, HBIS Group.

References

1. H. Chen and C. N. Jing, Application and development of hot forming technology for automobile lightening, *Heat Treatment of Metals* **41**, 61 (2016).
2. Y. Li, J. D. Li and T. L. Fu, New heating technology of hot stamping, *Heat Treatment of Metals* **39**, 66 (2014).
3. H. Kim, S. Jeon, W. Yang, B. Yoo, Y. Chun, H. Ha and H. Chun, Effects of titanium content on hydrogen embrittlement susceptibility of hot-stamped boron steel, *Journal of Alloys and Compounds* **735**, 2067 (2018).

4. G. H. Wu, K. M. Wu, O. Isayev, O. hress, S. Yershov and V. Tsepelev, Effect of austenitizing temperature on pearlite transformation of a medium-carbon steel, *Metallurgist* **62**, 1073 (2019).
5. Y. Nakagawa, K. Mori, T. Maeno and Y. Nakao, Reduction in holding time at bottom dead centre in hot stamping by water and die quenching, *Procedia Manufacturing* **15**, 1111 (2018).
6. L. Li, B. S. Li, G. M. Zhu and K. Y. Lang, Effect of niobium precipitation behavior on microstructure and hydrogen induced cracking of press hardening steel 22MnB5, *Materials Science & Engineering A* **721**, 38 (2018).
7. J. Li, X. Gao and L. Du, Relationship between microstructure and hydrogen induced cracking behavior in a low alloy pipeline steel, *Journal of Materials Science & Technology* **33**, 1504 (2017).