Study on the Impact Safety Improvement of Microalloyed Element on Automobile Hot Stamped Bumper

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Abstract. Bumper is one of the most important collision safety parts on the vehicle. Based on the simulation and test methods, this paper verifies the advantages of microalloying in improving the resistance to impact cracking and crack propagation of hot stamped automobile bumpers. Firstly, the two hot stamped steel plates with and without microalloyed elements are treated with the same quenching process, and then the fracture card models of the two materials are established through simulation and test. Based on the fracture card model, the drop weight impact performance of two kinds of bumper materials is simulated and compared. The results show that the sample containing microalloyed elements has better impact, intrusion resistance and energy absorption performance. The hot forming trial production of two kinds of bumper materials is carried out, and the drop weight test of the actual sample is compared. The test results are consistent with the simulation results. The results show that the crack propagation effect of the sample containing microalloyed elements is weaker than that of the sample without microalloyed elements in the same observation period.

Keywords: Hot stamped steel · Microalloying · Bumper · Safety performance · Fracture performance

1 Introduction

At present, energy conservation and environmental protection have become the two development themes of the automotive industry. Lightweight has become the most effective mean to improve vehicle safety, power and fuel economy [1–3]. As an important safety component of the bumper system, the collision performance of the front anti-collision beam has a very important impact on the collision safety of the whole vehicle. After years of development, the hot stamped front anti-collision crossbeam has realized

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large-scale application in the automotive industry at home and abroad [4]. However, in order to meet the increasingly stringent performance index requirements of collision safety regulations and the service reliability requirements in the actual environment, the current hot stamped front anti-collision beam still faces the following two key problems. First of all, the impact safety regulations at home and abroad are becoming increasingly stringent. The hot stamped front anti-collision beam will be subject to higher impact force during the impact performance test, and it is very easy to fracture. Therefore, the front anti-collision beam matrix should have higher strength and toughness. Secondly, the domestic automobile industry has not established the fracture model of parts under complex stress state when simulating and analyzing the impact performance of automobile safety components, which leads to great deviation between the model and the test, and it is difficult to achieve high-precision simulation [5–7]. The future development trend is to establish the fracture model of hot stamped steel (quenched) under complex stress state by means of test and simulation, and apply it to the impact performance simulation of actual hot stamped parts, so as to improve the accuracy of simulation analysis and guide the development of hot stamped parts. In addition, materials are the basis to improve the safety performance of hot stamped parts. In recent years, microalloying of niobium, vanadium and titanium has become a more and more common material technology means to improve the strength and toughness of hot stamped parts and meet the requirements of impact resistance, intrusion resistance and early fracture failure resistance of hot stamped parts [8–10].

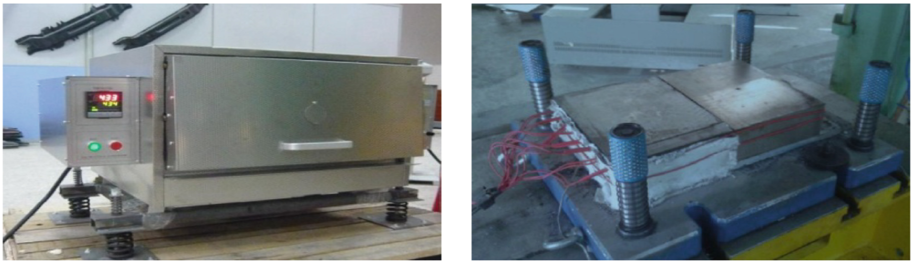
In this paper, a fracture model based on stress triaxiality and lode angle had been established for two kinds of hot stamped steel materials with and without microalloyed elements such as niobium and vanadium by means of test and simulation on the basis of conventional microstructure and properties evaluation. Using the established fracture model, the safety performance of the hot stamped front anti-collision beam of two materials had been further simulated, and the corresponding tests had been carried out to verify the effectiveness of microalloyed elements in improving the safety performance of the hot stamped front anti-collision beam.

2 Test Material

The chemical compositions of the two hot stamped steel grades selected in this paper are shown in Table 1. There is little difference in the content of main alloy elements between the two materials, and only one of them contains a certain amount of niobium and vanadium. Firstly, the conventional microstructure and properties of the two materials had been evaluated under the same quenching condition (the material had been heat

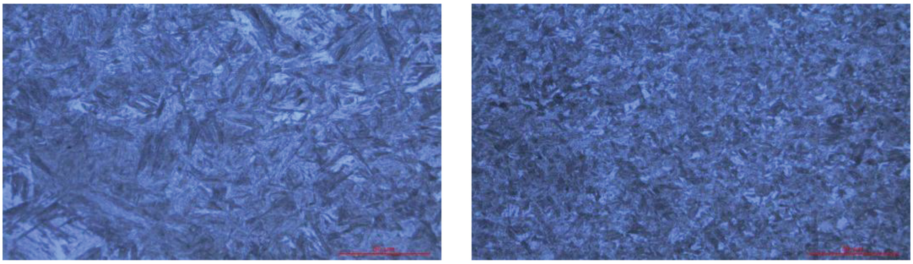
Table 1. Composition of two hot stamped steels (wt.%).

Brand	C	Si	Mn	P	S	Cr	Nb	V	Ti	B
PHS1500	0.23	0.20	1.23	0.009	0.002	0.17	0.003	0.002	0.032	0.0009
PHS1500NbV	0.23	0.22	1.26	0.008	0.002	0.17	0.034	0.033	0.030	0.0009

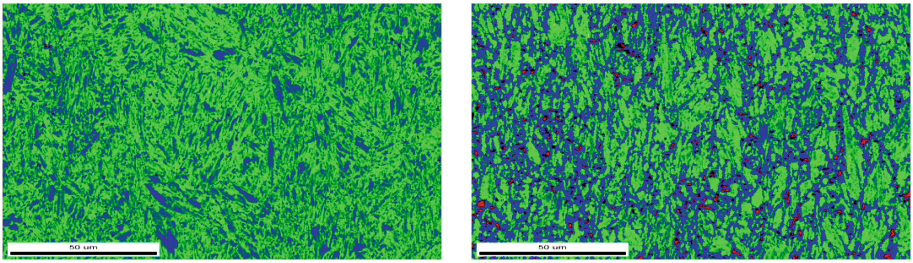


(a) Heating furnace (b) Quenching die

Fig. 1. Quenching system.



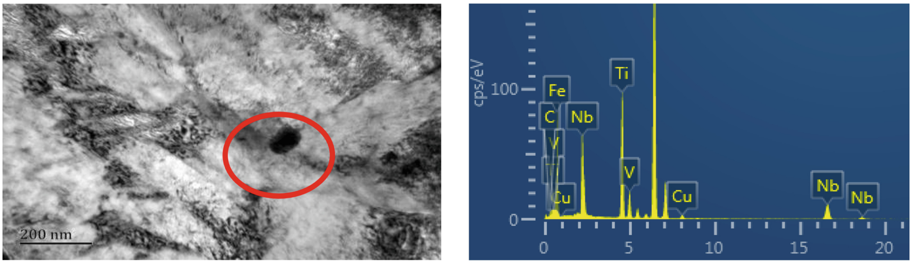
(a) PHS1500-OM (b) PHS1500NbV-OM



(a) PHS1500-EBSD-KAM (b) PHS1500NbV-EBSD-KAM

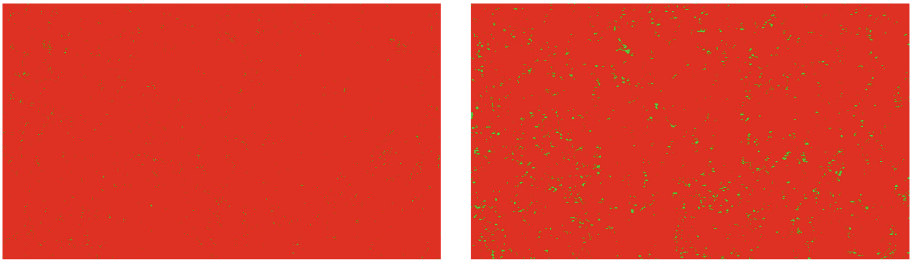
Fig. 2. Matrix structure characteristics of two component materials.

treated by die pressing quenching process, and the quenching process condition was 930 °C for 300 s). Figure 1 shows the appearance of the quenching system. Figure 2 shows the matrix structure morphology of the two materials after die pressing quenching. It can be seen that under the given quenching process conditions, the matrix structure of the steel plate containing microalloyed elements is finer, and the dislocation density in the matrix lath martensite is relatively lower. This is because the carbon content in the matrix of the materials containing niobium and vanadium decreases with the precipitation of carbide particles in different stages during heating, heat preservation and quenching. Therefore, the lattice distortion degree of quenching is relatively light, which reduces the dislocation density of matrix after quenching to a certain extent. In addition, as shown in Fig. 3, the nano carbide particles in the steel matrix containing niobium and vanadium also play an effective role in precipitation strengthening of the material, which is conducive



(a) Second phase (b) Energy spectrum

Fig. 3. Example of the second phase in the matrix of microalloyed material.



(a) PHS1500 (b) PHS1500NbV

Fig. 4. Residual austenite in matrix of two materials (Red: martensite; green: retained austenite).

to improving the strength and toughness of the matrix. As shown in Fig. 4, the matrix of materials containing niobium and vanadium contains more residual austenite, which further improves the toughness [11].

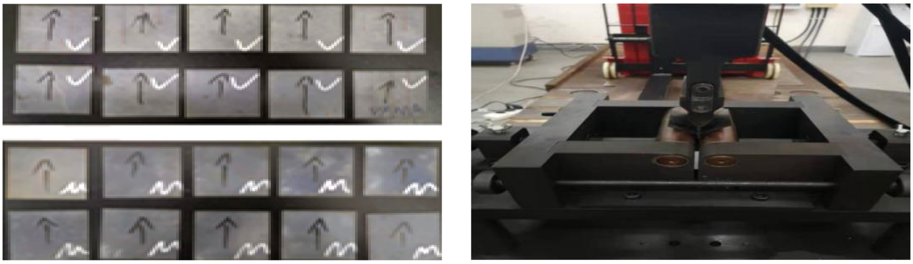
3 Material Level Safety Performance Assessment

3.1 Ultimate Cold Bending Performance

At present, for hot-stamped steel, the ultimate cold bending performance have been usually used to evaluate the impact safety of hot-stamped steel at home and abroad. For the hot-stamped steel with two components, the ultimate cold bending properties had been evaluated according to T/CSAE 154-2020 standard. The test principle and process are shown in Fig. 5. As can be seen from Table 2, samples containing niobium and vanadium have higher ultimate cold bending angle, which indicates that they have better safety performance.

3.2 Complex Stress Fracture Model

The quasi-static uniaxial tensile test and high-speed tensile test had been carried out for PHS1500 and PHS1500NbV materials (quenched state), the elastic-plastic mechanical property data of the materials under different strain rates had been obtained, and the constitutive model had been established. The shear test, R5 notch tensile test, R10 notch



(a) Sample (b) Test process

Fig. 5. Extreme sharp cold bending test sample and test process.

Table 2. The results of ultimate cold bending tests of two component materials.

No.	Cold bend angle (°)	No.	Cold bend angle (°)
PHS1500-1#	61.9	PHS1500NbV-1#	73.7
PHS1500-2#	71.6	PHS1500NbV-2#	68.6
PHS1500-3#	64.6	PHS1500NbV-3#	75.3
PHS1500-4#	61.8	PHS1500NbV-4#	67.9
PHS1500-5#	59.4	PHS1500NbV-5#	70.7

tensile test, central hole tensile test and cupping test of the two materials had been further carried out (Fig. 6). Combined with the application of digital image correlation (DIC), the fracture test data of the materials under different stress states had been obtained for LS calibration_MMC fracture failure model parameters in DYNA. Finally, the calibrated material constitutive model and fracture failure model had been used to characterize the deformation and fracture characteristics of the two materials.

The steps of establishing fracture model are as follows. Firstly, the uniaxial tensile test of the material is carried out to obtain the true stress true plastic strain curve. The data after the necking point of the curve is eliminated. Various hardening models (swift, hockett Sherby, voce, Ghosh, hollmon, ludvik, etc.) are used to uniformly fit and extrapolate multiple strain rate curves of materials (until the strain value is 1.0). According to the 24# material constitutive model in DYNA, different true stress true plastic strain curves are obtained by fitting different constitutive equations. Two models with the best fitting effect are selected for normalization, and different normalization coefficients are selected. Finally, the constitutive model of materials is established through simulation. Secondly, the shear test, tensile shear test, R5 notch tensile test, R10 notch tensile test, central hole tensile test and cupping test are carried out, and the numerical model are established. Thirdly, using the input true stress true plastic strain curve, the stress triaxiality and other parameters are obtained by simulation, and finally the fracture model is obtained by fitting. Finally, the fracture process of the specimen is simulated by the established fracture model, and verified with the actual test results. It is found that the material fracture model based on MMC model is difficult to accurately predict

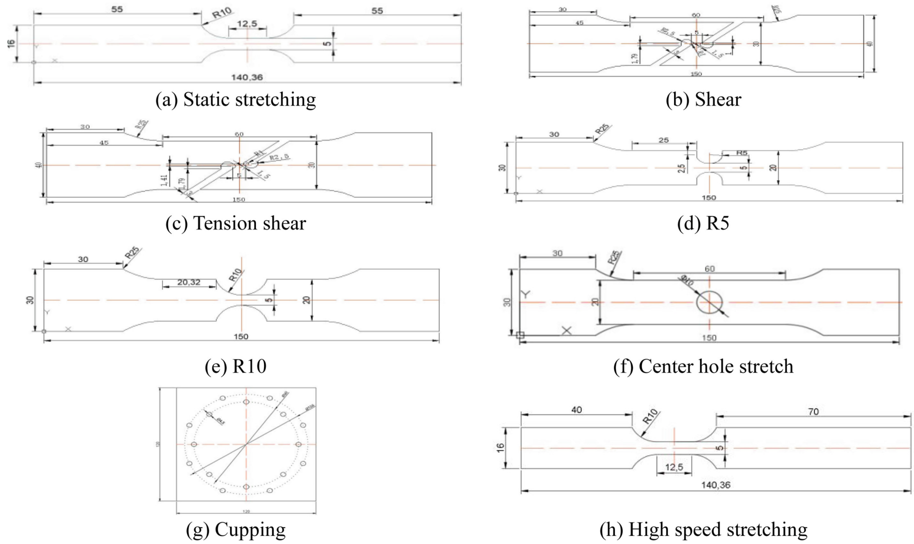

(a) Static stretching (b) Shear
(c) Tension shear (d) R5
(e) R10 (f) Center hole stretch
(g) Cupping (h) High speed stretching

Fig. 6. Fracture specimen.

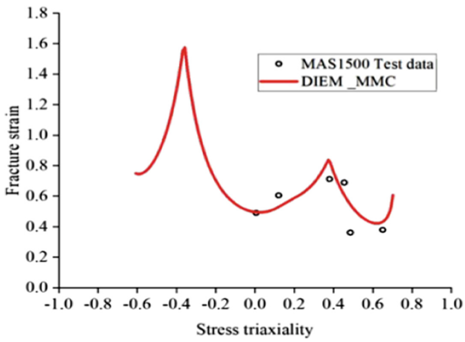


Fig. 7. DIEM_ MMC type two-dimensional failure curve.

the fracture of materials under pure shear stress, while the material fracture model based on DIEM model is difficult to accurately predict the fracture of materials under central hole tension, R10 notch tension and cupping stress states. Therefore, we had adopt the optimization method of subsection fitting. DIEM fracture model had been used to fit the triaxial stress range of 0.005–0.118 (including pure shear and tensile shear tests), and MMC fracture model had been used to fit the triaxial stress range of 0.118–0.664 (including central hole tension, R10 notch tension, R5 notch tension and cupping test). Finally, the two-dimensional fracture failure curve (DIEM_ MMC) with high accuracy had been obtained based on the fracture model (Fig. 7).

The team of this paper has found through long-term research that the fracture performance of materials under complex stress state can be judged by the fracture performance under R5 stress state. As shown in Fig. 8, it can be seen that the R5 fracture strain of

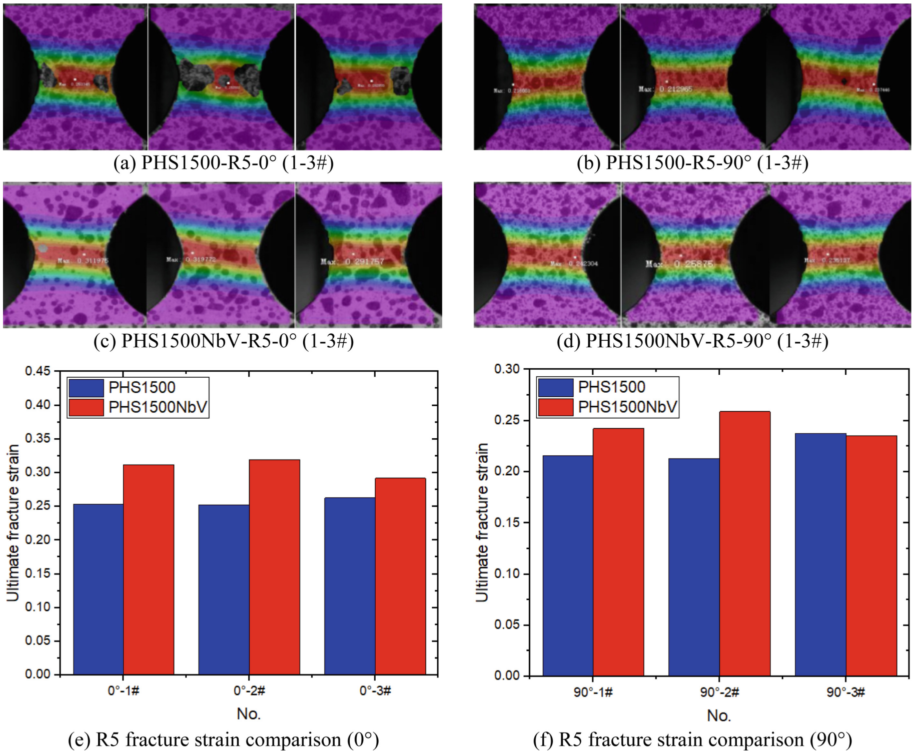


Fig. 8. Comparison of fracture failure parameters of two materials (R5) (0°-Parallel to rolling direction, 90°-Perpendicular to rolling direction).

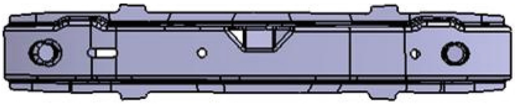
PHS1500NbV are higher than those of PHS1500, which further verifies its more excellent safety performance.

4 Part Safety Performance Comparison Verification

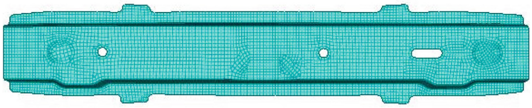
As shown in Fig. 9(a), according to the provided front anti-collision beam CAD model, we had use LS DYNA module in hyper mesh software for pretreatment and use hyper view software for post-processing. Then, the CAE model of front anti-collision beam had been established by meshed (Fig. 9(b)).

The hot stamped steel fracture model had been applied to the simulation of collision safety performance of actual parts, and the virtual evaluation of service performance under different working conditions had been carried out. The project simulates the crash performance with reference to the general safety performance evaluation method adopted by the automotive industry for the crash beam. Figure 10 shows the impact simulation conditions.

Figure 11 shows the impact simulation results of two types of crash beams. After impact, the deformation of the area where the anti-collision beam contacts the indenter is the most significant. Under the same working conditions, the ultimate fracture



(a) CAD model.



(b) CAE model.

Fig. 9. Simulation model of front anti-collision beam.

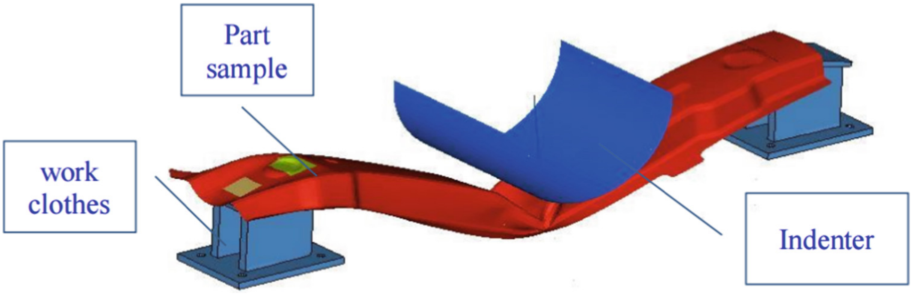
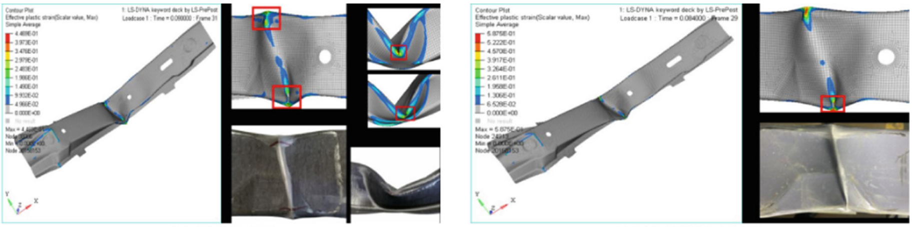


Fig. 10. Impact simulation conditions.

strain of parts containing niobium and vanadium is higher than that of common materials (PHS1500:0.447, PHS1500NbV:0.587), which verifies that microalloyed parts have better crash safety performance.

Figure 12 shows the process and results of the drop weight simulated crash safety test of two kinds of crash beams. It can be seen from Fig. 12(c)–(d) that under the same working conditions, the cracking parts of two kinds of parts are the same. It can be seen from figures (E)–(f) that the impact peak load force of micro alloy hot stamped parts is higher than that of common hot stamper steel parts. Secondly, there is little difference between the test data of the maximum displacement of the two materials during the collision, but the displacement recovery of the microalloyed parts is obviously higher after the collision unloading. The displacement of final microalloyed parts is less than 100mm, which is lower than that of PHS1500 parts (110–120 mm). Therefore, microalloyed parts have stronger anti-collision ability, that is, they have better safety performance.

The service performance of hot stamped parts involves not only its collision performance, but also other aspects, including the so-called crack propagation resistance. The crack growth resistance can be evaluated by the length and size change of the crack after collision cracking in a certain time range. If the original crack produced by the collision of the part within a given number of days shows a significant increase in length, it can be considered as having strong crack propagation tendency. The reasons for the further expansion of the original crack are generally complex, which may be related to



(a) PHS1500 (b) PHS1500NbV

Fig. 11. Simulation results of collision performance of parts made of two materials.

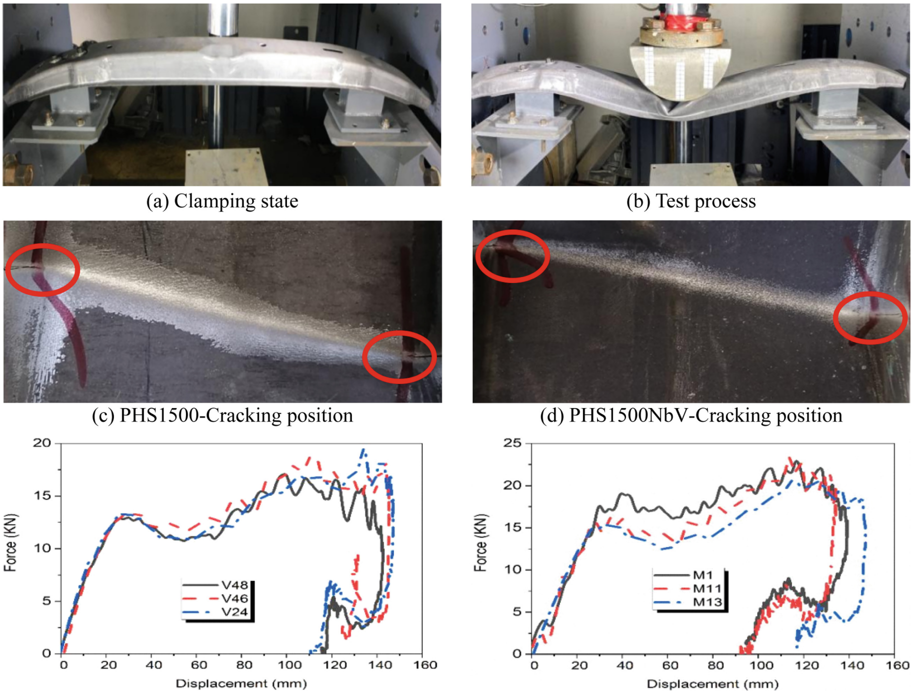


Fig. 12. Collision process and results of parts made of two materials (Blue, red and black represent the curve of three test part samples).

the release of residual stress in the local deformation area after the collision of parts, or to the delayed fracture of the stress concentration part at the tip of the original crack due to hydrogen penetration. In a word, the anti-propagation ability of crack is another embodiment of the important safety performance of parts.

Based on the above analysis, a comparative test on the crack propagation resistance of two kinds of hot stamped parts had been carried out. As shown in Fig. 13, two types of cracks along the side and end face of the part appear on the surface of the part after impact (the green and blue lines in Fig. 13 are side cracks, and the red and purple lines

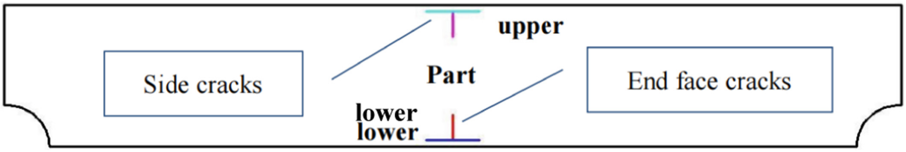


Fig. 13. Two types of cracks on the surface of hot stamped parts.

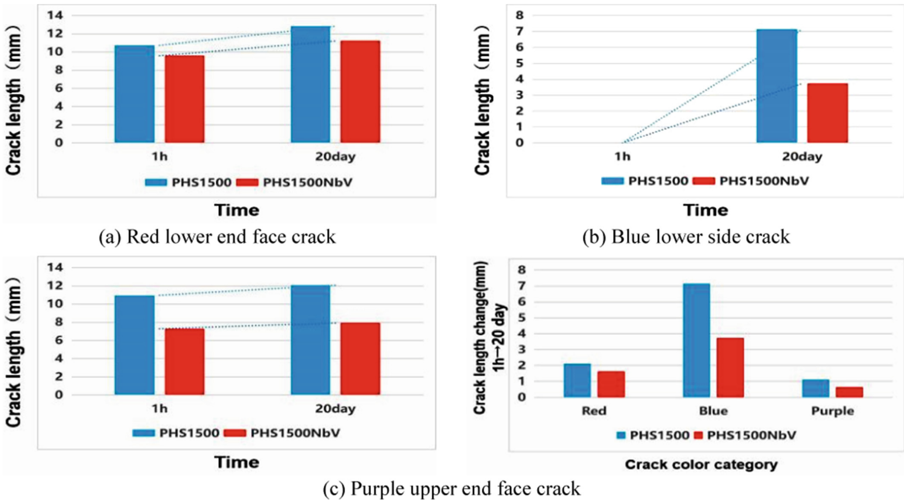


Fig. 14. Comparison of crack propagation characteristics of parts made of two materials (No green cracks on the upper side of the part surface).

are end face cracks). Two types of typical crack lengths of parts made of two materials had been tested 1 h and 20 days after the impact test. By comparing the change of crack length before and after the parts had been stored for a certain time, the safety performance advantages of microalloyed hot-stamped parts are evaluated from another aspect.

Figure 14 shows the test results. It can be seen that the length of the two types of cracks of the two kinds of parts increases after 20 days, and the crack propagation degree of the hot stamped crash beam with microalloying is weaker. This test result verifies that microalloying not only reliably improves the impact and fracture resistance of hot stamped parts, but also improves the service reliability of hot stamped parts. Obviously, the microstructure modification brought by microalloying is the fundamental reason to improve the safe service performance of parts.

5 Conclusions

In this paper, the fracture properties of PHS1500 and PHS1500NbV hot stamped steels under extreme sharp cold bending and complex stress conditions had been compared and analyzed. The results show that PHS1500NbV has higher extreme sharp cold bending angle and ultimate fracture strain (the same stress triaxiality). Based on the two materials, the corresponding hot stamped automobile anti-collision beam parts were developed. Based on the fracture model, the part level safety performance simulation and test had been carried out. The results show that the ultimate fracture strain (0.447) of PHS1500NbV hot stamped crash beam in the dynamic crash simulation process is also higher than that of PHS1500 parts (0.587). In addition, the crack growth of PHS1500NbV parts is weaker than that of PHS1500 parts after 20 days of impact and storage. The above results verify the safety performance advantages of micro alloyed hot stamped crash beam. Microalloying treatment has brought significant improvement of safety performance to hot stamped parts. Microstructure refinement, matrix dislocation density reduction, nano second phase precipitation and the formation of a small amount of retained austenite are the fundamental reasons for the improvement of safety performance of parts.

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