The effect of niobium-vanadiumcomposite microalloying on the strength and toughness of hot press forming steel

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This article investigates the effect of niobium-vanadium composite microalloying on the strength and toughness of hot press forming steel. The mechanical properties, laminated impact property, ultimate tip cold bending property, and high-speed tensile property of traditional 22MnB5 and niobium-vanadium composite micro alloyed 22MnB5 steels were measured, and the metallographic microstructure and microstructure under EBSD were observed. The results show that the hot press forming steel with Nb-V composite microalloying has a slight increase in elongation while significantly improving yield strength and tensile strength. During high-speed tension, hot press forming steel with Nb-V composite microalloying exhibits high strain rate sensitivity, which means the yield strength increases more significantly with the increasing of strain rate. Laminated impact energy (V-notch Charpy impact energy) increased by 5.5%. The extreme sharp cold bending angle of 22MnB5 has been increased from 55-60 to 65-70 (measured value under without decarburization layer). These property improvements are closely related to Nb-V composite microalloying, which can refine austenite grains, martensite bundle and martensite lath after quenching. Nb-V composite microalloying can more effectively refine carbide precipitation, and the dissolution of vanadium carbides during quenching heating can also effectively improve the hardenability of hot press forming steel, improve the quenching technological properties of hot press forming steel.

Keywords: Niobium-vanadium; Composite microalloying; Hot press forming steel; Strength and toughness; Grain refinement.

1. Introductions

The development direction of the automotive industry is electric, intelligent, and lightweight. Electrification is a new way to reduce urban pollution and replace automotive energy. Intelligence can reduce the labor for drivers, and also is a reflection of the level of automotive technology development. Lightweight is the most direct and effective means of energy conservation and emission reduction for automobiles, and it is the eternal theme for development of the automotive industry. Not only lightweight but also ensuring safety, according to the rule of thumb, it will inevitably lead to the application of high-strength steel and ultra-high strength steel. Such as the Volvo XC90, the amount of hot press forming steel used reaches 38%, which not only effectively achieves lightweight, the weight of the white body is reduced by 40%, but also at the same time, the five-star score for NCNP collisions was the highest in 2015 year, effectively achieved a fusion effect of lightweight and security. But after the strength of material is increased, the forming of parts

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becomes difficult. The hot press forming is an effective way to solve the formability and lightweight as well as also improving their safety of formed components. In other words, hot press forming can obtain high-strength and ultra-high strength complex shaped parts automotive safety structural components. At the same time, through integrated design, the number of parts can be reduced, and the strength of components can be flexibly distributed according to needs, improving the collision energy absorption ability.

However, hot press forming parts have high strength, low toughness, and insufficient collision energy absorption ability. In addition, when applied to the martensitic state of parts, the residual stress in hot press forming quenching parts is high, so they are sensitive to hydrogen induced delayed fracture. This article intends to improve the strength and toughness level of hot press forming steel through microalloying, and introduce more hydrogen traps through microalloying and carbide precipitation to improve the hydrogen induced delayed fracture resistance of hot press forming steel [1].

2. Steel and methods used in this experiment

The chemical composition of the experimental steel is listed in Table 1, which has been applied for an invention patent [2]. Among them, No. 1 steel is a common 22MnB5, and the matrix of No.2 steel is 22MnB5, that is microalloyed by small amount of niobium-vanadium composite, and niobium is added to form carbides at high temperatures. The precipitation and dissolution temperatures of niobium carbide are above 1200 ℃[3]. Based on the requirements of improving the strength [4-6], toughness, and hydrogen embrittlement resistance of 22MnB5, and considering the comprehensive influence of alloying elements on steel properties and the cost performance of steel, it is proposed to use niobium-vanadium composite microalloying to improve the property of 22MnB5, i.e. to increase strength, toughness, and hydrogen induced delayed fracture resistance. Niobium can form stable carbides at high temperatures, and vanadium can also form vanadium carbide, but the dissolution temperature is much lower than that of niobium-carbide. Under the presence of Mn, vanadium carbide may dissolve during heating in the critical region. Vanadium solid solutes in steel can effectively improve hardenability of steel [7]. Based on the solid solubility product equation and the influence of grain refinement on strength and toughness, experimental steels were designed as shown in Table 1.

According to Thermo Calc, JMatPro and other material composition design and analysis software can determine the chemical composition of experimental steel in Table 1.

Table 1. Chemical composition of experimental steel.

Number	C	Mn	Cr	B	Ti	Nb	V
1#	0.22	1.3	0.13	0.0021	0.027	/	/
2#	0.23	1.4	0.19	0.0023	0.011	0.041	0.043

3. Mechanical property measurement

The dynamic mechanical property were measured on the ZWICK-HTM 5020 testing machine, and the strain during the tensile process was measured using DIC. The experimental results of the high-speed tensile property of 22MnB5NbV and 22MnB5 are compared in Fig. 1.

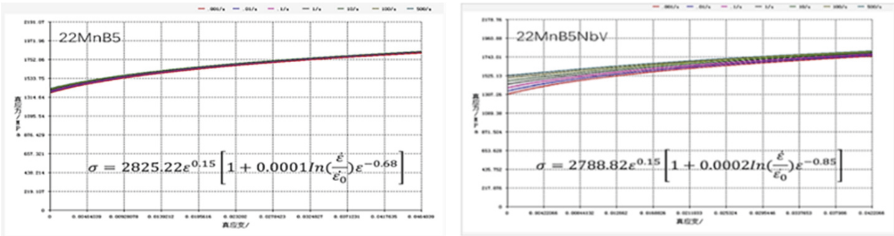


Fig. 1. Comparison of high-speed tensile properties between 22MnB5NbV and 22MnB5.

The curve in the figure shows that 22MnB5NbV has higher strain rate sensitivity than 22MnB5, which is related to the presence of a large amount of niobium-vanadium carbide precipitates in the microstructure, which can serve as effective obstacles to dislocation movement. In addition, the impact toughness of V-notch materials was measured using laminated impact testing, and the samples used are shown in Fig. 2. The impact experiment was conducted using an oscilloscope impact testing machine, and the average value of 5 samples was taken. The comparison of the total impact fracture energy is shown in Fig. 3. The average impact energy of 22MnB5NbV with niobium-vanadium composite microalloying is 52.54, and the average impact energy of 22MnB5 is 49.84, which increases the total impact energy by 5.4%. Obviously, this is beneficial for improving the energy absorption of automotive safety components during collisions.

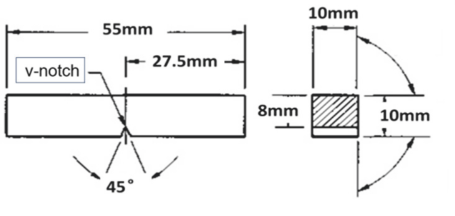


Fig. 2. Sample diagram of impact toughness of V-notch material.

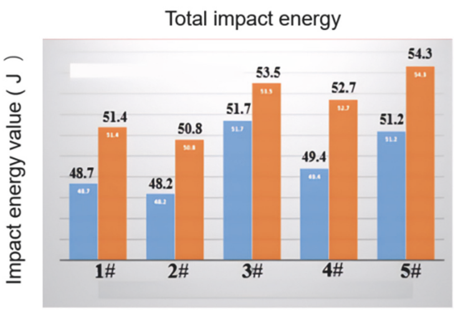


Fig. 3. Total work of impact fracture.

Considering that automotive components are subjected to complex stress states during collisions, studying the fracture performance of 22MnB5 under complex stress states through niobium-vanadium composite microalloying can better characterize the fracture characteristics of the parts during collisions. For this purpose, the mechanical properties for pure shear specimens, uniaxial tensile specimens, notch tensile specimens with different notch radii, and perforated specimens were experimentally measured. Planar stress failure curves and two-dimensional failure curves, as well as the three-dimensional failure curved surfaces for the two materials were drawn based on relevant experimental results. The three-dimensional failure curved surfaces of the two materials were compared to evaluate the safety performance of the two material parts. The diagrams of various experimental sample are shown in Fig. 4, and the failure curves of the two-dimensional planes are shown in Fig. 5. Fig. 5 shows that the curve of 22MnB5NbV plotted with stress triaxiality as the horizontal axis and failure strain as the vertical axis is higher than that of 22MnB5. The MMC (Modified Mohr Coulomb) model was used to draw the three-dimensional failure surface which is draw in the space that used failure strain as the longitudinal axis (Z- axis), stress triaxiality as the X-axis, and Lode angle as the Y-axis. The three-dimensional failure surfaces of 22MnB5NbV and 22MnB5 are shown in Fig. 6. It can be seen that from Fig. 6 the overall three-dimensional failure surfaces of 22MnB5NbV is higher than that of 22MnB5. This indicates that the composite microalloying improves the safety of hot press forming parts.

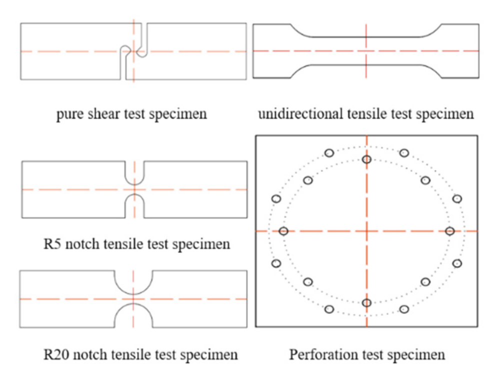
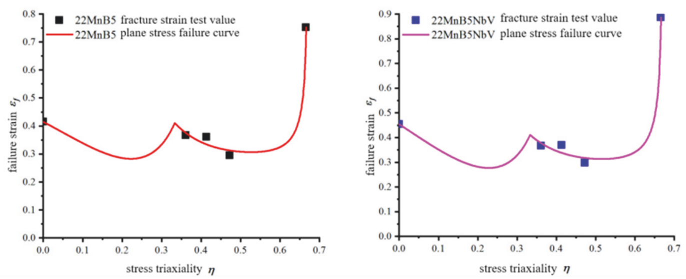


Fig. 4. Experimental specimens under different complex stress conditions.



(a) 22MnB5 plane stress failure curve. (b) 22MnB5NbV plane stress failure curve.

Fig. 5. Two types of two-dimensional plane failure curves.

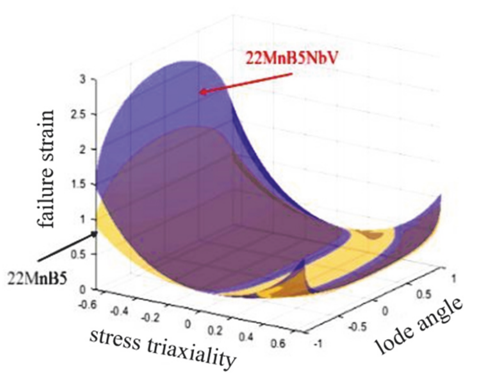


Fig. 6. 3D failure surface.

The addition of micro amounts of vanadium effectively improves the hardenability of hot press forming steel, and its end quenching curve is shown in Fig. 7.The addition of micro amounts of vanadium can effectively improves the hardenability of hot press forming steel, and its end quenching curve is shown in Fig. 7. Based on the thermal phase transition physical simulation model and related software, the microstructures of two types of steel after hot forming were predicted, and the results are shown in Fig. 8. It can be seen that from Fig.8 the martensite content in the B-pillar of 22MnB5NbV is much higher than that of 22MnB5, which is consistent with the end quenching curve shown in Fig. 5. At the same time, the application of this new steel can effectively improve the hardness value in different locations of B-pillars, which is beneficial for improving the overall strength of parts and the yield rate during industrial mass production. Selecting points 4 #, 7 #, and 10 # on the quenched B-pillar are to measure the hardness points. The comparison for measuring results of hardness is shown in Fig. 9. This hardness distribution result is consistent with the martensite distribution in Fig. 8 and also with the hardness distribution on the end quenching curve. Obviously, these results indicate that the addition of micro amounts of vanadium improves the hardenability and quenching process performance of hot press forming steel, and enhances the uniformity, consistency, and stability of overall performance of the parts.

The hydrogen embrittlement sensitivity of two types of steel was measured using methods such as U-shaped constant bending load experiment and constant tensile load experiment. The results are shown in Table 2. The data in the table indicates that niobium-vanadium composite microalloying can effectively improve hydrogen induced fracture performance of material.

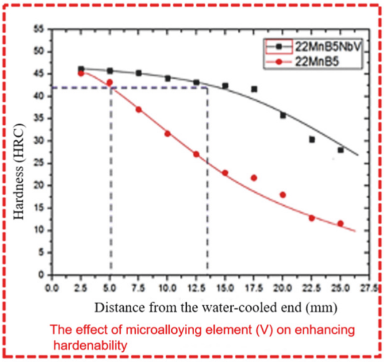


Fig. 7. Comparison of End Quenching Curve for Two Types of Steel.

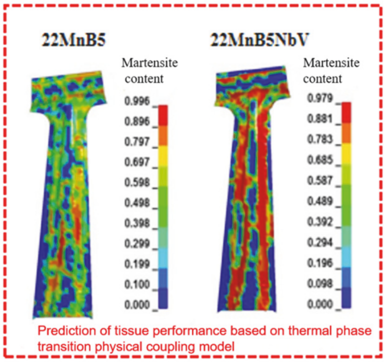


Fig. 8. Prediction of Structure Composition Based on Thermal Phase Transformation Physical Coupling Model.

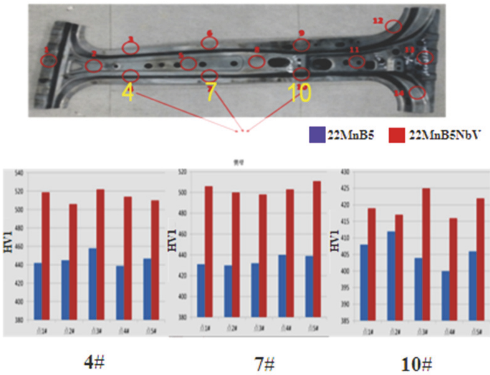


Fig. 9. Comparison of hardness measurements at three points for quenched B-pillar.

Table 2. Experimental results of hydrogen induced delayed fracture.

Protocol	Results	
	22MnB5	22MnB5NbV
U-shaped constant bending load test	Cracking occurred after soaking in a 0.5mol/L HCL aqueous solution for 12 hours under a bending load condition of 0.9 times the tensile strength.	Under a bending load condition of 0.9 times the tensile strength, no cracking occurs after soaking in a 0.5mol/L HCL aqueous solution for 300 hours.
Constant tensile load test	Hydrogen induced delayed fracture resistance=819MPa（0.5mA/cm^2） Hydrogen induced delayed fracture resistance=634MPa（1.0mA/cm^2）	Hydrogen induced delayed fracture resistance =1091MPa（0.5mA/cm^2） Hydrogen induced delayed fracture resistance =987MPa（1.0mA/cm^2）

The comparison of the measurement results of the extreme sharp cold bending angle shows that the bending angle of 22MnB5NbV is 18-20% more than that of 22MnB5. In the presence of a decarburization layer, the cold bending angle of 22MnB5NbV is 72-80 degrees, and that of 22MnB5 is 58-62 degrees. If the decarburization layer is removed, the cold bending angle of 22MnB5BbV is 65-73, and 22MnB5 is 55-60. The improvement of properties is related to the refinement of grains by niobium-vanadium composite microalloying, which leads to the refinement of martensitic lath and martensitic bundles. The microstructure comparison of the two steels is shown in Fig. 10.

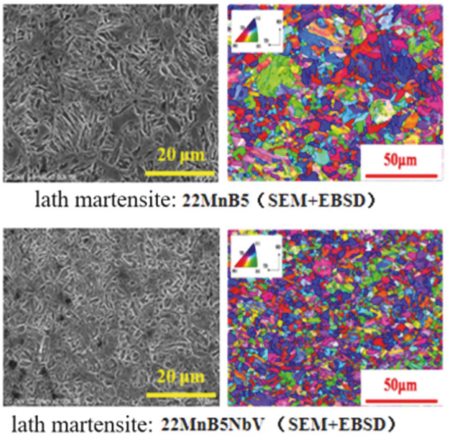


Fig. 10. Comparison of microstructure between two types of steel

4. Summary

(1) The results of high-speed tensile test, ultimate cold bending test, laminated impact test, and fracture property test under complex stress of experimental steels show that niobium-vanadium composite microalloying can improve the strength and toughness of hot press forming steel 22MnB5, and make the cold bending angle of extreme sharp cold bending meet the cold bending angle requirements of Mercedes Benz and BMW. The improvement of material strength and toughness is related to the comprehensive effects of niobium-vanadium composite microalloying on grain refinement, martensitic lath refinement and martensitic bundles refinement as well as precipitation strengthening.

(2) The addition of micro amounts of vanadium and the solid solution of vanadium carbides at quenching temperature can effectively improve the hardenability of 22MnB5, thereby can effectively improve the overall strength of the parts and the yield of industrial production. It can effectively eliminate the soft zone of quenched products.

(3) The results of hydrogen embrittlement experiments indicate that an effective hydrogen trap is formed due to the precipitation of niobium-vanadium complex carbides. The niobium-vanadium composite microalloying effectively enhances the hydrogen embrittlement resistance and delayed fracture resistance of hot press forming steel, thereby improving the reliability in the use process of hot press forming parts.

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