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THE DEVELOPMENT OF LIGHTWEIGHT COMMERCIAL VEHICLE WHEELS USING MICROALLOYING STEEL

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Abstract

Lightweight wheels can reduce weight about 100kg for commercial vehicles, and it can save energy and reduce emission, what's more, it can enhance the profits for logistics companies. The development of lightweight commercial vehicle wheels is achieved by the development of new steel for rim, the process optimization of flash butt welding, and structure optimization by finite element methods. Niobium micro-alloying technology can improve hole expansion rate, weldability and fatigue performance of wheel steel, and based on Niobium micro-alloying technology, a special wheel steel has been studied whose microstructure are Ferrite and Bainite, with high formability and high fatigue performance, and stable mechanical properties. The content of Nb in this new steel is 0.025% and the hole expansion rate is ≥100%. At the same time, welding parameters including electric upsetting time, upset allowance, upsetting pressure and flash allowance are optimized, and by CAE analysis, an optimized structure has been attained. As a results, the weight of 22.5in×8.25in wheel is up to 31.5kg, which is most lightweight comparing the same size wheels. And its functions including bending fatigue performance and radial fatigue performance meet the application requirements of truck makers and logistics companies.

Introduction

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Improvement of safety, reduction of energy consumption, and reduction of emission become one of the most highlighted issues for automotive industry in recent years[1]. One of the most significant solutions, i.e. lightweight engineering by application of new materials and process has been discussed and described for a long time [2]. Using lightweight wheels to reduce the commercial vehicle is an important method, especially for the wheels for wide base tyres, aluminum alloy forged wheels, and semi-solid aluminum alloy wheels [3]. Wheels are revolving parts under spring, so the energy- saving by reducing wheels is about 1.5 times than the other kind of part. In this paper, based on the Niobium micro-alloying technology (short for NMT), a 22.5in×8.25in lightweight steel wheel is tried to develop for the application of commercial vehicle. The weight aim of wheel is 31.5kg, for this lightweight wheel, the ring-expansion process crack and fatigue failure are easy to occur when thinner high strength steel (short for HSS) is applied in wheels, and it's difficult to meet the application requirements of truck makers and logistics companies for the wheels' bending fatigue performance and radial fatigue performance. In this paper, the lightweight aim is achieved and the issues are solved by development of new micro-alloying steel for rim, parameters optimization of flash butt welding(short for FBW), and wheel structure optimization by finite element method(short for FEM).

New micro-alloying steel for wheel rim

During the manufacturing of wheel rim, steel sheet is always linked to be a ring by FBW. After the process of flash butt welding, the ring is rolled and expanded to be a rim. In order to reduce the mass of wheels, we need to select thinner HSS to manufacturing the rims; however, ring-expansion process crack is easy to occur for the thinner HSS ring. For the sake of avoiding the crack, steel with a high hole expansion rate should be developed. Figure 1 shows the relationship of hole expansion rate and microstructure of steel, and considering the steel requirements for application of wheel, a special wheel steel is defined to be developed whose microstructure are Ferrite and Bainite.

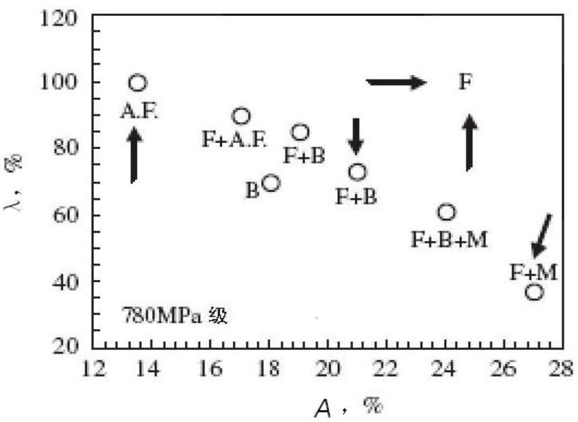


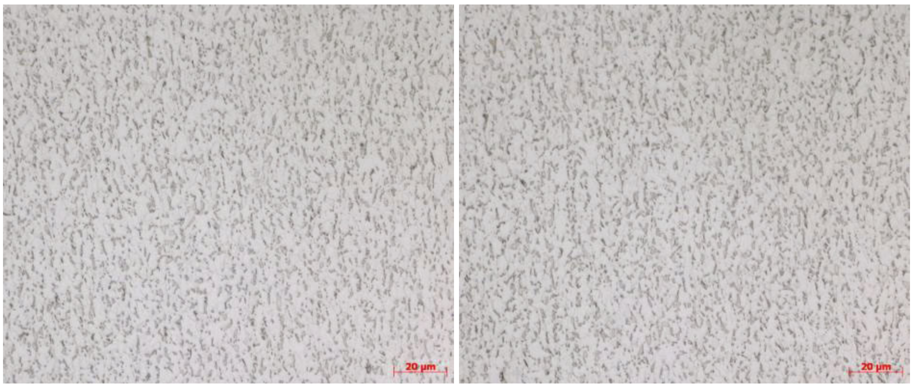
Figure 1. The relationship of hole expansion rate and microstructure of steel.

Both of Phosphorus and Silicon are used usually for alloy elements for hot roll steel sheets, P-bearing wheel steel and Si-bearing wheel steel are compared in lab, the results show that there are lots of Pearlite in microstructure of P-bearing wheel steel, and there exist Polygonal

Ferrite, Bainite and little Martensite in microstructure of Si -bearing wheel steel, and the Si can make the grains finer in the same conditions. So Si element is selected in this new steel. Niobium micro-alloying technology can improve hole expansion rate, weldability and fatigue performance of wheel steel[4]. The comparison of Nb-free wheel steel and Nb-bearing wheel steel is performed also in lab, the results shows that the grain of Nb-bearing wheel steel is finer and the microstructure is more homogeneous, and the hole expansion rate is bigger than that of Nb-free wheel steel. Finally, the chemical composition of 600MPa new rim steel is defined as in table 1.

Table 1 the chemical composition of new rim steel

C (%)	Si (%)	Mn (%)	P (%)	S (%)	Als (%)	Nb (%)	Cr (%)
0.04~0.08	0.4	1.2~1.8	≤0.015	≤0.004	0.045	0.025	0.25



(a) (b)

Figure 2 Microstructure (500×) of new rim steel: (a) 1/4 site of sample (b) center of sample

The rolling parameters of this new rim steel has been studied by thermal simulation, and the intermediate cooling temperature is defined as 680~710℃, air cooling time is 5~8 seconds, and coiling temperature is 400~450℃. The microstructure of new rim steel are shown in figure 2, the microstructure is homogeneous and finer, which is consist of 60~70% Ferrite and 20~30% Bainite. The mechanical properties of new rim steel are seen in table 2, the hole expansion rate is more than 100%, and elongation of more than 30%. Meanwhile, the non-metallic inclusions and banding microstructure are controlled and lower in this study. This new steel is used for rim, and another 400MPa (yield strength) micro-alloying wheel steel is used for rib, which is consist of Ferrite and Pearlite.

Table 2 Mechanical properties of new rim steel

Steel	Thickness, mm	YS, MPa	TS, MPa	Elongation,%	Hole expansion rate,%
RS590	4.5	538	625	36.0	104

Flash butt welding process optimization

FBW is used for the welding of wheel rim, and ring-expansion process crack is easy to occur for the thinner HSS ring using FBW, which is mentioned above. In order to solve the ring-expansion process crack issues, the effect of FBW process parameters on performance of wheels should be studied. The schematic diagram of FBW process is shown in figure 3.

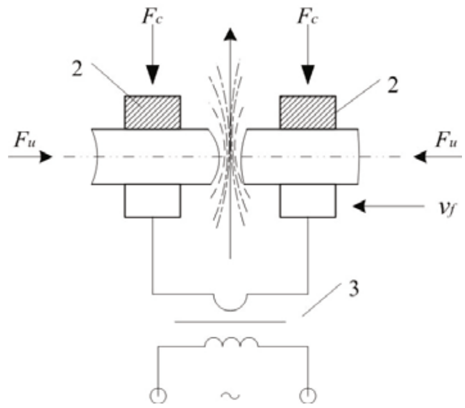


Figure 3 the schematic diagram of Flash butt welding process: 1- samples, 2-clamp electrodes, 3-resistance welding transformer, F_c-clamping force, F_u-upset force, V_f- flash velocity

The process parameters of flash butt welding process are including L_0- extension length, I_f -flashing current, δ_f–flash allowance, V_f- flash velocity, δ_u -upset allowance, V_u -upset speed, F_u-upset force, I_u-upset current, F_c-clamping force, S_t -upset current time etc., based on the results of laboratory study, 4 welding parameters including δ_f, δ_u, F_u and S_t affect the microstructure and mechanical properties of welding joints obviously. The influence principle has been attained by a depth study(not shown in this paper), and better mechanical properties can be got when S_t=0.4s, Therefore, under the condition of upsetting current time of 0.4s, the nature factors (flash allowance, upset pressure and upset allowance) were selected for the optimization of welding parameters, by means of the quadratic regression orthogonal combination design, which is shown in table 3, and the impact energy value, elongation and crack length of joints of bending experiments are used to verify the experiment results.

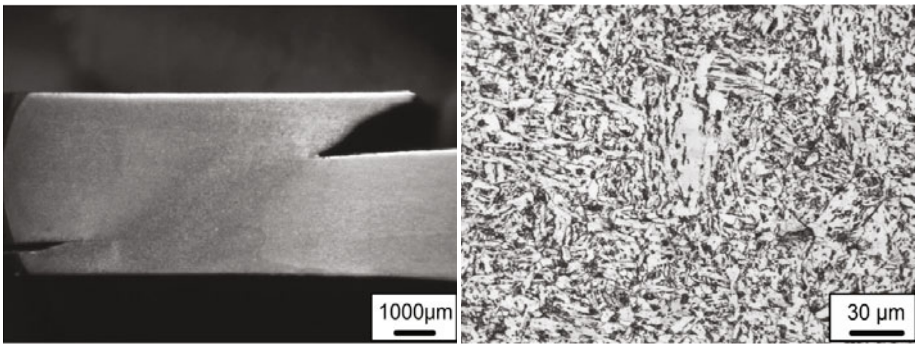
Table 3 Factors level code for the quadratic regression orthogonal combination design

xj(Zj)	Z_1(δ_f -flash allowance, mm)	Z_2(F_u-upset force, MPa)	Z_3(δ_u -upset allowance, mm)
r	16.0	7.0	7.5
1	15.0	6.5	7.0
0	12.0	5.0	5.5
-1	9.0	3.5	4.0
-r	8.0	3.0	3.5
Δj	3.0	1.5	1.5

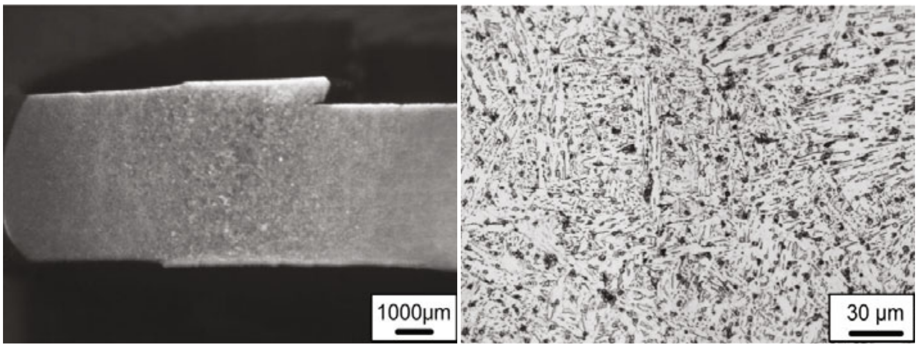
Table 4 Impact energy values and 4 optimization scheme of welding parameters

Optimization scheme	δ_f, mm	F_u, MPa	δ_u,mm	Impact energy value, J/cm^2
1	8.0	212	9.5	85.01
2	10.0	162	7.7	25.24
3	11.5	115	6.3	46.42
4	16.0	50	3.5	90.48

By the series of experiments, 4 optimization solutions of welding parameters and corresponding impact energy values are got, which are seen in table 4. And the macrostructure and microstructure of welding joints by different optimization process are shown in Figure 4.



(a) (b)



(c) (d)

Figure 4 Macrostructure and microstructure of welding joints by different optimization process: scheme 1- (a) macrostructure and (b) microstructure; scheme 4- (c) macrostructure and (d) microstructure

From figure 4(a), due to the excessive upset allowance, macrostructure deformation of welding joints is too large, which can't be used in manufacturing of wheels. And from table 4, the impact energy values of scheme 2 and scheme 3 are lower. So the result of scheme 4 is better, the bonding at the interface is well, and the impact energy values of scheme 4 is up to 90.48 J/cm^2, the tensile strength of welding joint is ≥590 MPa, and the elongation of welding joint is ≥24%. A bending experiment is carried out to check the bending property, and for scheme 4, there exist not any cracks when the welding joints are bended to 180°. Finally, two welding process were defined as followed: (1) δ_f=16 mm, δ_u=3.5 mm, F_u= 50MPa, S_t=0.4s; (2)δ_f=9 mm, δ_u=7 mm, F_u= 162MPa, S_t=0.4s.

Structure optimization by FEM

Finite element methods should be used for the structure optimization of lightweight automotive wheels, and the radial fatigue CAE simulation and bending fatigue CAE simulation are performed to check the results of lightweight structure design. Here, the model is established and modified by using Solidworks software, and then are imported into FEA software to analyze the stress. And the fatigue CAE simulations are carried out by Abaqus software. The equivalent stresses of points are attained after equivalence of symmetry cyclic by Gerber formula and Goodman formula. The weight of original rim is 14kg, with 5.25mm 400MPa wheel steel(yield strength), in this work, the new developed 600MPa new steel RS590 is used to replace the original steel to reduce the weight of rims, by the geometric structure optimization of ribs and rims, the thickness of rims is reduced to 4.5mm. The radial fatigue FEM simulation and bending fatigue FEM simulation are performed to analyze the fatigue life estimation of the dangerous points in the wheel with 4.5mm rim under radial load and bending load. The fatigue life estimation results are shown in table 5 and table 6.

Table 5 Fatigue life estimation of the dangerous points in the wheel with 4.5mm rim under radial load

Points location	Equivalent stress(Gerber), MPa	Fatigue life(Gerber), cycles	Equivalent stress(Goodman), MPa	Fatigue life(Goodman), cycles
Outsides of rims	281.1152	1.16E+06	230.0718	8.44E+06
Insides of rims	248.6017	3.91E+06	286.0869	9.75E+05
Air vents of ribs	254.347	1.28E+06	235.605	2.66E+06

Table 6 Fatigue life estimation of the dangerous points in the wheel with 4.5mm rim under bending load

Points location	Equivalent stress(Gerber), MPa	Fatigue life(Gerber), cycles	Equivalent stress(Goodman), MPa	Fatigue life(Goodman), cycles
Middle site of Air vents	248.6075	1.59E+06	248.6386	1.59E+06
Air vents of ribs	269.6645	7.28E+05	269.6299	7.28E+05
Air vents of ribs	266.5796	8.13E+05	266.4302	8.17E+05

According to simulation results, the least fatigue life of the dangerous points in the lightweight wheel under radial load is up to 1,160,000 cycles, which reaches the standard requirements; meanwhile, the fatigue life simulation results of the dangerous points in the lightweight wheel under bending load reach the standard requirements. And when the thickness of rim is reduced to 4.5mm, the total wheel is about 31.5kg.

Products and Bench testing

Based on the above study and results, by the development and application of new developed RS590 Nb-bearing steel, fatigue simulation and structural optimization design, and by overcoming the ring-expansion process crack problem of welded ring, and ultimately the thickness of rim is reduced to 4.5mm, and finally, the prototype of lightweight wheels are trial produced, which is seen in Figure 5. The weight of rim is about 11.5kg, and the wheel disk is about 20kg, so the total wheel is about 31.5kg. In order to check the fatigue performance of this wheel, a radial fatigue bench testing is performed, and the radial fatigue life of bench testing is up to 1,350,000 times cycles, which meets the application requirements of truck makers and logistics companies.

Figure 5 22.5in × 8.25in lightweight wheels

Conclusions

NMT can improve the hole expansion rate, weldability and fatigue performance of wheel steel, and based on NMT, a special wheel steel for application of rim has been developed, whose microstructure are ferrite and bainite, the content of Nb is 0.025%, and the hole expansion rate is ≥100%. This steel has high formability, high fatigue performance, and stable mechanical properties.

Flash butt welding process parameters were defined as followed: 1)δ_f=16 mm, δ_u=3.5 mm, F_u= 50MPa, S_t=0.4s;2) δ_f=9 mm, δ_u=7 mm, F_u= 162MPa, S_t=0.4s.

The weight of 22.5in×8.25in wheel is 31.5kg, which is the lightest wheel in this size. The bending fatigue performance and radial fatigue performance can meet the application requirements of truck makers and logistics companies.

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