

Research on the Regulation of Organization Performance and Heat Treatment Process of Low-Temperature Lightweight Steel

Jinxuan Ha*

School of materials science and engineering, North University of China, China

Abstract:

Ni-system low-temperature steels have been widely used in the past 50 years, and the Ni-free low-temperature steels independently developed in China still have problems such as low yield strength, poor low-temperature toughness, and anisotropic properties. In this paper, based on the compositional design idea of ultra-low carbon, high manganese, and medium aluminum, a Fe-Mn-Al system lightweight cryogenic steel with high strength and good plasticity, as well as good low-temperature toughness, was developed. The regulation technology of the organization and properties of the experimental steel was mastered through the study of the heat deformation behavior as well as the heat treatment process, and the plastic deformation mechanism and the strong toughening mechanism of the experimental steel at room temperature and at one 1960C were revealed. Compared with Fe-Mn-Al austenitic steels, Fe-Mn-Al duplex steels exhibit a series of anomalous thermal deformation characteristics. During hot deformation, both work hardening and dynamic softening occur preferentially in δ ferrite. The dynamic restitution of ferrite in the early stage of hot deformation caused a yield-like behavior on the rheological curve. An intrinsic model of transient stresses in Fe-Mn-Al duplex steels was developed. The model is empirically calculated to have a high prediction accuracy.

Keywords: Cryogenic steel, Organization evolution, Mechanical properties, σ - ferrite, Toughening mechanism

1 INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The development of materials is an important area in the evolution of civilization. As an important structural material, steel has been developed for thousands of years, and its mature application system, relatively low price, and strong production capacity make it still occupy a dominant position in the 21st century. In order to implement the Made in China 2025 program, the iron and steel industry has been increasing its investment in science and technology on the basis of energy saving and emission reduction, and impacting high-end application fields[1].

High manganese steels are the high strength steels that have been strongly developed and promoted by the automotive industry in the pre-mouth and foreseeable future[2]. However, TWIP steels have a reduced ultimate tensile strength due to their high Mn content, which causes a real confusion in steel processing and production as well as in automotive industry applications. In contrast, medium-high manganese steels have high strength and strain hardening rate while the Mn content is reduced from 25.35% to 15.20%, which greatly reduces the production difficulty. In addition, medium-high manganese steel generally has 900-1200MPa strength, excellent plastic toughness and formability to meet the requirements of high safety performance and low cost in the automotive industry[3]. As a result, medium-high manganese steels are gradually attracting the attention of the automobile manufacturing industry. The advantages of low density, high strength, high ductility and high strain hardening of medium-high manganese steel are favorable to its use in automobiles[4].

1.2 CURRENT STATUS OF LIGHTWEIGHT AND HIGH STRENGTH STEEL RESEARCH

1.2.1 FE-MN-AL-C STEELS

Mn is an austenitizing element. The addition of Mn to Fe-Al steels increases the austenite content of the steel by expanding the austenite phase region and promoting the formation of austenite at lower temperatures[5]. Furthermore, the high subcooling range associated with the expanded austenite phase region facilitates faster austenite grain growth, promotes a diffuse distribution of σ -ferrite in the matrix, and improves the plastic toughness of the steel. Fe-Mn-Al-C steels were initially designed to be only high manganese, aluminum, and carbon age-hardening steels to be used as a cost-saving alternative to expensive, high Ni-Cr steels in cold, highly corrosive environments[6]. With the development of technology, Fe-Mn-Al-C steel as a more promising steel grade, before the mouth has been able to provide more outstanding mechanical properties (yield strength: 0.4-1.0GPa, ultimate tensile strength: 0.6-2.0GPa, elongation: 30-100%. Moreover, for every 1 wt.% of Al element added to steel, the density of the material is reduced by 1.3 wt.%.

1.2.2 FE-MN-AL-C HIGH MANGANESE STEELS

Usually the Mn content in high manganese steel is more than 12%, but not higher than 32%, when the C content in the steel does not change, the increase in Mn content will make the original pearlite in the steel undergo a phase transition to martensite, which will then be transformed to austenite[7]. Fe-Mn-Al-C high manganese lightweight steel at room temperature is austenite, an increase in the content of Al will lead to the production of a large amount of ferrite and gradually increase, the weight reduction effect will also be Fe-Mn-Al-C is predominantly austenitic at room temperature, as a portion of the ferrite is present due to the addition of Al. In addition, Al increases the layer error energy of the steel, inhibits the nucleation of the α -martensite phase, and improves the stability of the austenite at low temperatures[8].

1.3 DEFORMATION MECHANISMS OF LIGHTWEIGHT HIGH-STRENGTH STEEL

1.3.1 TWIP EFFECTS

Twinning Induced Plasticity Steel is usually a new type of steel with a high Mn content, obtained after a series of processes such as rolling, annealing and quenching treatment to obtain an austenitic organization with a large number of annealed twins. Representative TWIP steels have C and Mn contents in the range of 0.5-1.2 wt.% and 12-30 wt. %, respectively. The reduction of C and Mn content may induce the TRIP mechanism. The TWIP effect is closely related to metal twinning deformation[9]. The probability of occurrence and size of the twin structure is directly influenced by the crystal structure and the energy of the laminar dislocations in the corresponding steel. After twinning deformation, some crystals move along specific twinning planes and twinning directions, and such movement is uniquely characterized by uniform shear with respect to other parts that are not deformed[10]. The orientation within the shear zone becomes a unique mirror relationship with the unsheared zone during deformation. The amount of shear in the parallel atomic layers is positively related to the distance between the faces, but not an integer multiple. The orientation of the deformed portion of the crystal changes during deformation, and some of the orientations that were previously impediments to deformation are transformed into favorable ones, which in turn promote slip. Slip and twinning occur alternately to drive the deformation process in steel and can substantially increase the plasticity. As the amount of strain continues to increase, a large number of deformation twins can be observed in the specimen with the aid of relevant testing methods, which is typical of the TWIP effect[11].

1.3.2 TRIP EFFECT

Transformation Induced Plasticity Steel is a new low carbon, low alloy steel that has been developed in recent years to meet the high strength and plasticity requirements of the automotive industry[12]. The idea of TRIP steel development is to optimize the formability of TRIP steel by both TRIP and TWIP with residual austenite. The phases present in TRIP steels are usually ferrite, residual austenite and martensite. After deformation, the phase transformation introduces strengthening and high

ductility[13]. The influence of the material organization on the mechanical properties is first considered in terms of the chemical composition, grain size, distribution and surroundings of the residual austenite; the grain size, volume fraction, chemical composition and shape of the ferrite, bainite, etc., also have a significant influence on the properties.

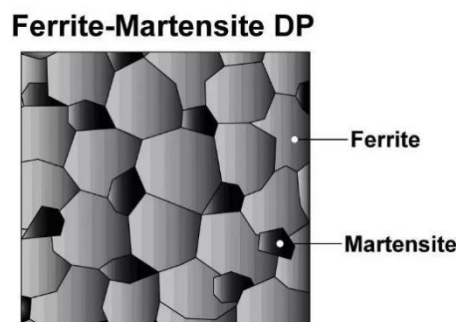


Fig. 1 Schematic diagram of TRIP steel microstructure

1.3.3 DISLOCATION SLIP MECHANISMS

Dislocation slip is the deformation mechanism present in high SFE steels[14]. This mechanism is based on different deformation mechanisms to explain the combination of strength and plasticity of Fe-Mn-Al-C system, including the theory of sex, microstrip induced plasticity theory. At present, the good combination of strength and ductility of high manganese steel is mainly due to microstrip-induced plasticity rather than shear band-induced plasticity proposed by Frommeyer and Briix. From the point of view of engineering applications, the use of microstrip-induced plasticity and the alloying of Al can significantly reduce the density of the steel and improve the mechanical properties, making it a strong candidate for advanced automotive steels. Dislocation slip includes planar slip and wave system slip[15]. It is generally believed that when the layer dislocation energy is relatively low, the two extended dislocations are easy to separate, have high three-dimensional mobility, and are difficult to cross-slip, so the dislocation slip is dominated by planar slip. When the mis-layer energy is high enough, the width of the extended dislocations shrinks under the action of shear stress, and even re-shrinks to integrate the original dislocations, and cross-slip occurs, at which time the dislocations will appear wave system slip and form a cell-like dislocation structure. The dislocation slip mechanism is currently recognized as the deformation mechanism of high-level dislocation energy residue.

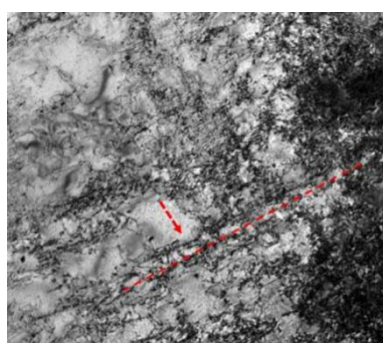


Fig. 2 Schematic structure of the dislocation slip mechanism of the TEM

2 RESEARCH CONTENT AND RESEARCH METHODOLOGY

2.1 CONTENT OF THE STUDY

By combining high manganese austenitic low-temperature steel with the composition design principle and strong toughening mechanism of Fe-Mn-Al system lightweight steel, it is proposed to develop a Fe-Mn-Al system lightweight low-temperature steel with high strength and good plasticity, and at the same time with good low-temperature toughness. Starting from the design

of alloy composition, through the study of thermal deformation behavior and heat treatment process, the essential connection between the layer misfit energy, deformation mechanism, organizational structure and mechanical properties of the experimental steel is analyzed.

The Al and C contents of the steel in this experiment were 8 wt.% and 0.9 wt.%, respectively. The amount of Mn contained in the steel was set to be 18 and 20 wt.% for both. After the preparation of the experimental steel, the four key elements were accurately determined and the results are displayed in Table 2.1. It can be seen that the actual experimental steel compositions basically conform to the design values, which favorably ensures the reliability of the experimental results. Further calculation of the density of the two experimental steels yields the density of 18Mn experimental steel:6.90g/cm³ . The density of 18Mn experimental steel:6.86g/cm³ , calculated as shown in Equation (2-1).

$$\rho_{\text{austenitic}} (\text{g/cm}^3) = 8.10 - 0.101(\text{wt. \%Al}) - 0.41(\text{wt. \%C}) - 0.0085(\text{wt. \%Mn}) \quad (2-1)$$

Table 1 Chemical composition of experimental steel (unit: wt.%)

makings	Mn	C	Al	Fe
18Mn	13.47	0.84	7.76	Bal.
20 Mn	15.91	0.85	7.86	Bal.

2.2 RESEARCH METHODOLOGY

2.2.1 THERMODYNAMIC CALCULATIONS

The TCFe7 database and TCWS user interface mode of Thereto-calc software were utilized for alloy composition design, and the effects of alloy compositions on phase composition, phase transition intervals, and densities were analyzed by calculating the equilibrium phase diagrams, property diagrams, and other physical properties to obtain the desired Fe-Mn-Al composition system. Static thermal simulation experiments were carried out on the experimental steels using a thermal expansion meter (DIL805A) to measure the phase transition points of the steels based on the volume expansion curves and to validate the calculations of the Thereto-calc software. A single-phase axisymmetric high-temperature compression test was performed on the experimental steel using a thermal simulation tester (Gleeble-3500). A thermocouple was attached to the core of the longitudinal surface of the specimen to record the temperature transition during thermal deformation in time. After the test, the specimen was cut along the axis to analyze the organization and morphology of the profiled core.

2.2.2 MICROSTRUCTURE CHARACTERIZATION

The tissue morphology and fracture n morphology of the experimental steel in different states were observed using an optical microscope (OM, Zeiss Axiovert 40); and the micro-zone elemental distribution of the microstructure was measured using a scanning electron microscope equipped with an energy spectrometer (EDS).

2.2.3 MECHANICAL PROPERTIES TESTING

According to the national standard GB/T 228.1-2010, the electronic universal tensile testing machine (CMTS 105) was used to carry out room temperature tensile test on the specimens, and the tensile rate was 5 mm/min. According to the national standard GB/T 13239-2006, the microcomputer-controlled electro-hydraulic servo universal testing machine (GNT 1000Y) was used to carry out low temperature tensile test. According to the national standard GB/T 229-2007, the specimen was impacted at room temperature and -196°C by using the ultra-low temperature impact testing machine (JBDW 300D), the impact speed was 5.24m/s, and the maximum impact work was 450 J. The specimen was impacted at room temperature and -196°C by using the oscillometric impact testing machine (NI75°C), and the test was carried out by using a high resolution rotary encoder to measure the displacement of the specimen. High-resolution rotary encoder was utilized to record the displacement one load and

displacement one energy curves; the microhardness of the experimental steel in different states was measured by using nanomechanical probe (Nanoindenter XP), with an accuracy of 400 nm for the measurement position and 0.01 nm for the displacement.

3 HEAT DISTORTION BEHAVIOR OF FE-MN-AL SYSTEM LIGHTWEIGHT LOW-TEMPERATURE STEEL

The high-temperature deformation behavior of steel in the austenitic region is the basis of controlled rolling theory, which not only can provide technical reference for the rolling process parameters and equipment capacity calibration of steel, but also has important guiding significance for improving the organization and properties of steel after hot forming. Normally, the hot deformation behavior of single-phase austenitic steel is mainly affected by the strain, strain rate and deformation temperature. However, for austenitic a ferrite duplex steels, their rheological stresses throughout the hot working process depend on the interaction of work hardening and dynamic softening of each phase organization. Therefore, the organization evolution of dual-phase steels during hot deformation also has a non-negligible influence on the rheological behavior of the steel.

3.1 STRESS-STRAIN CURVE

The true stress-strain curve of steel during thermal deformation is simultaneously affected by work-hardening, dynamic recovery and dynamic recrystallization, and can generally be divided into three stages: (a) work-hardening stage. Deformation of the material before the degree of work hardening is greater than the degree of softening caused by dynamic recovery, the rheological stress continues to rise with the increase in strain, but with the increase in the degree of dynamic softening, the rate of stress rise gradually decreases; (b) softening stage. At this time, work hardening is offset by the strong softening effect caused by dynamic recrystallization, the rheological stress reaches a peak and then begins to slowly decline; (c) steady state stage. At this time, dynamic crystallization can be fully carried out, the dynamic softening and processing hardening effects reach an equilibrium state, and the rheological stress is maintained at a stable value as the strain increases.

The true stress-strain curves of Fe-Mn-Al duplex steel at different deformation temperatures and strain rates are shown in Fig. 3. As can be seen in Fig. 3, when the strain rate is 0.01 s⁻¹ and the deformation temperature is >900°C, the rheological stress reaches the peak and then gradually decreases to a steady state stage, and the rheological curve is a typical "dynamic recrystallization type". Under other deformation conditions, the rheological stress continues to rise with the increase of strain, and the rheological curves are typical of "work-hardening type".

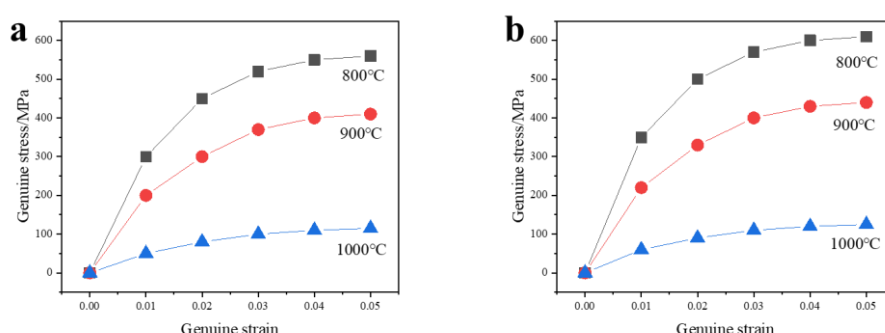


Fig. 3 True stress-one-strain curves of Fe-Mn-Al duplex steel at different temperatures and strain rates (a) 0.01 s⁻¹ (b) 0.1 s⁻¹

3.2 HEAT DISTORTION ORGANIZATION ANALYSIS

Thermodynamic calculations show that the organization of Fe-Mn-Al duplex steel consists of austenite and σ -ferrite in the temperature range of 800 °C-1000 °C. The volume fraction of austenite decreases from 79.3% to 41.2% and the volume fraction

of ferrite increases from 22.4% to 64.54% when the temperature mountain 800°C to 1000°C. The thermal deformation process of Fe-Mn-Al duplex steels actually occurs on the dual-phase matrix of austenite and σ -ferrite. The phase diagrams and property diagrams calculated based on Thermal-talc software are the results of thermodynamic equilibrium state, which cannot reflect the real organization state of Fe-Mn-Al duplex steels during the heat deformation process. In order to observe in situ the organization evolution of Fe-Mn-Al duplex steel during thermal compression, thermal simulation experiments were carried out in an ultra-high-temperature laser confocal microscope according to the process curve shown in Fig. 4.

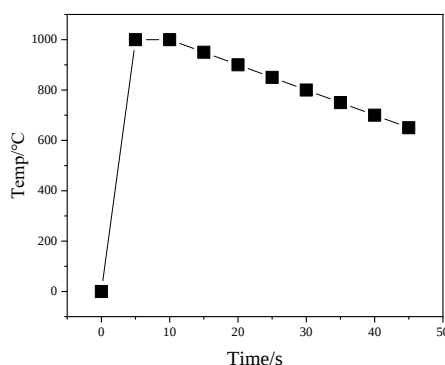


Fig. 4 CLSM thermal simulation process curve of Fe-Mn-Al duplex steel

Fig.5 shows the elemental changes of Fe-Mn-Al duplex steel. During the heating process of austenitic steel, the changes and interactions of the three elements, Fe, Mn and Al, are complex and interdependent: Fe is the matrix element, whose phase transformation and dissolution behavior determine the basic structure and properties of the steel; Mn strengthens and stabilizes the austenite phase by solid solution strengthening and enhances the strength and toughness of the steel; and Al improves the quality and high temperature properties of the steel by deoxidizing, fine grain Al improves the quality and high-temperature performance of steel through deoxidation, fine grain strengthening and oxidation resistance. The combined effect of these elements ultimately determines the microstructure and macroscopic properties of austenitic steels. The phase transformation behavior of Fe (64.54%), during the heating process, the phase transformation of Fe is mainly from α -Fe (body-centered cubic) at low temperatures to γ -Fe (face-centered cubic) at high temperatures, and to δ -Fe (body-centered cubic) at higher temperatures.

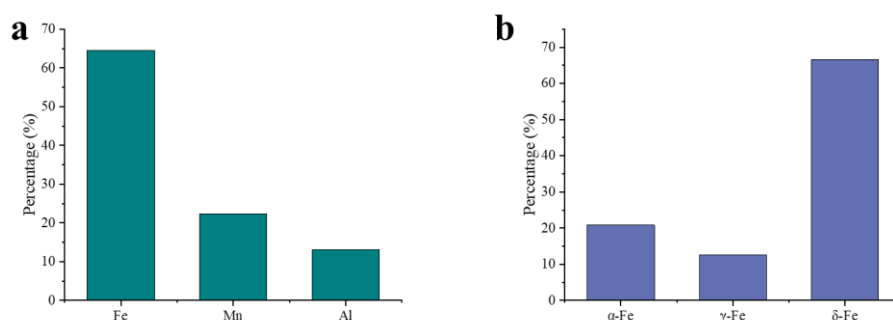


Fig. 5 Elemental changes in Fe-Mn-Al duplex steel (a) Elemental changes in Fe-Mn-Al (b) Elemental transformation of Fe

3.3 HYPERBOLIC SINE EQUATION FOR TISSUE PROPERTIES

Without considering the mechanism of thermal deformation of the material, the relationship between the characteristic stresses and the deformation parameters of steel can be expressed as Eq. (3-1) by the hyperbolic sine equation and the Zener-Hollomon parameter. Under high temperature low strain rate (low stress) conditions and low temperature high strain rate (high stress) conditions, the hyperbolic sine equation can usually be simplified to Eqs. (3-2) and (3-3).

$$Z = \dot{\epsilon} \exp(Q/RT) = A [\sinh(\alpha \sigma_p)]^n \quad (3-1)$$

$$\dot{\epsilon} \exp(Q/RT) = A' \sigma^{n'} \quad (3-2)$$

$$\dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = A'' \exp(\beta \sigma) \quad (3-3)$$

Usually, the α -value in different alloying systems is a constant value related to the alloy composition, and for common carbon and high-strength low alloy steels α -value is generally 0.015 MPa⁻¹. The addition of alloying elements such as Cr, Mo, Cu, Ni, etc. decreases the α -value. Fig. 6 shows the results of $\ln \dot{\epsilon} - \sigma$. The fitted plot of the linear relationship of the For Fe-Mn-Al duplex steels, the rheological profile is related to the inhomogeneous stress distribution between the two phases of the organization during deformation and the asynchronous dynamic softening behavior.

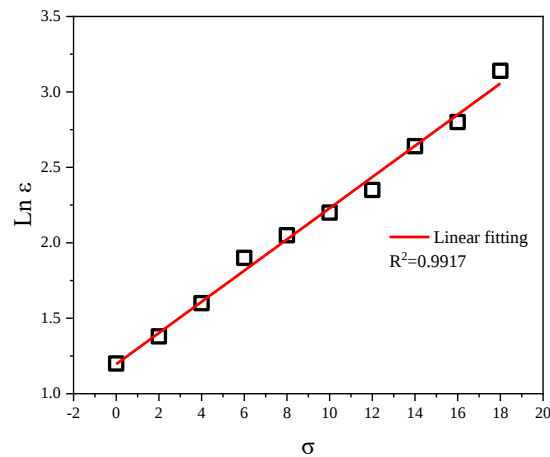


Fig.6 $\ln \dot{\epsilon} - \sigma$ The linear relationship between the

4 CONCLUSION

In this study, a lightweight low-temperature steel of Fe-Mn-Al system with high strength and low-temperature toughness was developed. Starting from the alloy composition design, the correspondence between the layer misfit energy, deformation mechanism, organizational structure and mechanical properties of the experimental steel was grasped, and the plastic deformation mechanism of the experimental steel under different loading conditions was revealed. During hot deformation, both work hardening and dynamic softening occur preferentially in σ -ferrite. σ -ferrite causes yield-like behavior on the rheological curve of Fe-Mn-Al duplex steel at the beginning of hot deformation. The continuous dynamic recrystallization behavior of σ -ferrite at deformation temperatures $>900^\circ\text{C}$ causes the rheological curve to exhibit dynamic recovery. The stress ontology model of Fe-Mn-Al duplex steel was developed by hyperbolic sine equation. Empirically, the correlation coefficients between the predicted and experimental values of this ontological model are greater than 0.9917 at both deformation temperatures and strain rates, providing a reference.

REFERENCE

- [1] An overview of the impact of aluminum alloy parts on automotive lightweighting[J]. Wei Zenglei. China Equipment Engineering,2022(06)
- [2] Automobile production and sales will increase steadily in 2021[J]. Yao Lan. Automobile, 2022(02)
- [3] Evolution of rust layers on carbon steel and weathering steel in high humidity and heat marine atmospheric corrosion[J]. Yueming Fan;Wei Liu;Shimin Li;Thee Chowwanonthapunya;Banthukul Wongpat;Yonggang Zhao;Baojun Dong;Tianyi Zhang;Xiaogang Li. Journal of Materials Science & Technology,2020(04)
- [4] Effect of Mn content on the organization and mechanical properties of lightweight Fe-10Al-0.8C-10/15Mn steel[J]. Li Junyang; Yao Liang; Jiao Siyuan; Xie Da; Shi Wen; Li Lin. Shanghai Metal,2017(04)
- [5] Effect of Al content on layer misfit energy and deformation twinning in Fe-Mn-Al-C system low-density steels[J]. ZHANG Xiaofeng;Leng Deping;ZHANG Long;HUANG Zhenyi;CHEN Guang. Journal of Materials Heat Treatment,2015(12)
- [6] Effect of solid solution treatment on the organization and properties of Fe-Mn-Al-C system low-density steel[J]. LIU Shaozun; LI Yong; WANG Chunxu; HUANG Shunche; HAN Shun; LIU Xianmin. Metal Heat Treatment,2015(09)
- [7] Effect of annealing temperature on the properties of cold-rolled Fe-Mn-Al-C low-density steel[J]. YANG Fuqiang;SONG Renbo;LI Yaping;SUN Ting;WANG Kaikun;KANG Tai. Journal of Materials Research,2015(02)
- [8] Analysis of the effect of chemical composition on the organization and properties of high manganese steel[J]. Liu Huaduo;Liu Zhe. KSA Forum (Second Half),2010(10)
- [9] Organization evolution of lightweight TWIP steels for automotive applications[J]. YAN Ling; LIU Rendong; YAN Pingyuan; ZHOU Jing; WANG Rui. Metal Heat Treatment,2010(04)
- [10] Study on the application of magnesium alloy in automobile body[J]. REN Lanzhu; DONG Ruijun; XU Hong; ZHANG Kaibang. Thermal Processing Technology,2016(10)
- [11] Hot Deformation and Dynamic Recrystallization Behavior of Austenite-Based Low-Density Fe-Mn-Al-C Steel[J]. Ya-Ping Li;Ren-Bo Song;Er-Ding Wen;Fu-Qiang Yang.Acta Metallurgica Sinica(English Letters),2016(05)
- [12] Properties and applications of third-generation high-strength automotive steels[J]. Wei Yuansheng. Metal Heat Treatment,2015(12)
- [13] Development of high performance nylon composites for automobiles[J]. Wu Fen;Du Ningning. Jiangsu Science and Technology Information,2015(07)
- [14] Strain Hardening Associated with Dislocation,Deformation Twinning,and Dynamic Strain Aging in Fe-20Mn-1.3C - (3Cu) TWIP Steels[J]. Lingyan Zhao;Dingyi Zhu;Longlong Liu;Zhenming Hu;Mingjie Wang.Acta Metallurgica Sinica(English Letters),2014(04)
- [15] Carbon fiber in automotive applications[J]. Feng Ruihua. New Material Industry,2014(08)