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Effect of Cooling Rate on the Microstructure and Mechanical Properties of C-Mn-Al-Si-Nb Hot-Rolled TRIP Steels

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Abstract. A novel thermomechanical process to manufacture hot-rolled TRIP steels has been proposed based on dynamic transformation of undercooled austenite (DTUA). The cooling rate between DTUA and isothermal bainitic treatment in the novel process is important. In the present study, effect of this cooling rate on the final microstructures and mechanical properties of a C-Mn-Al-Si-Nb TRIP steel was investigated. The results showed that the volume fractions of acicular ferrite and retained austenite were increased with the increment of cooling rate. As a consequence, higher yield strength and larger total elongation were obtained for the investigated steel with higher cooling rate. In addition, a value of 30.24 GPa% for the product of tensile strength and total elongation was acquired when the cooling rate was 25 K/s. This value has met the standard of the "Third Generation"of advanced high strength sheet steels.

1. Introduction

Transformation induced plasticity (TRIP) steels have been a promising candidate to reduce the automotive body weight due to its good combination of strength and ductility. This excellent performance is ascribed to its so-called TRIP effect occurring during deformation. The typical microstructure of TRIP steels consists of ferrite matrix and a dispersion of bainite, martensite and retained austenite. The retained austenite is metastable at room temperature and can transform into martensite induced by straining, leading to the postponement and stabilization of necking [1-3]. A novel thermomechanical process to manufacture hot-rolled TRIP steels has been proposed based on dynamic transformation of undercooled austenite (DTUA) [4-7]. The main feature of this process is that the formation of such mixed microstructure can be well controlled by the applied strain of hot deformation of the undercooled austenite. Moreover, the TRIP steels based on DTUA have a refined and homogeneous microstructure, usually with the average ferrite grain size of 1~2 μm, which is considered beneficial for the improvement of mechanical properties of TRIP steels [4-7].

In this novel process, cooling rate after dynamic transformation is an important process parameter and has an obvious influence on the final microstructure and mechanical properties of TRIP steels. In the present study, a C-Mn-Al-Si-Nb TRIP steel was selected to investigate the effect of cooling rate after dynamic transformation on the microstructure and mechanical properties of the steel.

2. Materials and experimental method

The chemical composition of the steel used in this study is shown in Table 1, where the A_3 temperature calculated by using Thermo-Calc and the A_{r3} temperature obtained by dilatometry under cooling rate of 5 K/s are also displayed, respectively. The casting blanks were first reheated for 2 hours at a temperature of 1473 K, and then hot-forged at 1423 K to 1173K followed by air-cooled to room temperature. The samples for compression were machined as the shape shown in [4]. The thermomechanical process to manufacture hot-rolled TRIP steels based on DTUA is indicated schematically in figure 1. After austenization at 1523 K for 5 min, the samples were cooled at 5 K/s to 1373 K, and deformed at 1 s^{-1} to strain of 30%. Then, the samples with fully recrystallized austenite microstructure were directly cooled at 5 K/s to 1053 K, where austenite was between A_3 and A_{r3} and considered to be undercooled. Subsequently the samples were deformed at 1 s^{-1} to strain of 50% at 1053 K, and then cooled at different rates (35, 25, 15 K/s) to 723 K where a 3 min hold was taken before quenched to room temperature. The whole processes above were performed in a Gleeble1500 hot simulation test machine.

Microstructure examinations were conducted using a LEICA DC 100 optical microscope (OM) with the etchant of LePera reagent [8]. The volume fraction and lattice parameter of retained austenite were determined by the method of X-ray diffraction [9], conducting by a MXP21VAHF diffractometer. Room temperature tensile tests were performed in a Reger 3010 tensile tester at a speed of 1.2mm/min, using the samples machined from the compressed samples with the dimension as shown in [4].

Table1. Chemical composition of the investigated steel (wt.%)

C	Si	Mn	Al	Nb	P	S	N	Fe	A_3/K	A_{r3}/K
0.2	0.5	1.49	1.04	0.038	0.02	< 0.0045	0.034	Bal.	1247	1013

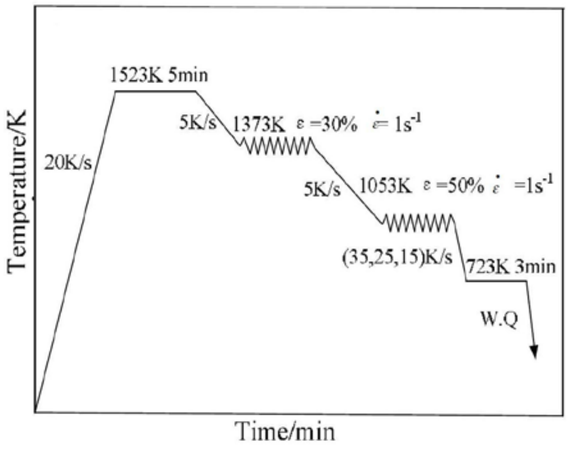

Figure 1. Schematic diagram of thermomechanical process

3. Results and discussions

Variation of microstructure as a function of cooling rate after dynamic transformation is displayed in figure 2. As can be seen, when the cooling rate was high (35 K/s), a great amount of acicular ferrite was observed in the microstructure (figure 2(a)). This kind of ferrite is considered as a bainitic structure with retained austenite and martensite layers between the ferrite laths. The acicular ferrite was also observed by Timokhina et al. in the TRIP steels with Nb addition [10]. As the cooling rate was reduced, the amount of acicular ferrite decreased, while the fraction and grain size of equiaxed ferrite increased due to the sufficient growth time at low cooling rate (as shown in figure 2(b) and (c)). The volume fraction of retained austenite also varied with the cooling rate, indicated in figure 3. Much more retained austenite could be obtained as the increment of cooling rate. This trend may be explained as follows: the austenite located between acicular ferrite was usually considered more stable owing to the geometrical restrictions of acicular ferrite laths [10]. Thus, this relatively stable austenite was more prone to be remained finally at room temperature. Because more acicular ferrite was formed at high cooling rate as discussed above, more retained austenite was expected to be acquired as well at high cooling rate. Moreover, for high cooling rate, the C and Nb atoms may not have enough time to precipitate in the form of carbides during cooling. Therefore, these solute C and Nb atoms could further increase the stability of austenite by solid solution strengthening [11-13].

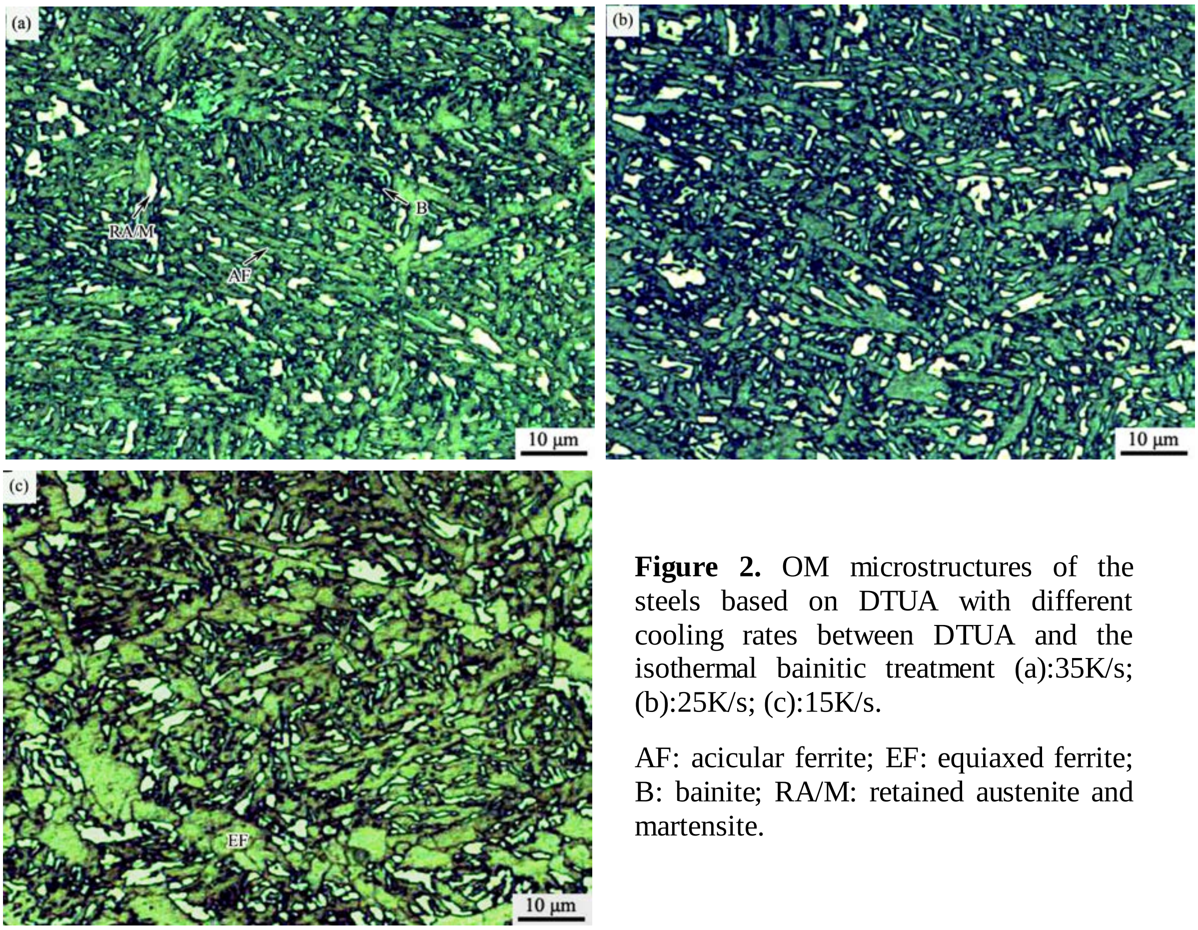

Figure 2. OM microstructures of the steels based on DTUA with different cooling rates between DTUA and the isothermal bainitic treatment (a):35K/s; (b):25K/s; (c):15K/s.

AF: acicular ferrite; EF: equiaxed ferrite; B: bainite; RA/M: retained austenite and martensite.

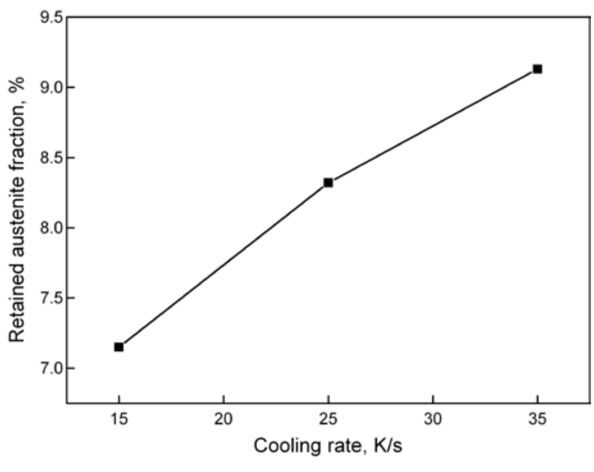

Figure 3. Variation of volume fraction of retained austenite with different cooling rates

The mechanical properties of the investigated steels were displayed in figure 4 with different cooling rates. The total elongation in figure 4(a) showed an increasing tendency with cooling rate, which was similar to the variation of retained austenite (as shown in figure 3). This consistency indicated the importance of TRIP effect on the improvement of ductility for TRIP steels. The yield strength, shown in figure4(b), was also raised with the increase of cooling rate, which may be owing to the increment of acicular ferrite and the refined microstructure at high cooling rate [10]. The tensile strength increased first and then decreased with cooling rate, leading to a maximum strength at cooling rate of 25 K/s. As a result, the product value of tensile strength and total elongation was also exhibited the maximum value at cooling rate of 25 K/s (indicated in figure 4(c)). This value is used to represent the ability of energy absorption of steels during crash and an important parameter to evaluate the comprehensive mechanical properties of TRIP steels. It is worth noting that the maximum value of product for tensile strength and total elongation obtained in the present study is 30.24 GPa%, which has met the standard of the" Third Generation" of advanced high strength sheet steels [14].

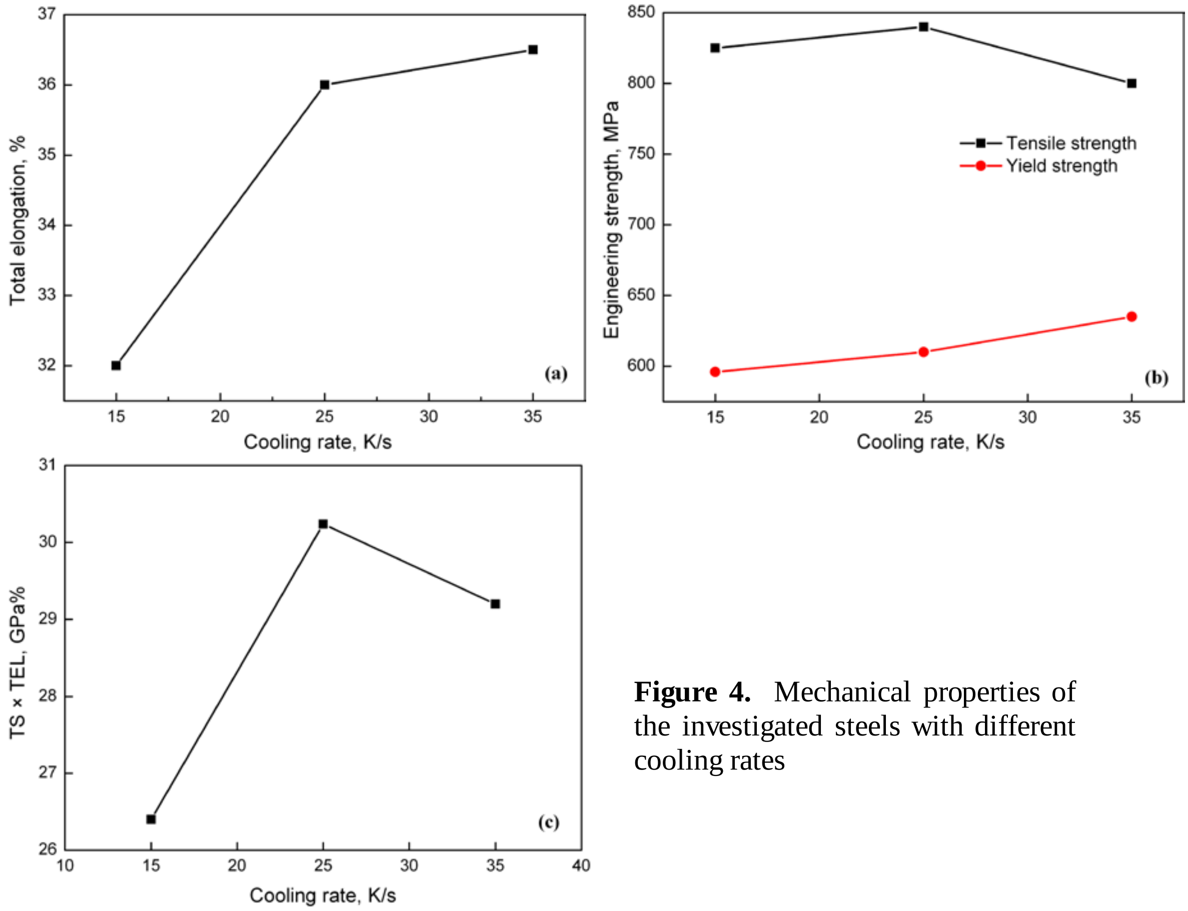

Figure 4. Mechanical properties of the investigated steels with different cooling rates

4. Summary

In the present study, the effect of cooling rate after dynamic transformation for a novel thermomechanical process to manufacture hot-rolled TRIP steels was investigated using a C-Mn-Al-Si-Nb steel. A great amount of acicular ferrite and fine grain size of microstructure were formed at high cooling rate. These microstructure features led to higher yield strength and larger volume fraction of retained austenite, as well as more excellent total elongation, at high cooling rate. As the decrease of cooling rate, the equiaxed ferrite with relatively larger grain size would be the dominant matrix phase due to enough growth time during cooling. In addition, when the cooling rate was 25 K/s, a maximum value of 30.24 GPa% for the product of tensile strength and total elongation was acquired. This value has met the standard of the " Third Generation"of advanced high strength sheet steels and indicates the superiority of this novel thermomechanical process.

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References

[1] Zackay V F, Parker E R, Fahr D and Busch R 1967 *Trans. A.S.M.* **60** 252
[2] De Meyer M, Kestens K and De Cooman B C 2001 *Mater. Sci. Tech.* **17** 1353
[3] De Cooman B C 2004 *Curr. Opin. Solid State Mater. Sci.* **8** 285
[4] Sun Z Q, Yang W Y, Qi J J and Hu A M 2002 *Mater. Sci. Eng.* A **334** 201
[5] Yang W Y, Qi J J, Sun Z Q and Yang P 2004 *Acta Metall. Sin.* **40** 135
[6] Yang W Y, Li L F, Yin Y Y, Sun Z Q and Wang X T 2010 *Mater. Sci. Forum* **654-656** 250
[7] Fu B, Yang W Y, Lu M Y, Feng Q, Li L F and Sun Z Q 2012 *Mater. Sci. Eng.* A **536** 265
[8] Lepera F S 1980 *J.Met.* **32** 38
[9] Miller R L 1964 *Trans A.S.M.* **67** 892
[10] Timokhina I B, Hodgson P D and Pereloma E V 2004 *Metall. Mater. Trans.* A **35** 2331
[11] Fu B, Yang W Y, Li L F and Sun Z Q 2013 *Acta Metall. Sin.* **49** 408
[12] Zhang Z R, Zhao Z Y, Li C Z, Jiang Z H and Li H B 2013 *Appl. Mech. Mater.* **395-396** 284
[13] Feng Q, Li L, Yang W and Sun Z 2014 *Mater. Sci. Eng.* A **603** 169
[14] Matlock D K and Speer J G 2009 *Microstruct. Texture Steels* 185