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Effects of finishing rolling temperatures and reduction on the mechanical properties of hot rolled multiphase steel*

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Abstract: Effects of finishing rolling temperatures and reduction on the mechanical properties of hot rolled multiphase steel were investigated. Thermo-mechanical control processing (TMCP) was conducted by using a laboratory hot rolling mill, in which three different kinds of finishing rolling temperatures and reduction and various austempering times were applied. The results showed that polygonal ferrite, granular bainite and larger amount of stabilized retained austenite can be obtained by controlled rolling processes, and that the strain-induced transformation to martensite from the retained austenite can occur gradually when the steel is deformed during tensile test. Mechanical properties increase with decreasing finishing rolling temperature and increasing amount of deformation. The most TRIP (transformation induced plasticity) effect, and ultimate tensile strength (*UTS*), total elongation (*TEL*) and the product of ultimate tensile strength and total elongation (*UTS*×*TEL*) are obtained at 20 min.

Key words: Hot rolling conditions, Retained austenite, Hot rolled multiphase steels, Mechanical properties
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INTRODUCTION

Growing interest in the weight reduction of cars coupled with a focus on passenger safety can be satisfied only by the development of TRIP (transformation induced plasticity) steels that can provide the highest combination of strength, formability and energy absorption (Timokhina *et al*., 2004; Bouquerel *et al*., 2006; Samek *et al*., 2006). This resulted in the development of C-Mn-Si TRIP steels (Srivastava *et al*., 2006; Sakuma *et al*., 1991; Sugimoto *et al*., 1993). Generally, the microstructure of multiphase TRIP steels containing a significant amount of stable retained austenite is generated by a standard two stage heat-treatment (Mihaly *et al*., 2004). The two stages consist of intercritical annealing and austempering at the bainite transformation temperature. The majority of the studies focused on high strength cold-rolled TRIP steel sheets, taking into account the benefit of the heat treatment (Valentin *et al*., 2004; Meyer *et al*., 1999; Sugimoto *et al*., 1992).

Multiphase TRIP steels in the cold-rolled and annealed state were extensively studied. However, it is a troublesome process for steel sheets to be heat-treated on the run-out table. These TRIP steels are not well suited for industrial practice in automotive manufacturing. Thermomechanical controlled processing (TMCP) eliminates the need for further heat treatments (Godet *et al*., 2006). Multiphased TRIP steel microstructures are obtained by direct hot rolling and subsequent austempering. 400 °C is an optimum austempering temperature, at which the sheet is coiled (Pereloma *et al*., 1999).

In the present study, austempering after hot rolling without subsequent heat treatment was conducted by means of a laboratory hot rolling mill and a salt bath. Microstructures of three different kinds of finishing rolling temperatures and reduction and various austempering times for the hot rolled multi-

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phase TRIP steel were observed in detail, and their mechanical properties were examined. Furthermore, the mechanism of TRIP effects in hot rolled multiphase TRIP steel is discussed.

EXPERIMENTAL PROCEDURE

The steel used in this study was prepared as a vacuum melted 130-kg ingot followed by hot forging to produce an 80 mm×120 mm×800 mm thick slab. The chemical composition of the multiphase steel is given in Table 1. Cylindrical specimens, 15 mm in length and 8 mm in diameter, were machined from the slab. All the experiments were conducted with computerized, closed-loop Gleeble 1500 thermomechanical test system. Specimens were electrically heated at rate of 10 °C/s to 1100 °C, held at this temperature for 180 s and cooled down to different deformation temperatures of 870, 900, 930, 960, 990, and 1020 °C, at 5 °C/s, respectively. Double-pass compression tests were employed with compressive strain values of 30% and 40% respectively at strain rate of 1 °C/s, and interpass times were set at 3, 5, 10, 50, 100, 500 and 1000 s, respectively. A schematic illustration of the double-pass compression test is shown in Fig.1. The stress-strain curves were recorded, and the fractions of recrystallized austenite were calculated by the back extrapolation method (Laasraoui and Jonas, 1991). The T_{nr} which denotes the austenite nonrecrystallization temperature was evaluated through softening fraction-interpass time curves.

Continuous cooling transformation (CCT) diagram was measured by the same thermomechanical simulator shown in Fig.2.

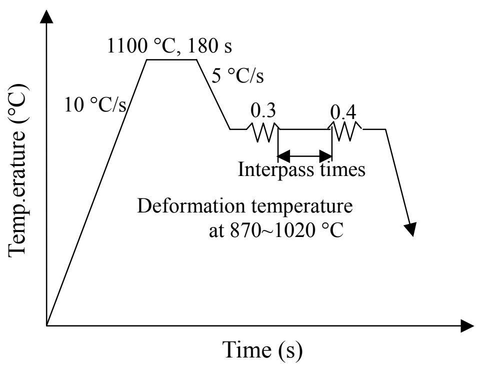


Fig.1 Schematic illustration of the double-pass compression test

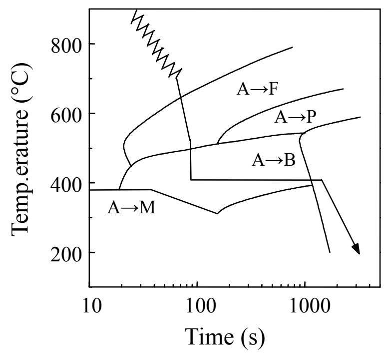


Fig.2 Continuous cooling transformation curve after finishing deformation at 850 °C and a typical processing path during TMCP in a laboratory hot rolling mill

Table 1 Chemical composition of the test multiphase steel (wt.%) (T_{nr} is 910 °C)

C	Si	Mn	S	P	Al
0.233	1.365	1.540	0.004	0.007	0.080

The slab first was hot-rolled down to 20 mm by a ∅450 hot rolling mill, and then machined to form the 17 mm×20 mm×650 mm plates, and finally hot-rolled down to 2.0 mm in thickness by a ∅180 hot rolling mill. The processing schedule is shown in Fig.3. After austenitizing at 1020 °C for 300 s, the specimens were deformed to Pass (1) and Pass (2) compressive strain at cooling rate (5 °C/s) in the austenite recrystallization region, and then deformed to Pass (3) and Pass (4) at cooling rate (15 °C/s) in the low-temperature no-recrystallization region or the two-phase region (austenite plus ferrite), respectively. The slabs were controlled rolled interval during four pass deformations in hot rolling to attain three different finishing rolling temperatures of 700, 750, 800 °C, in which temperature three different kinds of finishing rolling reductions (30% *R*1, 40% *R*2 and 50% *R*3) were applied. Specimens of 20 mm in thickness were hot-rolled down to 2.0, 2.4 and 2.8 mm, respectively for finishing rolling reductions of *R*3, *R*2 and *R*1. After finishing rolling, specimens were cooled at 10 °C/s to the accelerated-cooling start temperature of 520~540 °C in order to obtain an amount of polygonal ferrite. This was followed by a salt bath quench where the specimen was held isothermally for 20 min at 400 °C, to transform the austenite to bainite. To clarify the effect of the isothermal holding time, the duration at the salt bath was set 2, 5, 10, 15, 20, 30, 60 and 120 min, respectively, with finishing rolling temperature of these specimens ($R3$) being 700 °C. The specimen was then air cooled to room temperature.

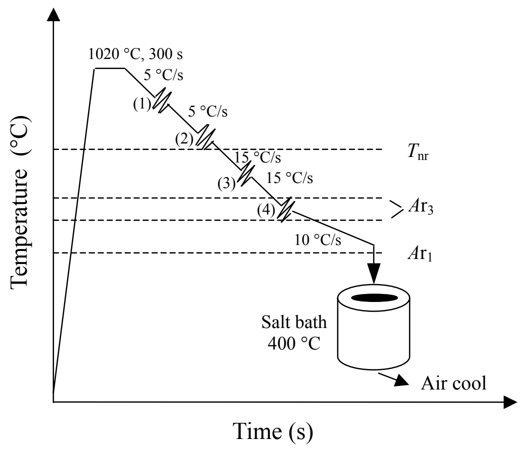


Fig.3 Rolling schedule for the laboratory rolling

Tensile tests were carried out by using an INSTRON 4206 machine in order to study the mechanical properties of the present steel. Strength-ductility balance ($UTS \times TEL$) was represented by the product of ultimate tensile strength (UTS) and total elongation (TEL). Transverse sections of the specimens before and after tensile test for light optical microscopy (LOM) were polished and etched with 4% nital. These specimens for LOM were also colour etched using the LePera method (Girault *et al.*, 1998). The bainite fractions were assessed with image analysis software of Leica on colour etched cross sections of the specimens.

The microstructure was investigated further by scanning electron microscopy (SEM) using an SSX-550 microscope. At the same time, more detailed microstructural characterization was conducted by transmission electron microscopy (TEM) using an EM 400T microscope.

X-ray diffraction analysis was carried out using a D/max 2400 diffractometer equipped with monochromator and Cu K_α radiation to determine the volume fraction of retained austenite (V_γ) with the modified Miller's method (Ryu and Speer, 2002).

$$V_\gamma=1.4I_\gamma/(I_\alpha+1.4I_\gamma), \quad (1)$$

where I_α and I_γ are the integrated intensities of the $(200)_\alpha$ and $(211)_\alpha$ peaks and the $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ peaks, respectively.

RESULTS

Mechanical properties

The effects of finishing rolling temperature and reduction on the mechanical properties of the multiphase TRIP steels are remarkable. The relation between mechanical properties and finishing rolling temperature of the specimens is shown in Fig.4.

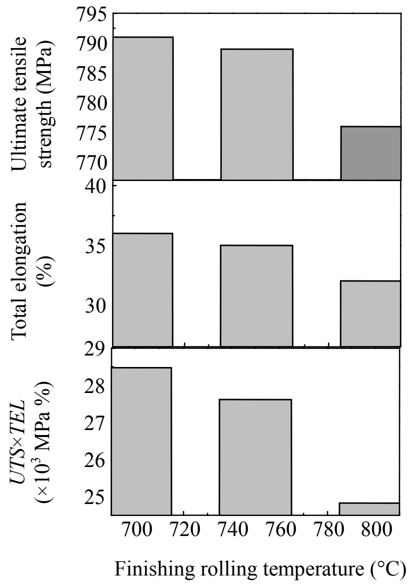


Fig.4 Mechanical properties of the specimens dependence on finishing rolling temperature

In Fig.4, mechanical properties of the multiphase TRIP steels are very high in most cases. Their mechanical properties increased considerably with decreasing finishing rolling temperature. When they were deformed to 50% at 700 °C, UTS of the specimen reached maximum values (791 MPa), and its TEL reached maximum values (36%).

Mechanical properties of the specimens dependence on finishing deformation at 700 °C are shown in Fig.5. In Fig.5, mechanical properties of the specimens increase obviously with increasing amount of deformation at 700 °C. UTS, TEL and $UTS \times TEL$ of the specimens ($R3$) for 50% reduction at 700 °C reach maximum values.

Microstructure

The micrographs after different finishing rolling temperature with $R1$, $R2$ and $R3$ consist of polygonal ferrite, granular bainite and retained austenite. The ferrite grain size decreased and the amount of granular bainite increased somewhat with decreasing finishing rolling temperature and increasing of finishing rolling reduction. The metallographic result of the specimen at the optimum procedure is presented in Fig.6.

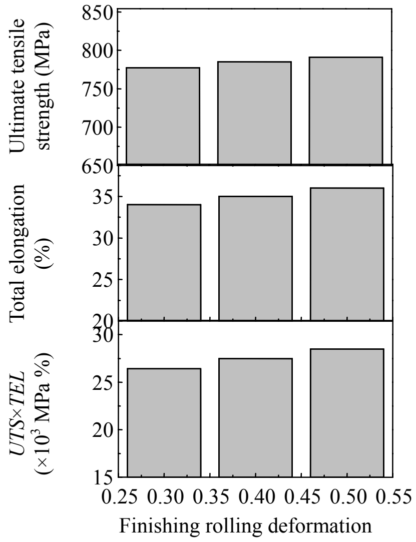


Fig.5 Mechanical properties of the specimens dependence on finishing rolling deformation at 700 °C

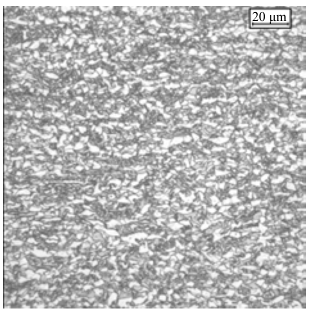


Fig.6 Optical micrograph of the specimen at finish rolling temperature of 700 °C for 50% reduction (*R*3)

Influence of austempering

The isothermal holding time during austempering affects the microstructure and mechanical properties of multiphase TRIP steels. Fig.7 shows the relationship of *UTS*, *TEL* and *UTS*×*TEL* with austempering time for the specimens finishing deformation at 700 °C.

In Fig.7, mechanical properties were affected by austempering after hot rolling. Total elongation increases with increase of isothermal holding time, and reaches the peak values at 20 min. At the peak time, the maximum value (36%) of *TEL* is obtained, and at same time, *UTS* and *UTS*×*TEL* reach quite high value (791 MPa and 28476 MPa %, respectively) for multiphase TRIP steels. *TEL* of the specimens minimized when it was held in a salt bath for 2 min after finishing rolling, although it still reached 26%. *TEL* decreases in spite of *UTS* keeping increasing when isothermal holding time increases up to 120 min. *TEL* of the specimen still reached high value (29%) at too long holding duration.

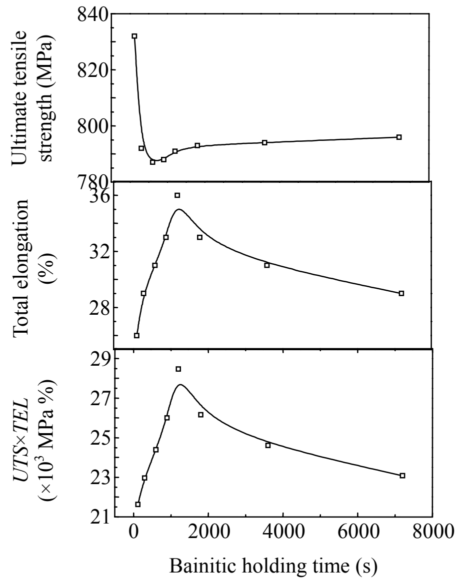
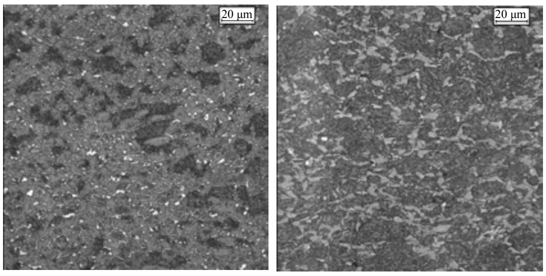


Fig.7 Mechanical properties of the specimens at various isothermal holding times

When the present steels were austempered after hot rolling, the microstructures contained a lot of retained austenite, which can be identified in a color etched LOM micrographs. With this etchant the various phases appear as different colours under the microscope. Microstructures variations of the specimens at finishing deformation at 700 °C holding duration for 20 min and 120 min, are shown in Fig.8.

In Fig.8, ferrite appears grey, bainite appears black, martensite and retained austenite appear white. White martensite-austenite islands are obvious when the specimens are held for 20 min (Fig.8a). The amount of granular bainite increases sharply with increasing holding time and reaches maximum values for the specimens at isothermal holding time of 120 min (Fig.8b).

Increasing the holding duration from 2 to 120 min for the steels resulted in microstructure variation. Cementite appeared as coarse blocky islands within the bainitic ferrite matrix of the specimen held for 120 min after finish rolled at 700 °C, as shown in Fig.9. The presence of retained austenite and martensite in multiphase TRIP steels were also confirmed by TEM studies. The particles of retained austenite are quite fine, and martensite was discovered to accompany martensite-austenite islands increasing obviously on the TEM micrograph for the same specimens after tensile test.



(a) (b)

Fig.8 Color-etched micrographs of steels for different holding times. (a) 20 min; (b) 120 min

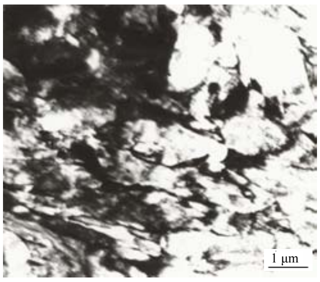
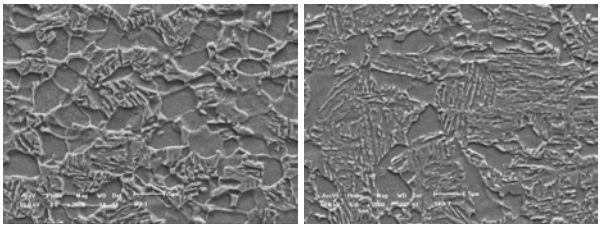


Fig.9 TEM micrographs showing the formation of cementite

All constituents (polygonal ferrite, granular bainite and retained austenite) can clearly be seen by SEM. Fig.10 shows typical SEM micrographs of steel ($R3$) after finish rolled at 700 °C holding duration for 20 min and 120 min respectively. Ferrite (black), retained austenite (grey), martensite-austenite islands (white) and granular bainite can be seen in Fig.10. Granular bainite contains some islands that are distributed in the ferrite matrix, and usually comprised of retained austenite and/or martensite/austenite constituents. Larger amount of austenite (grey) can be retained by the specimens before tensile test (M. Fig.10a), and martensite-austenite islands (white) increased obviously after tensile test (Fig.10b).

Retained austenite volume fraction before and after tensile test for the same specimens at 20 min was further determined by the X-ray diffraction patterns, as shown in Fig.11. After tensile test, the amount of retained austenite at necking of the specimen decreases from 22% to 15%.



(a) (b)

Fig.10 SEM micrographs of the specimens. (a) Before tensile testing; (b) After tensile testing

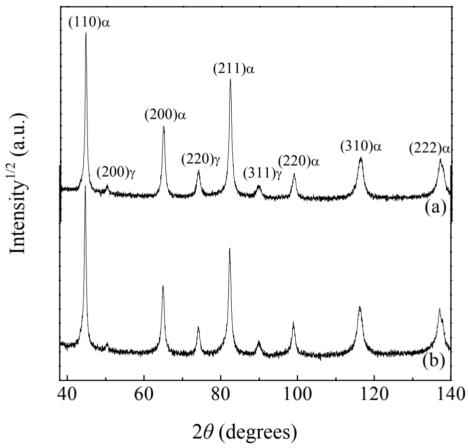


Fig.11 X-ray diffraction patterns of steel (R3)
(a) Before tensile test; (b) After tensile test

Retained austenite volume fraction was further determined by the X-ray diffraction patterns. They are 22% and 18% for the steels finish rolled at 700 °C and isothermal holding 20 min and 120 min respectively before tensile test. The amount of retained austenite at necking of the specimen decreases after tensile test and they are only 15% and 14% when holding for 20 min and 120 min respectively.

DISCUSSION

The thermo-mechanical processing schedule can affect the retained-austenite characteristics for hot rolled multiphase steel. The specimens were subjected to four pass deformation in hot rolling (Fig.3), latter two pass deforming at temperatures below the austenite no-recrystallization temperature (Pass (3) and Pass (4) compressive strain) resulted in the pancaking of austenite, and this altered the substructure of the austenite prior to transformation (Yue *et al*., 1997). Severe finishing rolling reduction (50%) in the nonrecrystallized austenite region reduced the austenite grain thickness and ferrite grain size prior to transformation. After hot rolling, the prior austenite grains are fragmented by deformation bands. As a result, the small particles of austenite tend to be stable (Figs.8 and 10). It was reported that the retained austenite crystals present after hot rolling in the nonrecrystallized regions contained a high dislocation density inside the grains (Timokhina and Hodgson, 2003). All finishing temperatures (700, 750 and 800 °C) were actually in fully austenitic region, in spite of the lower finishing temperature, and higher dislocation density in the austenite grains. Therefore, retained austenite is more stable in specimens finishing deformation at 700 °C. Smaller austenite size helps the retention of austenite instead of martensite formation (Goel *et al*., 1987), and a higher dislocation density of retained austenite contributes to an increase in the mechanical stability of the retained austenite (Timokhina and Hodgson, 2003). On the other hand, the deformation temperature also has an influence on the ferrite nucleation site, and the decrease of deformation temperature will enhance intragranular nucleation. High strength was obtained when the specimen finished deformation at 700 °C (Fig.4), which is likely related to refining of the ferrite grain.

The specimens were cooled at 10 °C/s to temperature of 520 to 540 °C after three different kinds of finishing rolling temperatures, it is just in the two-phase region (austenite plus ferrite) according to the CCT diagram of the steel (Fig.2). Austenite transformed to ferrite in this temperature range, and proeutectoid ferrite appeared. Therefore, a good deal of polygonal ferrite formed (Figs.6, 8, 10).

The present steel, containing alloying elements of Si (Table 1), was austempered after hot rolling. Si dissolves in ferrite as it is a ferrite-formation element when polygonal ferrite forms, which raises the chemical potential of carbon in ferrite and enhances carbon diffusion into austenite. Hence, the ferrite matrix is cleaned, and the carbon in untransformed austenite becomes enriched. Austenite can be transformed to bainitic ferrite when the steel was held at bainite transformation range. The concentration of carbon in the remaining austenitic core is very high. While C is enriched in the remaining austenite stabilizes this austenite, because the stability of retained austenite corresponds to the concentration of carbon. Finally, larger amount of stabilized austenite is retained in multiphase TRIP steels (Figs.6, 8, 10, 11).

Austenite transformed to bainite after the steel was quenched in a salt bath held at 400 °C. The mechanical properties variations of the specimens are related to the rate of bainite reaction. When the holding time increased from 2 to 20 min, the austenite either transformed to bainite or remained untransformed during subsequent air cooling. The carbon concentration in the remaining austenite increased with bainite growing due to the carbon rejection from bainitic ferrite. This, in turn, increased the stability of the remaining austenite. The longer time resulted in more complete bainite reaction that leaves less volume of remaining austenite. And that, cementite precipitation occurred with increasing holding duration (i.e., beyond 120 min in the present case) because the carbon concentration of the remaining austenite exceeded a certain value (Hanzaki *et al*., 1995), this resulted in a decrease of carbon concentration in the remaining austenite. *TEL* decreases relatively and *UTS* does not when held at 120 min (Fig.7). It could be possible that some amount of martensite is formed at final cooling because remaining austenite is no longer stable enough due to some cementite formation at 120 min. Therefore, it is likely related to the presence of martensite in the microstructure that *UTS* keeps growing up to 120 min.

The maximum TRIP effect occurs at 20 min. However, this result is not consistent with industrial processing because 20 min is not applicable for real industrial conditions of cooling time of coiled steels. Therefore, it is suggested that longer cooling (quasi-isothermal condition) temperature of austempering should be adjusted under actual condition.

TMCP is the most important stabilizing factor of the metastable retained austenite against deformation induced transformation to martensite. Small particles, high dislocation density and high content of C of the retained austenite result in the greatly increased stability of residual austenite in the present steels. As a result, the strain-induced transformation to martensite from the retained austenite occurs gradually when the steel is deformed during tensile test (Fig.11).

In this study, small particles, high dislocation density and high content of C of the retained austenite result in the greatly increased stability of residual austenite, causing the M_S temperature to be below room temperature. The stability of retained austenite is a crucial aspect in providing the TRIP effect. Hot rolling conditions affect the mechanical properties of the present hot rolled multiphase steel. Hot deformation was severe for 50% reduction (R3) at 700 °C. Severe deformation affects the distribution of retained austenite in the microstructure, which influences the retained austenite stability. The stability of the retained austenite influences the mechanically induced transformation of retained austenite under straining at room temperature, and excellent mechanical properties were obtained when the strain-induced transformation of austenite develops gradually during plastic straining (Figs.4, 5, 7).

CONCLUSION

(1) Finishing rolling temperatures and reduction affect the microstructure of multiphase TRIP steels, and polygonal ferrite, granular bainite and larger amount of stabilized retained austenite can be obtained. The stability of the retained austenite influences the mechanically induced transformation of retained austenite under straining at room temperature.

(2) Mechanical properties increase with decreasing finishing rolling temperature and increasing the amount of deformation for the stabilization of retained austenite due to refined particle, higher dislocation density and C enrichment, and the strain-induced transformation to martensite from the retained austenite occurs gradually when the steel is deformed during tensile test.

(3) The maximum values of *UTS*, *TEL* and *UTS*×*TEL* and the maximum TRIP effect are obtained at 20 min due to the presence of stable retained austenite.

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