Dependency of Deformation Behavior of Retained Austenite in TRIP Steels on Microstructural and Chemical Homogeneity

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Abstract The room-temperature stability of the retained austenite against strain-induced martensitic transformation, its deformation behavior, the response to the bainitic isothermal treatment, the appearance of yield point elongation and other peculiarities of plastic flow, and the mechanical properties of transformation-induced plasticity (TRIP) steel were tailored based on the chemical homogeneity and the relative distribution of the retained austenite, bainite, and ferrite in the microstructure. The presence of ferritic-pearlitic banded structure in the initial microstructure resulted in an inhomogeneous TRIP microstructure, in which the retained austenite and bainite were confined to some bands and it was found to be responsible for the resultant inferior mechanical properties. The appearance of discontinuous yielding for the chemically inhomogeneous material was related to the martensitic transformation of unstable retained austenite at the initial stage of tensile deformation. These results are essential for better understanding of the behavior of advanced high-strength steels and their applications.

KEY WORDS: Thermo-mechanical treatment (TMT); Transformation-induced plasticity (TRIP) steel; Mechanical properties; Microstructure

1 Introduction

Transformation-induced plasticity (TRIP) steels, produced by intercritical annealing (IA) followed by bainitic isothermal transformation (BIT), have a multiphase microstructure consisting of ferritic matrix, bainite, retained austenite, and probably martensite [1, 2]. During deformation, the metastable retained austenite will transform to martensite (known as TRIP effect), which increases the local strain hardening rate and delays necking [3]. While the distribution of retained austenite in the microstructure (microstructural

homogeneity) and its chemical homogeneity regarding the substitutional alloying elements seem to be important factors in the response of TRIP steels [4, 5], but these aspects have not been systematically studied yet. The aim of this work is to investigate the effects of microstructural and chemical homogeneity on TRIP effect and the response of TRIP steels during the BIT treatment.

2 Experimental

The 0.2C–1.6Mn–0.7Si–0.9Al (in wt%) TRIP steel was prepared by vacuum induction melting (VIM). The homogenization treatment was performed by soaking at 1350 °C for 300 min. The hot rolling operations were conducted on both as-cast and homogenized specimens at nominal temperature of 1150 °C up to 70% reduction followed by air/furnace cooling. Afterward, cold rolling was used to achieve a thickness of 1 mm. The A_{r1} and A_{r3}

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temperatures were determined by dilatometry as 713 and 890 °C, respectively. The IA treatment was conducted at 790 °C for 6 min, in which the fraction ratios of ferrite to austenite based on the lever rule are estimated to be 0.65:0.35. The BIT treatments were carried out at 400, 430, and 460 °C for 6 min to produce the TRIP microstructures with different amount of retained austenite.

Optical microscopy (using 2% Nital and LePera's reagents) and SEM/EDS analysis along the thickness direction (by consideration of relative weigh percent of Mn with respect to combined weigh percent of Mn, Al, and Si) were used for microstructural investigations and elemental analysis, respectively. A Rigaku X-ray diffractometer with CuK_α radiation was used to find the lattice parameters to calculate the carbon concentration of retained austenite by the equation

$$a_\gamma = 0.35467 + 4.67 \times 10^{-7} C,$$

where C is the content of carbon, in wt% [6].

The mechanical properties along the rolling direction were investigated by tensile specimens according to JIS-Z-2201 standard with the gage length of 8 mm. For calculating the incremental work-hardening exponents (n) for investigating TRIP effect, the Hollomon equation ($\sigma = k\varepsilon^n$) was expressed as $\ln \sigma = \ln k + n \ln \varepsilon$, and at a given strain, the slope of the plot of $\ln \sigma$ versus $\ln \varepsilon$ was determined. Simply, it can be expressed as $n = d \ln \sigma / d \ln \varepsilon$.

3 Results and Discussion

3.1 Chemically and Microstructurally Homogeneous Steel

The 70% hot-rolled and subsequently furnace-cooled microstructure from the homogenized state with the manifestation of the achieved chemical homogeneity (for Mn) is shown in Fig. 1a. Cold-rolled microstructure, as the feedstock for TRIP heat treatment, has a highly sandwiched ferrite between pearlite areas. As it can be seen in Fig. 1b, by increasing the BIT temperature during TRIP heat treatment, the amount of retained austenite and the size of austenite islands are increased. Despite this fact, the TRIP microstructures shown in Fig. 1b also reveal that the retained austenite has distributed nearly homogeneously. However, by increasing the BIT temperature, the amount of carbon in the retained austenite decreases and it is anticipated that its stability is decreased. This can be responsible for the higher initial work-hardening rate in the case of the BIT temperature of 460 °C (Fig. 1c).

As it can be seen in Fig. 1c, for the BIT temperature of 460 °C, the work-hardening rate curve exhibits first a

minimum and then a subsequent maximum before its final steep decline. The appearance of the maxima shows the prevalence of TRIP effect in the early stages of deformation process, which reveals that the stability of retained austenite was low. The subsequent steep decline of work-hardening rate for this specimen is similar to those of ordinary metals and confirms that most of the retained austenite has been consumed at low strains and resulted in inferior uniform elongation (based on the Considère's criterion: $d\sigma/d\varepsilon = \sigma$). In the case of lower BIT temperatures, while a distinct peak corresponding to TRIP effect is not seen, the higher stability of austenite governs its availability up to higher strains and more profitable TRIP effect with improved formability.

Figure 1d shows the corresponding incremental work-hardening exponents versus true strain. It can be seen that by increasing the BIT temperature, the level of n increases and its maxima shifts to lower strains. These results are in accordance with lowering the stability of retained austenite by increasing the BIT temperature.

3.2 Chemically Inhomogeneous but Microstructurally Homogeneous Steel

The 70% hot-rolled and subsequently air-cooled microstructure from the as-cast state is shown in Fig. 2a. The EDS spectrum shows that the distribution of Mn is highly inhomogeneous, which can be ascribed to the segregation of alloying elements during dendritic solidification as it is evident from the as-cast microstructure, as shown in Fig. 2a. The cold-rolled microstructure as the feedstock for the production of TRIP steel is very complex due to the initial hot-rolled one. It can be seen in Fig. 2b that the retained austenite has distributed nearly homogeneously in the TRIP microstructures and analogous to Fig. 1b; by increasing the BIT temperature, the amount of retained austenite and the size of austenite islands increases. The XRD analyses were performed on these samples, and the average weight percent of carbon in the retained austenite for the BIT temperatures of 400, 430, and 460 °C was determined as 1.61, 1.41, and 1.29, respectively. These results are in accordance with the observed increase in the amount of retained austenite. The tensile curves of the BIT temperatures of 400 and 430 °C show, respectively, unusual high yield strength and discontinuous yielding. These peculiarities are connected to the chemical inhomogeneity as elaborated in the following.

The M_s temperature of completely austenitic microstructure can be calculated as 430 °C by equation of the form $M_s = 539 - 423C - 30.4\text{Mn} - 7.5\text{Si} + 30\text{Al}$ [5]. Based on the lever rule, by intercritical annealing at 790 °C, a microstructure consisting of 35% austenite and 65% ferrite is expected to be achieved and the level of

Fig. 1 Chemically and microstructurally homogeneous steel: **a** EDS spectrum and hot-/cold-rolled microstructures; **b** microstructures and tensile curves for different BIT temperatures; **c** corresponding work-hardening rate analysis; **d** instantaneous work-hardening exponents versus true strain

carbon in the austenite phase becomes as high as 0.5 wt%. As a result, the M_s temperature of the austenite phase will be around 300 °C, which is below the BIT temperature of 400 °C. However, the high yield strength for the BIT temperature of 400 °C can be ascribed to the formation of some martensite during BIT due to the presence of some prior unstable austenite areas with higher M_s temperature. The latter is a result of rapid cooling, which disturbs the distribution of carbon during preprocessing and subsequent formation of austenite during intercritical annealing in both lean and rich regions from alloying elements [5].

In the case of the BIT temperatures of 430 °C, during BIT martensite does not form and the austenite present in both lean and rich regions from alloying elements enriches

with carbon due to bainitic transformation, but the amount of carbon in the final retained austenite somehow differs in different parts of the microstructure. Normally, the discontinuous yielding behavior in low carbon steels arises from the interaction between dislocations and interstitial solute atom atmospheres [7], but the mechanism of discontinuous yielding in TRIP steels has not been discovered yet [8] and it has been reported that it is supposedly related to the martensitic transformation of unstable retained austenite at the initial stage of tensile deformation [9]. This seems to be the case for the appearance of discontinuous yielding in the case of the BIT temperatures of 430 °C.

Figure 2c shows the corresponding true stress/work-hardening rate versus true strain curves. It can be seen that

Fig. 2 Chemically inhomogeneous and microstructurally homogenous steel: **a** EDS spectrum, as-cast microstructure, and hot/cold-rolled microstructures; **b** microstructures and tensile curves for different BIT temperatures; **c** corresponding work-hardening rate analysis; **d** instantaneous work-hardening exponents versus true strain

the general trend similar to that of Fig. 1c exists showing that the TRIP effect enhances in the initial stage of deformation with increasing the amount of austenite, which is the case of the BIT temperature of 460 $^{\circ}\text{C}$. However, the occurrence of discontinuous yielding in the case of the BIT temperature of 430 $^{\circ}\text{C}$ resulted in a very sharp decrease in the work-hardening rate at the initial stages of deformation. The austenite yields during the yield point elongation and stacking faults are generated. The intersections of these stacking faults serve as effective nucleation sites for martensite embryos [10]. So, the strain-induced martensitic transformation occurs in the majority of the austenite phase right after the completion of the yield point elongation, which results in the sudden increase in the work-hardening rate to high values and very sharp TRIP effect. Since the

amount of the austenite after this sudden transformation is low, the TRIP effect falls rapidly. These results are confirmed by the instantaneous n values as shown in Fig. 2d. Analogous to Fig. 1d, by increasing the BIT temperature, the level of n increases and its maxima shifts to lower strains, but the BIT temperature of 430 $^{\circ}\text{C}$ does not follow this trend, which can be easily explained by the occurrence of discontinuous yielding as described before.

3.3 Chemically and Microstructurally Inhomogeneous Steel

The 70% hot-rolled and subsequently furnace-cooled microstructure from the as-cast state is shown in Fig. 3a, which shows a ferritic-pearlitic banded structure. Banding

Fig. 3 Chemically and microstructurally inhomogeneous steel: **a** EDS spectrum and hot-/cold-rolled microstructures; **b** microstructures and tensile curves for different BIT temperatures; **c** corresponding work-hardening rate analysis; **d** instantaneous work-hardening exponents versus true strain

is a result of the chemical segregation of some alloying elements (e.g., Mn) during solidification that are rejected from the first formed delta ferrite dendrites [11]. Subsequent hot rolling of the steel in the austenitic condition leads to pancaked high solute regions with different degrees of activity of carbon. During austenite decomposition, alloying elements raise or lower the A_{r3} temperature. If this temperature is lowered by the solute, then proeutectoid ferrite nucleates first in the solute lean regions. Conversely, if the A_{r3} temperature is raised by the solute, then proeutectoid ferrite forms preferentially in the solute-rich regions. The result is the development of banded structure, as shown in Fig. 3a. The EDS spectrum shows that the distribution of Mn is highly inhomogeneous. The

banded structure preserved in the cold-rolled microstructure but with reduced layer spacing. This is the third feedstock for the production of TRIP steel.

Figure 3b shows the microstructures and engineering tensile curves after TRIP heat treatments. It can be easily seen that the microstructure is inhomogeneous, and the retained austenite and bainite are confined to some bands which were pearlitic areas in the cold-rolled microstructure of Fig. 3a. Analogous to previous cases, the initial work-hardening rate in the case of the BIT temperature of 460 $^{\circ}\text{C}$ is higher.

Figure 3c shows the corresponding true stress/work-hardening rate versus true strain curves. It can be seen that for the BIT temperature of 460 $^{\circ}\text{C}$, the work-hardening rate

curve exhibits a rather poor-defined peak at low strains when it compares with the case of the BIT temperature of 460 °C in Fig. 2c. This can be partly attributed to the higher stability of austenite due to both its higher carbon content and the presence of high amount of bainite around it in the bands. During furnace cooling, the carbon atoms partition toward high-Mn locations, which results to the formation of pearlite in the initial microstructure, austenite at the IA temperature, and finally retained austenite with high carbon content and bainite in the bands, as shown in Fig. 3b.

The XRD analyses were performed on the samples of Fig. 3b, and the average content of carbon in the retained austenite for the BIT temperatures of 400, 430, and 460 °C was determined as 1.33, 1.5, and 1.66 wt%, respectively. It can be seen that the levels of carbon for the two specimens with BIT temperature of 460 °C are in accordance with the aforementioned explanation. The effect of the bainite as the surrounding phase can be attributed to its high strength, which retards the formation of martensite, thus increasing the stability of retained austenite [12].

Figure 3d shows that by increasing the BIT temperature, the level of n increases and its maxima shifts to lower strains. These results are in accordance with expected trend. However, it can be seen that the level of n is generally lower compared with Figs. 1d and 2d. This can be ascribed to its inhomogeneous microstructure, which is responsible for the poor TRIP effect response [13].

4 Conclusions

In summary, the effects of the chemical homogeneity and the distribution of the retained austenite in the microstructure of transformation-induced plasticity steel upon the stability of the retained austenite, the TRIP effect, the response to the

bainitic isothermal treatment, the appearance of yield point elongation and other peculiarities of plastic flow, and the mechanical properties were characterized. Based on the preprocessing route, the chemical inhomogeneity may induce the microstructural ununiformity in the form of the banded structure or the peculiarities in tensile behavior. These results are essential for better understanding of the behavior of TRIP steels to exploit all of their potential for different applications.

References

- [1] Y. Chen, X. Chen, Q.F. Wang, Acta Metall. Sin. (Engl. Lett.) **15**, 339 (2002)
- [2] J. Chiang, J.D. Boyd, A.K. Pilkey, Mater. Sci. Eng., A **638**, 132 (2015)
- [3] X.C. Xiong, B. Chen, M.X. Huang, J.F. Wang, L. Wang, Scr. Mater. **68**, 321 (2013)
- [4] C. Wang, H. Ding, M. Cai, B. Rolfe, Mater. Sci. Eng., A **610**, 65 (2014)
- [5] G. Azizi, H. Mirzadeh, M.H. Parsa, Mater. Sci. Eng., A **639**, 402 (2015)
- [6] E.J. Melero, N.H. van Dijk, L. Zhao, J. Sietsma, S.E. Offerman, J.P. Wright, S. van der Zwaag, Acta Mater. **55**, 6713 (2007)
- [7] R. Schwab, V. Ruff, Acta Mater. **61**, 1798 (2014)
- [8] P.J. Gibbs, E. De Moor, M.J. Merwin, B. Clausen, J.G. Speer, D.K. Matlock, Metall. Mater. Trans. A **42**, 3691 (2011)
- [9] Z. Guo, L. Li, W. Yang, Z. Sun, Metall. Mater. Trans. A **64**, 1704 (2015)
- [10] E. De Moor, S. Lacroix, A.J. Clarke, J. Penning, J.G. Speer, Metall. Mater. Trans. A **39**, 2586 (2008)
- [11] D.M. Stefanescu, ISIJ Int. **46**, 786 (2006)
- [12] I.Y. Pyshmintsev, M. De Meyer, B.C. De Cooman, R.A. Savray, V.P. Shveykin, M. Vermeulen, Metall. Mater. Trans. A **33**, 1659 (2002)
- [13] S. Yadegari, S. Turteltaub, A.S.J. Suiker, P.J.J. Kok, Comp. Mater. Sci. **84**, 339 (2014)