Enhancement of work-hardening behavior of dual phase steel by heat treatment

Verbesserung des Kaltverfestigungsverhaltens von Dualphasenstahl durch eine Wärmebehandlung

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The work-hardening response and mechanical properties of dual phase steels originated from different initial microstructures under low and high martensite volume fractions were investigated using a typical carbon-manganese steel. The modified Crussard-Jaoul analysis was used for studying the work-hardening stages and the deformation behavior of ferrite and martensite. It was revealed that the initial martensitic microstructure before intercritical annealing is much better than the full annealed banded ferritic-pearlitic and spheroidized microstructures in terms of work-hardening capacity and strength-ductility trade off. By increasing the amount of martensite, via intercritical annealing at higher temperatures, the ductility decreased but the tensile toughness of dual phase steels increased toward reaching the domain of extra-advanced high-strength steels due to the enhancement of work-hardening rate.

Keywords: Dual phase steels / microstructure / mechanical properties / strain-hardening rate / tensile toughness

1 Introduction

Owing to their excellent combination of strength-ductility, high initial work hardening rate, continuous yielding, and relatively low alloying elements, low-carbon ferritic-martensitic dual phase steels have found widespread applications in automotive and other industries [1-3].

At a given martensite fraction, the mechanical properties and work-hardening behavior of dual phase steels are largely determined by the morphology, size, and distribution of the martensite phase and also ferrite grain size, which themselves are dependent on the initial microstructure [2, 4]. The initial microstructure depends on the heat treatment and thermomechanical processing routes [5-12]. By increasing the martensite fraction, the strength usually enhances but the premature damage initiation as a result of the presence of martensite in the ferritic matrix (incompatibility of deformation of phases) is expected to be more severe [13, 14]. Moreover, since the amount of carbon is constant, by increasing the fraction of martensite, the carbon content of martensite decreases, and as a result, the strength of martensite declines. Hence, the ductility of martensite phase increases. Therefore, it can be deduced

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that by controlling the morphology and amount of martensite, it is possible to manipulate the properties of dual phase steels, and hence, research in this area is still underway.

One of the heat treatment routes to alter the initial microstructure is the spheroidization treatment, which can produce discrete martensite islands [12, 15]. Moreover, the initial banded ferritic-pearlitic microstructure can be used to achieve dual phase steel with banded morphology. Furthermore, the initial martensitic microstructure can be considered to obtain a widely dispersed martensite phase in the ferrite matrix. The martensite volume fraction can also play an important role in the obtained microstructures for a given initial microstructure. The present work aims to deal with this subject.

2 Experimental details

2.1 Processing

A steel with 0.18 carbon, 0.14 silicon, 1.29 manganese, 0.022 copper, 0.083 nickel was used in this work. The sheet was austenitized at 1050 °C followed by furnace cooling to room temperature to develop a fully annealed ferritic-pearlitic microstructure. This sheet was also austenitized at 1050 °C followed by water quenching to obtain the martensitic microstructure. Figure 1. The quenched microstructure was considered as the starting one for obtaining the spheroidized sheet by soaking at 700 °C for 24 h followed by air cooling to room temperature. Therefore, three microstructures are available: (a) Ferritic-pearlitic banded structure, (b) quenched martensite, and (c) spheroidized microstructure. Finally, the three obtained microstructures were intercritically annealed at 735 °C and 800 °C for 15 minutes and then water quenched to produce dual phase microstructures with martensite volume fractions of ~0.30 and ~0.65, respectively.

2.2 Characterization

The 2 % nital solution was used for revealing microstructures. The tensile specimen was prepared according to JIS standard with gage length of 12 mm and the strain rate was 1 mm/min. The modified Crussard-Jaoul analysis was used for studying the work-hardening behavior, where it is based on the Swift formula expressed as $\varepsilon = A + Bo^p$, where $A$ and $B$ are material constants and $p$ is the inverse of work-hardening exponent [16-18]. Therefore, $\sigma = \sqrt{\varepsilon - A}/B$, then $d\sigma/d\varepsilon = \sigma/(p(\varepsilon - A))$, and finally $\ln(d\sigma/d\varepsilon) = (1 - p)\ln\sigma - \ln(pB)$. As a result, plots of $\ln(d\sigma/d\varepsilon)$ versus $\ln\sigma$ can be used to analyze work-hardening behavior. Finally, hardness measurements were performed using a Vickers hardness tester under a load of 20 kg (HV 20).

3 Results and discussion

3.1 The initial banded microstructure

The full annealed sample has a well-defined banded microstructure and after intercritical annealing at 735 °C, a martensitic-ferritic banded microstructure, inherited from the initial pearlitic-ferritic banded microstructure has been produced (denoted as DP1) [19, 20], Figure 2. By increasing the intercritical annealing temperature to 800 °C, a higher fraction of martensite (0.65 vs. 0.30) was achieved as a result of the presence of a higher amount of austenite pro-
duced at 800 °C (denoted as DP2), Figure 2. This interconnected banded structure reveals that the austenite nucleates in the place of pearlite, consuming the surrounding ferrite, and also nucleates on the remnant ferrite grain boundaries.

While the full annealed sample shows yield point phenomenon related to the Cottrell atmospheres around dislocations produced by interstitial atoms, the yield point phenomenon is absent for DP1 and DP2 steels due to the generation of sufficient amount of unlocked dislocations in the ferrite near the martensite islands as a result of transformation of austenite to martensite during quenching after intercritical annealing [2, 21–24], Figure 2. These dual phase steels have higher tensile strengths but lower total elongations compared with the full annealed sample, and the strength of DP2 is higher than that of DP1. This shows that the strength enhances by increasing the amount of martensite [25–27]. The hardness measurements revealed that the full annealed, DP1, and DP2 steels have Vickers hardness numbers of 162 HV 20, 193 HV 20, and 460 HV 20, which are consistent with the trend observed for tensile strength.

### 3.2 The initial quenched microstructure

The quenched steel exhibits a typical lath martensite morphology, Figure 3. This sample shows a high tensile strength of ~1400 MPa. After intercritical annealing at 735 °C, the martensite particle sizes are much finer than that produced from full annealed sample (DP1) and they are uniformly dispersed in the microstructure (denoted as DP3), Figure 3. This good distribution leads to a better combination of mechanical properties [11, 15, 18, 28, 29], where both DP1 and DP3 steels have total elongation of ~35 % but the tensile strength of DP3 is 1.14 times that of DP1, Figure 3. Again by increasing the intercritical annealing temperature from 735 °C to 800 °C (DP4), the strength enhances from 647 MPa to 1091 MPa, Figure 3. It is interesting that the total elongation slightly declined from 35 % to 32 %. However, this is not the case for DP1 and DP2, where the tensile strength increased from 565 MPa to 896 MPa but total elongation decreased from 35 % to 26 %, Figure 2. Therefore, it can be concluded that the initial martensitic microstructure before intercritical annealing is much better than the full annealed banded microstructure. The hardness measurements reveal that the quenched, DP3, and DP4 steels have Vickers hardness numbers of 507 HV 20, 255 HV 20, and 475 HV 20, which are consistent with the trend observed for tensile strength.

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**Figure 2.** Optical micrographs and the corresponding tensile curves of dual phase steels produced from the initial banded microstructure. In the dual phase microstructures, the darker phase is martensite.

**Figure 3.** Optical micrographs and the corresponding tensile curves of dual phase steels produced from the initial quenched microstructure. In the DP microstructures, the darker phase is martensite.
3.3 The initial spheroidized microstructure

The spheroidized steel shows spheroidized cementite particles, originated by decomposition of martensite during tempering at 700 °C, and they are uniformly dispersed in the microstructure, Figure 4. The hardness measurements revealed that the hardness drops from 507 HV 20 to 180 HV 20 by spheroidization of martensite due to the dominancy of recovery processes and decreasing the tetragonality by loosing carbon from solid solution. After intercritical annealing at 735 °C (DP5), the spheroidized martensite particles can be seen in the microstructure in place of carbide particles, Figure 4. However, after intercritical annealing at 800 °C (DP6), the martensite phase morphology shows some features similar to the initial quenched microstructure, Figure 4. This reveals that the austenite (and hence martensite after quenching from the intercritical temperature) firstly formed in place of spheroidized carbides but grew in the tempered martensitic matrix, which inherited the features of the initial martensitic microstructure.

The hardness values of DP5 and DP6 are 170 HV20 and 367 HV20, respectively. It is interesting that the hardness of DP5 and spheroidized steel are near each other. The tensile curves also support this finding, Figure 4. Moreover, the hardness and tensile strength of DP6 are inferior compared with those of DP2 and DP4, while these steels have nearly the same ductility, Figure 4. These results reveal that the initial spheroidized microstructure is not appropriate to produce dual phase steel and the initial martensite microstructure is better than the initial full annealed one.

3.4 Summary of tensile properties

The relationship between tensile strength and elongation of various steel grades [3] and the results of the present study are shown, where the non-dual phase steels considered in the present work follow the conventional trend observed in the literature with tensile toughness (TS × El [30, 31]) values of ~20 000 MPa·% or lower, Figure 5. This is also the case for the dual phase steels originated from the spheroidized and full annealed initial microstructures (DP1, DP2, DP5, and DP6), Figure 5. However, dual phase steels produced by intercritical annealing of martensite show much better strength-ductility balance, Figure 5. In fact, DP4 falls within the range considered as extra-advanced high strength steels with tensile toughness approaching to ~35 000 MPa·%, which reveals that this dual phase steel has an excellent combination of strength and ductility.
The work-hardening plots based on the modified Crussard–Jaoul analysis reveal that there is one stage of deformation for the ferritic-pearlitic microstructure, except at the beginning of plastic deformation due to the occurrence of yield-point phenomenon, Figure 6. For the dual phase steels with martensite volume fraction of 0.3 (DP1, DP3, and DP5), three stages of work-hardening can be detected: Stage I is a transient stage and represents the glide of mobile dislocations in ferrite present near the martensite regions. Moreover, Stage II belongs to the deformation of constrained ferrite. Finally, Stage III is related to the concurrent deformation of hardened ferrite (experiencing dynamic recovery) and martensite [16-18, 28, 32], Figure 6. In the case of DP4 with martensite volume fraction of 0.65, Stage I is nearly horizontal, which implies that this sample can maintain its high work-hardening capacity. Moreover, the slope of Stage II is positive, which might be related to the transformation of retained austenite during deformation similar to transformation induced plasticity (TRIP) steels and needs more experimental works to elucidate it [17, 33, 34]. Furthermore, the Stage III is more pronounced for DP4, indicating the concurrent deformation of martensite and hardened ferrite, which was expected for this high volume fraction of martensite with consequent lower carbon content [4, 35].

At a given flow stress, the work-hardening curve of the DP4 locates above others, which reveals that the work-hardening rate of this steel is higher, Figure 6. As a result, this steel shows a good combination of mechanical properties. The curve corresponding to DP5 falls below those of other dual phase steels. This poor work-hardening response is responsible for inferior tensile properties of this steel.

4 Conclusions

The work-hardening response and mechanical properties of dual phase steels originated from different initial microstructures under low and high martensite volume fractions were investigated using a typical carbon-manganese steel. The following conclusions can be drawn from this study:

1. The initial martensitic microstructure before intercritical annealing is much better than the full annealed banded ferritic-pearlitic and spheroidized microstructures in terms of work-hardening capacity and strength-ductility balance. In fact, the spheroidization annealing resulted in obtaining martensite phase as discrete islands and the initial banded microstructure yielded banded martensite morphology but the initial martensitic microstructure resulted in a uniform dispersion of martensite phase in the microstructure with a morphology inherited from lath martensite.

2. By increasing the amount of martensite, the ductility decreased but the tensile toughness of dual phase steels increased toward reaching the domain of extra-advanced high-strength steels due to the enhancement of work-hardening rate. In fact, the tensile toughness of other dual phase steels was less than \( \approx 20000 \text{ MPa}\% \) but it was \( \approx 35000 \text{ MPa}\% \) for dual phase steel with 65 % martensite produced by intercritical annealing of initial martensitic microstructure.

3. The analysis of work-hardening rate based on the modified Crussard-Jaoul analysis revealed that the deformation of martensite phase becomes more pronounced with increasing the martensite percent from 30 % to 65 %.
5 References


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