Effects of Heavy Warm Deformation on Microstructure and Mechanical Properties of a Medium Carbon Ferritic–Pearlitic Steel

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The study of medium-carbon steel (0.36% C) with deformation induced spheroidized cementite produced by heavy warm deformation (HWD) was carried out as a potential substitution of conventional quenching and tempering (QT) or soft annealing (SA).

After austenite deformation the HWD samples were cooled and heavily deformed (ε ~ 1.6) at the temperatures below the γ–α transformation with a subsequent simulated coiling. To estimate the treatment sensitivity the effect of the heating due to the heavy deformation on the mechanical properties was studied using both isothermal and adiabatic processing routes.

The mechanical properties after the various treatments show that the strength–ductility relation after HWD and QT are superior to that after CC or SA. The reason is in the presence of lamellar pearlite in the microstructure after CC and also partially after SA that deteriorates the reduction of area. A similar effect is observed after the adiabatic HWD treatment: the deformation heating at high HWD temperatures may lead to partial pearlite-austenite-pearlite transformation, which results in some lamellar pearlite in the final microstructure.

HWD at 670°C with subsequent coiling simulation allows to get a microstructure with dispersed spheroidized cementite distributed homogeneously in fine grained ferritic matrix with an average grain size of 2 μm and an amount of high angle grain boundaries (HAGB) of about 65%. The features of ferrite and cementite after both HWD and QT have some important resemblances: fine homogeneous distributed cementite and fairly high amount of HAGB. As a result, the mechanical properties of the HWD samples are well comparable to those after QT.

KEY WORDS: heavy warm deformation; spheroidized cementite; cementite distribution; microstructure; EBSD; mechanical properties.

1. Introduction

After conventional hot rolling of medium carbon steels, lamellar pearlite is usually formed during γ–α transformation. It is well established that the lamellar pearlite deteriorates the ductility of steels thus significantly limiting their applications. Spheroidized cementite is more beneficial for toughness, cold formability and machinability. To obtain higher cold formability and/or better machinability, that is to obtain a fair combination of strength and ductility, a hot strip should be subject to either durable annealing or to quenching with a subsequent tempering.

The use of heavy warm deformation of strip below the γ–α transformation temperature allows to accelerate the spheroidization of pearlitic cementite by four orders of magnitude compared to annealing without deformation. This can help to avoid long or expensive processing such as soft anneal or quenching-tempering to obtain the required combination of mechanical properties.

2. Material and Experimental Procedure

The medium carbon steel with (mass%) 0.36 C, 0.53 Mn, 0.22 Si, 0.011 P, 0.002 S was employed in the present work. Specimens with initial thickness of 60 mm, width of 50 mm and length of 45 mm were cut out from a commercial slab. The processing procedures described here were carried out using Max-Planck-Institute hot deformation simulator.

This servohydraulic press is capable to perform multi-step hot compression tests of large specimens along various thermomechanical processing routes thus providing realistic simulations of industrial hot forming operations. In the present work, the plane strain compression tests with strain rate of 10 s⁻¹ were used. The size of the specimens for hot compression was sufficiently large to subsequently machine out the standard specimens to determine conventional mechanical properties. The following processing routes were studied:

Continuous Cooling (CC). After soaking at 1 000°C the specimens were cooled to 900°C (austenite range) and de-
formed at this temperature (strain $\varepsilon=0.3$). The specimens were then cooled to room temperature with the rate of about 7 K/s in the range from 800 to 500°C. This treatment was aimed to estimate the mechanical properties of steel with ferrite-lamellar pearlite microstructure.

Soft Annealing (SA). After soaking at 1 000°C and deformation at 900°C, $\varepsilon=0.3$, the specimens were cooled to room temperature at $\sim$7 K/s, then reheated to 710°C and annealed for 16 h. This treatment was aimed to simulate the process of globularization to obtain microstructure with spheroidized cementite.

Quenching and Tempering (QT). After soaking at 1 000°C and deformation at 900°C, $\varepsilon=0.3$, the specimens were quenched at 150 K/s to obtain martensite microstructure. The specimens were then tempered at 600–670°C for 2 h. This treatment was carried out to obtain fine ferrite–cementite mixture with good combination of strength and ductility.

Heavy Warm Deformation (HWD). After soaking at 1 000°C and deformation at 900°C, $\varepsilon=0.3$, the specimens were cooled at 7–8 K/s to 500°C to allow for the completion of $\gamma$–$\alpha$ transformation. Then the specimens were reheated and compressed in four passes ($\varepsilon=0.4$ per pass) at the temperatures within the range of 600–710°C. Subsequent simulation of coiling was carried out by holding the specimen at the deformation temperature for 2 h.

To study the effect of adiabatic heating during HWD, the specimens were deformed in two alternative ways (Fig. 1). According to isothermal process, the deformation temperature was kept approximately constant by performing controlled cooling between the passes for the period of 0.5 s. In adiabatic process, no pauses were allowed between the passes so that the temperature increased by up to 60°C due to deformation heating.

Evaluation Technique. The dilatometrical tests were carried out to obtain CCT diagrams after the deformation of austenite. The microstructure was investigated using light and scanning electron microscopy. Softening in ferrite was studied by electron back scattering diffraction (EBSD). The mechanical properties were measured in standard tensile tests.

3. Results and Discussion

3.1. Microstructure

The microstructures after various processing are shown in Fig. 2. After deformation of austenite and subsequent continuous cooling (Fig. 2(a)), colonies of lamellar pearlite and proeutectoid ferrite were observed, with the latter located at the boundaries of the former austenite grains. Soft annealing for 16 h of steel with initial microstructure shown in Fig. 2(a) leads to a partial spheroidization of lamellar pearlite, but the microstructure also contains about 30% of lamellar pearlite (Fig. 2(b)). The spheroidized cementite particles are located at the areas of the former pearlitic colonies. The proeutectoid ferrite positions itself in the vicinity of the former austenite grain boundaries. Both mi-
Microstructures after continuous cooling and soft annealing are fairly coarse.

After quenching and tempering (Fig. 2(c)) the microstructure consists of the former martensite laths with fine precipitated cementite particles. HWD leads to the formation of fine and completely spheroidized cementite homogeneously distributed in the ferrite matrix (Fig. 2(d)). Compared to continuous cooling and soft annealing, the microstructures both after quenching-tempering and HWD are fairly fine.

### 3.2. Mechanical Properties after HWD.

The yield and tensile strengths (Fig. 3) decrease with increasing deformation/coiling temperatures for both isothermal and adiabatic HWD. The data fall on the same curves independently of the adiabatic heating. The uniform and total elongations (Fig. 4) increase with temperature and are also located on the same lines for both isothermal and adiabatic HWD.

On the contrary, the reduction of area (Fig. 5) can depend on the deformation heating especially if the starting deformation temperature $T_o$ is high. The reduction of area grows when deformation/coiling temperatures increase to 650°C in both cases of HWD. Then, for isothermal HWD, the reduction of area remains at the same high level as the temperature increases to 710°C, but the adiabatic HWD leads to a drop in the reduction of area at the deformation starting temperature of 710°C.

This decrease in the reduction of area can be explained by the differences in microstructure after isothermal and adiabatic HWD (Fig. 6). In case of the isothermal process, the microstructure is typical for heavy warm deformation and consists of ferrite matrix with spheroidized cementite. In case of the adiabatic deformation, the microstructure also contains some lamellar pearlite. Obviously, at high starting temperature (>700°C) the deformation heating (~60°C) leads to a partial re-austenitization with subsequent transformation of this new austenite into (lamellar) pearlite that reduces the reduction of area.

### 3.3. Effect of Processing on Microstructure/Properties Relationship.

The correlation between tensile and yield strength of the steels after the various treatments (Fig. 7) depends on the microstructure. At the same tensile strength, the yield strength after CC and SA is by 140 MPa lower than that after HWD. As shown in Figs. 2(a) and 2(b), the mi-
The microstructure of both CC and SA specimens contains a network of coarse proeutectoid ferrite. This leads to a decrease in yield strength as compared to that after HWD (Fig. 7), in which case the microstructure contains homogeneous fine grain ferrite. Apart of the proeutectoid ferrite, the CC microstructure also has lamellar pearlite. The SA microstructure consists of both lamellar pearlite and spheroidized cementite. Relatively coarse partially spheroidized cementite particles produce a simultaneous decrease in both the tensile and yield strengths after SA as compared to CC.

After HWD and QT the microstructure represents a mixture of fine grain ferrite and fine spheroidized cementite. The fine ferrite microstructure characteristic for steel after HWD (ferrite grain size of about 1–2 \( \mu \text{m} \), cf. Fig. 6) leads to high yield strength. Although HWD and QT produce the same tensile strength, the yield strength after QT is by about 60 MPa lower. The reason can be in the presence of residual stresses after QT. The stress–strain curves after QT do not show any yield point elongation. Therefore, this difference in yield strength can also be attributed to the discrepancy between the 0.2% offset stress (QT) and the true yield strength (HWD). In the cases of all other routes the yield point elongation is characteristic.

The correlations between the strength and the elongation show that the points in the plots corresponding to the HWD and QT specimens with fine grain ferrite and spheroidized cementite microstructure (FC) fall on the same curve (solid lines in Figs. 8 and 9). The points that correspond to the microstructure that contains ferrite and fully or partially lamellar pearlite (FP), fall on the other curves (dashed lines). At the same tensile strength, the specimens with lamellar pearlite exhibit essentially higher elongation (Fig. 8). The reason for that can be in different ductility of different kinds of ferrite. Soft proeutectoid ferrite in cases of CC and SA, with a lower density of defects, contributes to a higher level of elongation. In the HWD specimens that have been undergone adiabatic deformation at high temperature (\( \Delta \) symbols in the plots), ferrite is softened mostly just because of the temperature increase.

The correlations between the reduction of area and the yield strength, as well as between the reduction of area and the total elongation (Figs. 10 and 11), show that the points corresponding to the HWD and QT specimens with fine grain ferrite and spheroidized cementite microstructure (FC) fall on the same curve (solid lines) located higher than the curves for specimens with ferrite and some lamellar pearlite (FP) in the microstructure (dashed lines). In principle, the point of steel after the soft annealing can be assigned to both of the correlations (cf. Figs. 10 and 11). After long soft annealing the microstructure still contains approximately 30% of lamellar pearlite. As the result, HWD with fully spheroidized cementite allows for higher reduction of area (of about 70%) than that after long soft annealing. Moreover, the reduction of area of about 66% after SA can only be attained at essentially lower yield strength, as compared to HWD (340 and 540 MPa, respectively). Obviously, the reason is again the different microstructure. Compared to HWD the ferrite after SA is significantly coarser and softer than after HWD resulting in lower yield strength and higher elongation. On the other hand, the inhomogeneous distribution of cementite and the presence of lamellar pearlite deteriorate the reduction of area after SA.
3.4. Comparison between Specimens after HWD and QT

Figures 8–11 show that HWD and QT result in the same level of mechanical properties. Electron scanning image (Fig. 12) allows for more detailed estimations of ferrite and cementite morphologies. It can be seen that in both cases the cementite particles can be classified into two size groups: relatively large particles of about 0.3–0.7 μm and 0.4–1.0 μm for QT and HWD, respectively, on one hand, and very fine particles (<0.1 μm), on the other hand. The quantitative estimation reveals approximately the same density of large particles for QT and HWD (about 20×10^6 mm^-2), but the density of small particles is higher after QT than that after HWD (120 and 60×10^6 mm^-2, respectively).

The ferrite morphology after QT and HWD can be characterized as follows. For QT (Fig. 12(a)), thin laths with the width of about 0.5–1.0 μm and the angle between the laths families of around 60° are characteristic after martensitic transformation. EBSD study reveals high misorientation...
angles (near 60°) between thin ferrite laths. The misorientation inside the laths varies within 6°. This means that after tempering, certain internal stresses that have been induced by martensitic transformation are still retained in ferrite grains. High dislocation density survives even in tempering at 670°C. Approximately 70% of all internal surfaces are high angle grain boundaries, HAGB (>15°). This is in agreement with the earlier work\(^5\) that reported about 65% of HAGB in a high carbon steel quenched and tempered at 650°C.

The HWD ferrite grains (Fig. 12(b)) are equiaxed with the average size of about 1–2 μm. EBSD of the HWD specimens (Fig. 13) shows a considerable number of low angle grain boundaries, LAGB (Fig. 13(a)), although the fraction of HAGB is similar to that after QT, i.e. of about 65%. In high carbon steel warm rolled at 650°C the majority of ferrite grain boundaries are LAGB (about 53%),\(^6\) which indicates that the ferrite matrix is built of fine subgrains originating from recovery. Indeed, the ODF for the studied steel (cf. Fig. 13(b)) reveals a typical rolling texture\(^6,7\) with well developed γ- and α-fibers. These observations imply that the primary recrystallization does not occur and the softening of ferrite can be attributed to a very strong recovery or to a continuous recrystallization. For the steel studied here with lower carbon content deformed at higher temperature with subsequent coiling these mechanisms can result in a fairly high fraction of HAGB, as compared to a steel with higher carbon.\(^5\)

It can be said that some features in the microstructures after QT and HWD are alike. In both cases fine cementite particles are homogeneously distributed in the ferrite matrix. Ferrite units are small, the distances between boundaries are short (around 1 μm) and HAGB fractions are high (65–70%). As the result, the mechanical properties after HWD proved to be well comparable to those after QT.

On the other hand, the difference in ferrite morphology between QT and HWD can lead to different yielding behavior. The residual internal stresses after QT suppress yield point elongation. For this reason the yield strength after QT, actually measured as the stress at 0.2% offset strain, appears to be by 60 MPa lower than that after HWD at the same tensile strength.

### 4. Summary

1. The study of the medium carbon steel after isothermal and adiabatic heavy warm deformation (HWD) with subsequent coiling was carried out with the aim to produce spheroidized cementite. The results were compared with the conventional quenching-tempering, soft annealing and continuous cooling of pre-deformed austenite.

2. The strength after HWD decreases and the elongation increases with the deformation/coiling temperature independently of the increase in temperature during the adiabatic deformation.

3. The reduction of area grows when deformation/coiling temperatures increase to 650°C in both cases of HWD. As the temperature increases to 710°C, the reduction of area for isothermal HWD remains at the same high level, but the adiabatic HWD leads to a drop in the reduction of area because of a partial re-austenitization with a subsequent formation of lamellar pearlite at the high deformation starting temperature.

4. Compared to the long soft annealed the specimens after HWD exhibit a higher level of both reduction of area and yield strength.

5. The mechanical properties after HWD proved to be well comparable to those after QT, because some features in the microstructures after QT and HWD are alike. In both cases fine cementite particles are homogeneously distributed in the ferrite matrix; ferrite units are small, the distances between boundaries are short (around 1 μm) and HAGB fractions are high (65–70%).

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