Investigation on High Strength Hot-rolled Plates by Quenching-partitioning-tempering Process Suitable for Engineering

Shu ZHOU,1) Ke ZHANG,2) Nailu CHEN,2) Jianfeng GU1) and Yonghua RONG2)

1) Shanghai Key Laboratory of Materials Laser Processing and Modification, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240 China. 2) School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240 China. E-mail: yhrong@sjtu.edu.cn

(Received on January 31, 2011; accepted on June 17, 2011)

Designed Fe-0.25C-1.5Mn-1.2Si-1.5Ni-0.05Nb (mass%) hot-rolled plates with different thicknesses are subjected to a novel quenching-partitioning-tempering (Q-P-T) process suitable for engineering with water quenching followed by salt bath tempering or water quenching followed by air cooling. A passing underwater quenching equipment (PUQE) is specially designed for realization of the Q-P-T process suitable for engineering. The tensile results show that the Q-P-T samples exhibit both high yield strength of over 900 MPa and elongation of over 15%. Microstructural characterization indicates that the high strength is attributed to the dislocation-type lath martensite or bainite and the dispersively distributed NbC-carbides in the martensite matrix, and the adequate elongation results from the flake-like retained austenite between martensite laths. In addition, effects of the retained austenite in Q-P-T steels on mechanical properties and the feasibility of Q-P-T processes for engineering industry applications are discussed.

KEY WORDS: hot-rolled plate; Q-P-T process; martensite; retained austenite; mechanical property; engineering application.

1. Introduction

In recent years, advanced high-strength steels (AHSS) containing substantial amounts of retained austenite have been more and more attractive due to the combination of high strength and adequate ductility.1,2) As a soft phase in AHSS steels, carbon-enriched retained austenite contributes to formability and toughness due to the transformation induced plasticity (TRIP) effect during plastic deformation.3,4) Recently, an alternative processing concept, “quenching and partitioning” (Q&P), has been proposed by Speer et al.5,6) based on the fact that carbon can partition (diffuse) from the supersaturated martensite into the neighboring untransformed austenite, thereby stabilize the retained austenite at room temperature due to carbon enrichment. Different from conventional quenching and tempering (Q&T) heat treatments, Q&P involves a desired quenching temperature (QT) between the martensite-start (Ms) and martensite-finish (Mf) temperatures, which is usually much higher than room temperature applied in Q&T process. In addition, a subsequent partitioning step at or above the QT in Q&P process is performed to accomplish the partitioning of carbon from the supersaturated martensite into austenite, in which alloying with Si or/and Al7,8) is to suppress cementite (Fe3C) formation for obtaining the greatest amount of retained austenite. The calculation of volume fraction of the retained austenite as a function of QT has been done by Speer et al. based on the “Constrained Carbon Paraequilibrium” (CCE) theory.5,8,9) According to CCE theory, the formation of carbides is assumed to be avoided in Q&P process, which excludes the potential of precipitation strengthening. Aiming at improving the Q&P technology on this point, Hsu10) proposed a novel heat treatment method named quenching-partitioning-tempering (Q-P-T) process. Compared with Q&P process, carbide former elements (such as Nb, Mo and V) are added into Q-P-T steels to form fine stable carbides during partitioning process so as to strengthen the steels. Therefore, the whole isothermal holding process above QT is determined by both the precipitation of carbides and the carbon partitioning, namely, tempering including partitioning. A proper QT in Q-P-T process is calculated based on Q&P principle and thus high volume fraction of retained austenite can be obtained. Our previous researches11,12) showed that steels subjected to Q-P-T processes exhibited high strength with adequate ductility, which permitted Q-P-T steels a new member of AHSS steels.

In our laboratory, two molten salt baths (or a boiling water sink and a molten salt bath) are used for quenching and tempering in Q-P-T process, respectively. However, they cannot be directly applied to the heat treatment of high strength hot-rolled plates owing to the limit of the plate size and the virose risk of salt. In addition, low-carbon hot-rolled plates in industry treated by spraying water usually exhibit low strength since the cooling rate is too slow to avoid the formation of the ferrite or pearlite. In order to achieve high strength with adequate ductility for the designed plates, we propose a combination process of water quenching and air cooling, and specially design a passing underwater quench-
ing equipment (PUQE) which can realize high cooling rates for the Q-P-T process of plates with different thicknesses.

2. Experimental Procedures

The chemical composition of the experimental steel is listed in Table 1. The ingots were prepared in the Technical R&D Center of Laiwu Steel Group, and cut into blocks with 650 mm in width, 110 mm in length, and 90 mm in thickness, respectively. These blocks were then austenitized at 1200°C for 1 hour followed by hot rolling to 12 mm or 20 mm plates. The final dimensions of the steels are 100×60×12 mm³ or 300×130×20 mm³. The continuous-cooling-transformation (CCT) diagram of the steel (Fig. 1) was determined from the dilatometric data obtained by a Gleeble-3500 thermal simulator, and the QT is set from 250 to 300°C based on CCE theory.

With the aid of commercial software MSC.Marc and its user-defined subroutines, the temperature variations in 12 mm plates during different Q-P-T processes were calculated by using computer simulation based on a temperature-phase transformation field coupled three-dimensional (3D) non-linear finite element method (FEM) analysis. Then, the mechanical properties of the samples subjected to the above Q-P-T processes were tested. Two optimized Q-P-T processes for 12 mm plates were determined combined with the results of computer simulation and mechanical properties, and the calculated cooling curves of these two Q-P-T processes were shown in Figs. 2(a) and 2(b). One process is that the 12 mm plate is austenitized at 930°C for 900 s followed by quenching in water for 7 s to a temperature between $M_s$ and $M_f$ instead of molten salt quenching, followed with tempering at 400°C for 120 s (Q-P-T 1) in molten salt bath. Another process is that the austenitized plate is firstly cooled in air for 15 s, which is typically the time needed to transfer the heated plate from furnace to water, and then quenched in water for 5 s with a subsequent air cooling for 1800 s (Q-P-T 2) as a step of tempering. Similarly, a proper Q-P-T process (Q-P-T 3) for 20 mm

Table 1. Chemical composition of the steel used in the present work (mass%).

| C | Si | Mn | Ni | Nb | P | S | $M_s$ (°C) | $M_f$ (°C) | $Ac_3$ (°C) |
|---|---|---|---|---|---|---|-------|-------|-------|
| 0.256 | 1.2 | 1.48 | 1.51 | 0.053 | 0.017 | 0.008 | 405±5 | 210±3 | 880±5 |

Fig. 1. Measured CCT diagram of the experimental steel with a critical cooling rate of 30°C/s for martensite formation.

Fig. 2. Simulated cooling curves of the four processes: (a) Q-P-T 1; (b) Q-P-T 2; (c) Q-P-T 3; (d) Q&T.
plate with a larger size is proposed with increased processing time, including the austenitizing time of the plate for 3,600 s, transferring time for 40 s in air, and the passing time underwater for 15 s (quenching), followed by final air cooling for 1,800 s (tempering), as shown in Fig. 2(c). In order to compare the differences of the effects between the novel Q-P-T process and the traditional Q&T process on microstructures and mechanical properties, Q&T heat treatment is carried out (Fig. 2(d)), in which the 12 mm plate was austenitized at 930°C for 900 s followed by quenching in water to room temperature, and then tempering at 400°C for 1,800 s in molten salt bath. The difference between Q&T and Q-P-T process lies in that QT (room temperature) in the former is much lower than that in the latter. Moreover, a PUQE (Fig. 3) is specially designed for realization of Q-P-T 3 process and can be used to Q-P-T process in the industry production. Its dimensions are set to 6 m in length, 2 m in width and 2 m in height. The length of the effective cooling area with violently flowing water in the PUQE is 5 m and the height of the water surface can be controlled by adjusting the relative flow rate of water-in and water-out.

Tensile samples with a diameter of 5 mm (9 mm) and a gauge length of 25 mm (45 mm) parallel to the rolling direction were cut from about the 1/3 width and 1/4 thickness of the as-treated 12 mm (20 mm) plates. They were tested at room temperature using a SANS 5105 testing machine fitted with a 100 kN load cell. An extension rate of 0.5 mm/min was used in all the experiments. Two samples for each process were subjected to tensile tests and the average values were calculated. If test values of the two samples for a given process have a large difference (above 10%), the third sample will be tested.

In order to determine the volume fraction of austenite at room temperature in the samples, X-ray diffraction experiments were performed in a D/max 2550 X-ray diffraction analyzer at 35 kV and 200 mA. The samples were step-scanned with a scanning speed (2θ) of 5°/min over a 2θ range of 35° to 105° using Cu Kα radiation. Retained austenite composition was calculated from the integrated intensities of (200), (220) and (311) austenite peaks, and those of (200) and (211) peaks of ferrite.10

For metallographic characterization, samples were polished and etched in 2% nital solution for observation in a FEI SIRION 200 scanning electron microscope (SEM) operating at 5 kV.

Specimens for transmission electron microscopy (TEM) were prepared by slicing into 100 μm discs and grinding down to 40 μm thick foils. Subsequently, these foils were electropolished at −20°C in a MTP-1A twin-jet polisher using the electrolyte consisted of 4% perchloric acid and 96% ethanol solution. The specimens were examined in a JEM 2100F microscope (JEOL) at an operating voltage of 200 kV.

3. Results

3.1. Mechanical Properties of the As-treated Steels

The tensile properties of the samples after different heat treatment processes are listed in Table 2, together with the volume fractions of retained austenite. It can be seen that all the samples with Q-P-T processes exhibit a combination of high yield strength (over 900 MPa) and elongation (over 15%), indicating the Q-P-T processes with water quenching proposed in the present study instead of quenching in salt bath are suitable for the heat treatments of hot-rolled plates with 12 mm or 20 mm thickness. The XRD patterns of the samples are presented in Fig. 4 for determination of the volume fractions of retained austenite. By quantitative XRD analysis, it can be calculated that the austenite fraction of the Q&T sample is less than 4%, while those in all Q-P-T samples are above 10%. In addition, for the step of tempering including partitioning, it is known that cooling in the air after water quenching in Q-P-T 2 and 3 processes is much more convenient and secure to be operated than tempering in salt baths, although Q-P-T 1 sample has the highest strength and elongation among the three Q-P-T processes.

3.2. The Microstructure Features of Samples after Different Heat Treatment Processes

SEM micrographs of the 12 mm plates treated by dif-

Table 2. The mechanical properties of the as-treated samples at room temperature. YS is the yield strength; UTS is the ultimate tensile strength; EI is the elongation; \( V_r \) is the volume fraction of retained austenite.

| Sample | Heat treatment | YS, MPa | UTS, MPa | EI, % | UTS−EI, MPa<% | \( V_r \), % |
|--------|----------------|---------|----------|------|----------------|--------|
| 1      | Q&T            | 1255    | 1375     | 12.2 | 16775          | 3.6    |
| 2      | Q-P-T 1        | 1197    | 1390     | 18.1 | 25159          | 11.1   |
| 3      | Q-P-T 2        | 1085    | 1255     | 16.5 | 20708          | 12.1   |
| 4      | Q-P-T 3        | 930     | 1280     | 15.2 | 19532          | 11.7   |
Different processes are shown in Fig. 5. Based on the measured CCT diagram and the calculated cooling curves during heat treat processes, it can be seen that both the quenching temperatures and tempering temperatures of Q&T and Q-P-T processes are lower than $M_s$ temperature ($405^\circ C$), therefore, it is can be concluded that the microstructures in Fig. 5 are typical martensite laths. However, retained austenite and dispersive distributed carbides is not distinguishable in these micrographs because of their relatively small content and fine size.

For 12 mm Q-P-T samples ($100x60x12$ mm$^3$), Fig. 5 shows almost the same microstructures (martensite laths) in the whole section of the Q-P-T samples, which is consistent with the prediction results based on Figs. 2(a) and 2(b). As the thickness increases to 20 mm, considering the much larger dimension of Q-P-T 3 sample ($300x130x20$ mm$^3$), the difference of cooling rates from the surface to the inner area of the sample section cannot be neglected (Fig. 2(c)), which may lead to a variation in its microstructures. Figure 6 shows the microstructure variation at different areas of Q-P-T 3 sample. It can be seen from that lath martensite forms on the surface and subsurface, while a multi-phase microstructure of lath martensite and bainite is observed in the inner area because of its longer time staying above $M_s$, which agrees to the prediction of microstructure based on Fig. 2(c). In addition, Q-P-T 3 process shows a much coarser microstructure due to longer austenitizing time ($3600$ s) than those of the other two processes, which may be a reason for its lowest yield strength among the samples of the three Q-P-T processes. However, retained austenite and carbides of Q-P-T 3 sample are still unable to be discriminated.

TEM observation was carried out for further identification of various phases in Q-P-T samples, especially retained austenite and carbides. Figure 7 shows that the main microstructure features of the samples treated by Q&T, Q-P-T 1 and 2 processes are the dislocation-type lath martensite structures accompanying flake-like retained austenite between martensite laths. According to the selected-area electron diffraction (SAED) pattern (Fig. 7(g)), the orientation relationships between the martensite matrix and the retained austenite in these three samples can be identified as K-S relationship: $[111]_\alpha // [101]_\gamma \ (110)_\alpha // (111)_\gamma$ and N-W relationship: $[001]_\alpha // [101]_\gamma \ (110)_\alpha // (111)_\gamma$. The average width of retained austenite in Q-P-T samples are 50–100 nm, which is much higher than that in Q&T sample (20–40 nm). Moreover, it is clearly that Q-P-T samples exhibit more volume fraction of retained austenite, which is consistent with the results of XRD. Therefore, it can be concluded that Q-P-T process increases the ductility of the steels with a little or without sacrificing the strength, which can be attributed to the effect of Q-P-T process on stabilizing substantial amount of flake-like retained austenite at room temperature.

Figure 8 shows the niobium carbides determined by the SAED pattern in Q-P-T 1 and 2 samples subjected to different tempering steps after water quenching. It can be seen that there exist spherical NbC with two different typical sizes in the samples. The fine carbides (average size of 5–20 nm) with a large amount mainly precipitate from martensite matrix during tempering due to their much lower solubility of carbon in martensite than that in austenite, as shown in Figs. 8(b) and 8(e). However, the relatively coarse carbides with an average size of 200±10 nm probably precipitate from austenite during hot rolling or austenitization (Fig. 8(e)). The crystallographic orientation relationship can be identified as: $[011]_\alpha // [011]_{MC}, (100)_\alpha // (011)_{MC}$ for Q-P-T 1 sample (Fig. 8(c)) and $[112]_\alpha // [112]_{MC}, (111)_\alpha // (110)_{MC}$ for Q-P-T 2 sample (Fig. 8(f)). The large amount of fine Nb-containing carbides dispersedly distributed in the
martensite matrix leads to a significant precipitation strengthening effect in Q-P-T steels, which is similar to our previous researches on the cold-rolled sheets treated by Q-P-T processes. However, compared with those fine carbides formed in Q-P-T 1 process with an average size of 5–10 nm, the carbides precipitated in Q-P-T 2 process finally increases to 10–20 nm for its much longer period time of air cooling (1800 s) after water quenching, and thus lead to a
lower ultimate tensile strength of Q-P-T 2 sample.

A further investigation on the microstructure features of Q-P-T 3 sample was performed by TEM analysis. Representative TEM micrographs (Figs. 9 and 10) present multi-phase microstructures of the subsurface and inner areas of Q-P-T 3 sample. In the surface of Q-P-T 3 sample, the microstructure consists of typical long martensite laths with high dislocation density and flake-like retained austenite (Figs. 9(a) and 9(b)), and carbides are hardly observed since the tempering is not enough in the surface. In the inner area, the microstructure comprises flake-like retained austenite, majority of long martensite laths with high dislocation density and minority of shorter laths with low dislocation density in which shorter laths may be bainite (Figs. 9(d) and 9(e)), and fine spherical carbides dispersively distributed in martensite and bainite are clearly observed owing to the enough tempering in the inner of sample (Fig. 10). These carbides are identified as NbC by the SAED pattern (Fig. 10(c)). Comparing Fig. 10 with Fig. 8, it can be seen that the carbides in Q-P-T 3 sample are more and larger than those in Q-P-T 2 sample. As a result, slightly high strength and low elongation for Q-P-T 3 sample with respect to Q-P-T 2 sample are attributed to more and larger carbides in Q-P-T 3 sample.

4. Discussion

4.1. Effect of Retained Austenite in Q-P-T Steels on Mechanical Properties

In order to study the effect of retained austenite on mechanical properties, true stress-strain curves and the corresponding work-hardening behaviors of Q-P-T and Q&T samples are investigated, as shown in Fig. 11. It can be obviously seen from Fig. 11(a) that the true stress-strain curves of Q-P-T samples exhibit much broader plateaus than that of Q&T sample, indicating that Q-P-T steels exhibit better uniform elongation during deformation. Comparing these three true stress-strain curves of Q-P-T samples, Q-P-T 3 sample shows the earliest yield behavior owing to its coarse microstructure, and Q-P-T 1 sample exhibits the best combination of strength and ductility, which is attributed to its fine multi-phase microstructure containing dislocation-type lath martensite, flake-like retained austenite (50–100 nm) and dispersive distributed NbC (5–10 nm) in the martensite matrix. As mentioned above, the features of retained austenite and NbC-carbides in Q-P-T 2 sample are similar
to those in Q-P-T 3 sample, and thus they exhibit very close tensile strength and elongation.

The work-hardening behavior is analyzed based on the following Hollomon equation associated with the necking criterion:18

$$\sigma = K \varepsilon^n$$ (Hollomon equation).......................... (1)

Where $\sigma$ is the true stress, $\varepsilon$ is the true strain, $K$ is a constant, and $n$ is the work hardening exponent. Then, the incremental work-hardening exponent $n$ can be written as:

$$n = \frac{\varepsilon}{\sigma} \frac{d\sigma}{d\varepsilon}$$ ........................................ (2)

When $\frac{d\sigma}{d\varepsilon} = \sigma$ (necking criterion), then $n = \varepsilon_u$, ....(3)

where $\varepsilon_u$ is the maximum value of uniform elongation.

It can be seen from Fig. 11(b) that the work-hardening behaviors of Q-P-T samples with 12 mm or 20 mm thickness present three stages: (1) when $\varepsilon < 0.01$ (0.03), $n$ decreases rapidly in a normal way (stage I); (2) when $0.01$ (0.03) $< \varepsilon < \varepsilon_u$, corresponding to the uniform tension stage, $n$ decreases much more slowly, or even has a slightly increase accompanying with a plateau, which can be attributed to transformation induced plasticity (TRIP) by the transformation from retained austenite to martensite (stage II); (3) when $\varepsilon > \varepsilon_u$, the exponent decreases again during necking stage (stage III). However, for Q&T sample, no TRIP effect can be observed from the rapid monotonous decrease of $n$ values with increasing tension strain because the volume fraction of retained austenite is too low (less than 4%).

4.2. The Promotion of Q-P-T Process Applicable for Engineering Industry

In order to get a knowledge of the cooling ability of PUQE and validate the simulated cooling curves for determination of the Q-P-T process, the temperature histories of hot-rolled plate with 20 mm thickness at two positions (1/8 thickness and 1/2 thickness) during Q-P-T 3 process in PUQE were measured by K-type thermocouples, as shown in Fig. 12. It can be calculated that the average cooling rates of the subsurface and inner areas are respectively 30°C/s and 20°C/s during passing water with intensive water flow, which ensures that no proeutectoid ferrite forms and the microstructure of the 20 mm sample comprises majority of martensite, minority of bainite, and retained austenite. Then, tempering including partitioning is accomplished by the heat transferred from the inner area during the subsequent air cooling, during which the unformed retained austenite is carbon-enriched and the fine NbC-carbides precipitate dispersively in both martensite and bainite (Figs. 9 and 10). It is worthy to point out that these measured cooling curves are consistent with the calculated curves in Fig. 2(c), and it is reasonably believed that the simulated curves in Figs. 2(a) and 2(b) are suitable for determination of Q-P-T 1 and 2 processes. The cooling rate of PUQE is also verified by microstructure, in other words, there is little pro-eutectoid ferrite or pearlite during the whole Q-P-T 3 process, but a final multi-phase microstructure consisting of lath martensite, NbC carbides, bainite and retained austenite (Fig. 6). The mechanical properties produced by the multi-phase microstructure exhibit a yield strength larger than 900 MPa and an elongation over 15%.

As the length of the equipment is limited to about 6 m, the cooling rate of the plate during water quenching is only controlled by the speed of hot-rolled plates passing the 5 m long water area, which leads to the application of the PUQE in the Q-P-T process for plates with a limited range of thickness. Therefore, we propose an adjustable equipment...
consisting of multi-PUQEs (each PUQE as a unit) with air cooling in between, which can be used to perform a multicycle Q-P-T process. By adjusting the moving speed of the hot-rolled plates and the number of the units, plates with the extension of considerable thicknesses can be performed on this multi-cycle PUQE. The related investigation is underway.

5. Conclusions

Designed Fe-0.25C-1.5Mn-1.2Si-1.5Ni-0.05Nb hot-rolled plates with 12 mm and 20 mm thicknesses are treated by a novel quenching-partitioning-tempering (Q-P-T) process suitable for engineering. In order to realize Q-P-T process from laboratory to industry production, a combined process of water quenching and air cooling is proposed instead of molten salt quenching in laboratory and a related PUQE is designed. The preliminary studies for Q-P-T process performed in PUQE are carried out with water-quenching plus salt bath tempering or water-quenching plus air cooling. The conclusions from experimental results are described as follows:

1) The tensile results show that all the Q-P-T samples exhibit high yield strength of over 900 MPa and elongation of over 15%.

2) Microstructural characterization indicates that the high strength is attributed to the dislocation-type lath martensite or bainite and the dispersive distributed NbC-carbides in martensite matrix, while the relatively high elongation results from the flake-like retained austenite between martensite laths.

3) Compared the novel Q-P-T process with traditional Q&T, the results indicate that the elongations of Q-P-T samples are much higher than those of Q&T sample because the amount of retained austenite in the former is much higher than that in the latter. The analysis of the work-hardening exponent as a function of true strain reveals that the high elongation results from the TRIP effect by transformation of retained austenite to martensite in Q-P-T samples.

4) A PUQE with enough cooling rate is able to realize the Q-P-T process of 20 mm hot-rolled plates with high mechanical properties. However, it is only applicable for plates with a limited range of thickness, and thus an adjustable equipment consisting of multi-PUQEs for wider application is discussed.

Acknowledgement

This study was financially supported by the National Natural Science Foundation of China (No. 51031001) and by the project of Laiwu Steel Group (Shandong, China).

REFERENCES

1) G. Buzzichelli and E. Anelli: ISIJ Int., 42 (2002), 1354.
2) T. Senuma: ISIJ Int., 41 (2001), 520.
3) P. J. Jacques: Curr. Opin. Solid State Mater. Sci., 8 (2004), 259.
4) C. Garcia-Mateo and F. G. Caballero: ISIJ Int., 45 (2005), 1736.
5) J. G. Speer, D. K. Matlock, B. C. De Cooman and J. G. Schroth: Acta Mater., 51 (2003), 2611.
6) J. G. Speer, D. V. Edmonds, F. C. Rizzo and D. K. Matlock: Curr. Opin. Solid State Mater. Sci., 8 (2004), 219.
7) H. K. D. H. Bhadeshia and D. V. Edmonds: Metall. Trans. A, 10 (1979), 895.
8) H. K. D. H. Bhadeshia and J. W. Christian: Metall. Mater. Trans. A, 21 (1990), 767.
9) D. P. Koistinen and R. E. Marburger: Acta Metall., 7 (1959), 59.
10) T. Y. Hsu: Proc. 6th Pacific Rim Int. Conf. on Advanced Materials and Processing, Mater. Sci. Forum, Cheju Isl, South Korea, (2007), 2283.
11) X. D. Wang, N. Zhong, Y. H. Rong, T. Y. Hsu and L. Wang: J. Mater. Res., 24 (2009), 260.
12) N. Zhong, X. D. Wang, L. Wang and Y. H. Rong: Mater. Sci. Eng., A, 506 (2009), 111.
13) J. S. Pan, Y. J. Li and D. Q. Li: J. Mater. Process. Technol., 122 (2001), 241.
14) C. C. Liu, X. J. Xu and Z. Liu: Finite Elem. Anal. Des., 39 (2003), 1053.
15) B. Smoljan: J. Mater. Eng. Perform., 11 (2002), 75.
16) J. Durnin and K. A. Ridal: J. Iron Steel Inst., 206 (1968), 60.
17) X. D. Wang, W. Z. Xu, Z. H. Guo, L. Wang and Y. H. Rong: Mater. Sci. Eng., A, 527 (2010), 3373.
18) W. C. Leslie: The Physical Metallurgy of Steels., McGraw-Hill Co., New York, USA, (1981), 1.