A high strength steel with yield strength on the order of 700 MPa had been developed successfully with the addition of titanium alloy element based on a low-carbon steel. The results show the hot deformation accelerates ferrite and pearlite transformation and retards bainite transformation under continuous cooling condition. The strengthening factors of this steel are attributed to the tiny interlocked distribution of bainite laths and titanium carbide precipitation. When the amount of bainite is more than 70%, the yield strength of steel is higher than 700 MPa, and simultaneously ratio of tensile of yield is more than 1.07, and good mechanical performances are obtained. As a result of the presence of finely dispersed cementite particles which improve the work hardening capacity, the ductility of steel is improved, with the steel’s elongation being about 19%. Many tiny TiC precipitates are observed under transmission electron micrograph (TEM), and these particles result in precipitation strengthening.

"Development of a Hot-rolled Low Carbon Steel with High Yield Strength"

Hai-Long YI, Lin-Xiu DU, Guo-Dong WANG and Xiang-Hua LIU

State Key Laboratory of Rolling & Automation, Northeastern University, Liaoning, Shenyang 110004, China.
E-mail: longhaiyi_2004@tom.com; longhaiyi_2004@yahoo.com.cn

(Received on November 25, 2005; accepted on February 10, 2006)

1. Introduction

The recent development of sheet steels has been dedicated mainly to automotive use because the requirements of car makers concerning materials are high and challenging. Using the high strength steel, both the automobile weight and fuel consumption are reduced and the safety of the automobile is raised simultaneously, so hot-rolled high strength sheet steels have been applied to suspension parts in automobiles.

In recent years, the domestic and foreign scholars have used different strengthening methods to make the yield strength achieve 700 MPa, but the types and amounts of alloys used cause the steel products’ cost increase.1–9 In this study, a new type of hot-rolled high strength sheet steel with excellent elongation was successfully developed. The CCT curves of this steel under deformed and undeformed conditions were investigated, and the strengthening mechanisms were also researched systematically. These results will be applied to the practical hot-rolling operation in order to obtain proper microstructures and mechanical properties for high strength steel.

2. Experimental Procedure

2.1. Experimental Materials

Table 1 indicates the chemical composition of the steel used. This is a low carbon steel bearing 0.18% Ti. The steel was melted in a 50 kg vacuum induction furnace. The concepts used to design the alloy chemistry are as follows: C is effective for strengthening steels, but it degrades weldability, which is indispensable for the assembly of auto bodies; Mn is effective for strengthening steel through both solid solution hardening and transformation hardening, but it degrades spot weldability and galvanizability. So the Mn content is therefore suppressed to less than 2.0%; In order to make the yield strength value achieve 700 MPa, precipitation hardening and grain refinement hardening should be used. So, addition of Ti is used in this steel.

2.2. Experimental Methods

The thermo-simulation process covers: cylindrical specimens of 15 mm height and 8 mm diameter were prepared from the rolled slab for the measurement of CCT curves using Gleeble-1500 thermal mechanical simulator. The samples were heated to 1 200°C, thermally held for 300 s, and cooled to deformation temperature (900°C) at 10°C/s, then deformed with strains of 0 and 0.4, respectively. After that the samples were cooled to ambient temperature at different cooling rates (0.1°C/s, 0.5°C/s, 1°C/s, 2°C/s, 5°C/s, 10°C/s, and 20°C/s). The expansion curves were recorded, and the CCT curves under deformed and undeformed conditions were measured.

The hot-rolled process covers: the ingots were rolled to 30 mm thick slabs after soaking at 1 200°C. The slabs were reheated to 1 200°C, held for 1 h and hot-rolled to 5 mm thick by 6 passes using φ 450 mm trial rolling mill. Finishing temperature was controlled at 790–820°C. After finishing rolling, they were water-cooled to coiling temper-
ature (550°C) at different cooling rates (20°C/s, 30°C/s, and 40°C/s).

Mechanical properties were determined on a tensile testing machine using the rolled specimens. The yield strength (YS; MPa), tensile strength (TS; MPa), and elongation (EL; %) were measured at room temperature according to ASTM E8 specification10) (dimensions: 180 mm×25 mm, gage length: 50 mm) using computerized tensile testing system. Microstructures of the specimens in a cross section along rolling direction were observed with a scanning electron microscope (SEM). Thin foils were prepared from the specimens for the observation of the finer ferrite and precipitation with transmission electron microscope (TEM). In order to determine the existence of retained austenite, XRD diffractometry was also used.

The volume fraction of ferrite was determined by standard procedures of point counting. Each sample was analyzed using 20 different fields, so the volume fraction is an average value. Because the microstructure consists of only ferrite and bainite, the volume fraction of bainite can be estimated by subtracting the volume fraction of ferrite from 100%. In order to obtain the bainite lath sizes, quantitative measurement was made under TEM. The procedure as follows: 100 laths were used in this statistic, the greatest length which in the parallel laths is identified as the length of bainite lath, the maximum width in the vertical direction as the width of the lath.

3. Results

3.1. The Results of Thermo-simulation

For practical purposes it is most important to know how deformation affects the kinetics of ferrite-pearlite and bainite transformations under continuous cooling condition. Continuous cooling transformation diagrams (CCT) provide a complete picture of the austenite transformation kinetics.

Figure 1 shows the CCT curves of this steel under deformed and undeformed conditions. The first and most important effect is that the hot deformation accelerates transformation of austenite to ferrite. In local austenite regions near and at the grain boundaries, the energy level increases due to deformation, and the austenite stability decreases, which favoring the ferrite nucleation process.11) Deformation also accelerates the pearlite transformation, the pearlite nucleation in both undeformed and deformed austenite proceeds mainly at grain boundaries.11) The rate of nucleation for deformed samples is higher than that for undeformed ones. For the bainite transformation, bainite start temperature (Bs) of deformed specimens is lower than that of undeformed ones. This behavior is due to the deformation accelerates bainite transformation under continuous cooling condition.12) The factors stabilizing deformed austenite are: 1) enhanced resistance to shear of a deformed grain refined austenite; 2) retardation of carbon diffusion, the greater redistribution of carbon between the phases needed for bainite transformation in deformed austenite. Formation of high density of defects in the austenite structure is supposed to suppress the bainite transformation proceeding by a shear mechanism, especially when a subgrain structure forms in austenite as a result of hot deformation.11)

3.2. The Results of Hot-rolling

Figure 2 shows the low magnification SEM of specimens at different cooling rates. It shows that when the cooling rate is 20°C/s, the microstructure is fine ferrite with small amount of bainite. As the increasing of cooling rate, the amount of bainite increased. The microstructure is mainly bainite when the cooling rate is 30°C/s, and fine and small amount of ferrite precipitates at the original austenite boundaries, as shown in Fig. 2(b). When the cooling rate reaches 40°C/s, the microstructure is almost bainite. This means that with the increasing of cooling rate, the steel enters the bainite region from austenite region, and the critical cooling rate is 20°C/s for forming bainite in this experiment conditions.

The amounts of bainite at different cooling rates were calculated, and the results are shown in Table 2. Figure 3 shows the YS and TS of specimens at different cooling rates. Coupled Table 2 with Fig. 3, when the majority of microstructures are ferrite, the YS (510 MPa) is relatively low although the ferrite grain is fine and homogeneous. If the amount of bainite reaches about 70%, the yield strength had achieved up to 700 MPa. When the cooling rate is 40°C/s and the amount of bainite above 90%, the yield strength had achieved up to 835 MPa. The above results show that the bainite plays an important role in increasing
properties of steel.

4. Discussion

4.1. Characterization of Bainite Microstructure

In order to analyze the strengthening mechanism of this low carbon steel, No. 3 specimen was observed through SEM and TEM. Figure 4 shows the relatively high magnification SEM of No. 3. The microstructure of No. 3 specimen is fine bainite, and the bainite laths are very fine. This guarantees the material having higher mechanical properties. Figure 5 shows the fine structure of bainite in No. 3 specimen observed with transmission electron microscope. From the Fig. 5, the styles of the bainite laths are interlocked each other and the laths are very fine.

A linear relationship has been determined between the yield stress and the reciprocal of the average bainitic lath diameter which is a function of the lath width and length. The results of measured lath sizes show that the average value of length is $6.9 \mu m$ and the average value of width is $0.17 \mu m$. The high strength of this steel was attributed to this fine structure of bainite.

The tiny bainite lath depends on the grain size of prior austenite. The austenite is refined through accumulated deformation, so the total grain boundary area is increased. The grain interfaces are fixed down by the strain induced precipitation of Ti, and would be the preferential nucleation sites for bainite transformation. The laths formed around austenite grain restrain the laths from traversing through the austenite grains, therefore thin and relatively short intersecting structures of bainite laths were formed.

4.2. Relationship between Strength and Ductility

XRD diffraction was used to analyze the tested specimen, and no retained austenite was detected in the specimen shown in Fig. 6. This means the improvement of elongation is not result from the exiting of retained austenite. As usually, with the increasing of strength, the amount of work hardening is reduced by grain refinement. A large volume fraction and a fine dispersion of cementite particles...
effectively increase the work hardening rate by promoting the accumulation of geometrically necessary dislocations around the particles. The good ductility in the present case can be attributed to the presence of finely dispersed cementite particles which improve the work hardening capacity.

Figure 7 shows the curves between yield strength and elongation at different accelerated cooling rates. The different strength and ductility obtained under three different crafts do not disappear other long. When the yield strength achieves 835 MPa, the elongation is 19%. The above results show as the yield strength achieves more than 700 MPa, the steel products still hold good elongation, and have good ductility.

4.3. Ti Compound Precipitation

Based on the solubility products of Ti and N, and Ti and C in austenite as indicated below, the amounts of TiN and TiC precipitates formed at the soaking temperature of 1 200°C are calculated in the present steel system.\(^\text{(1)}\)

\[
\log [\text{Ti}] [\text{N}] = -16.586/T + 5.90
\]

\[
\log [\text{Ti}] [\text{C}] = -7.000/T + 2.75
\]

According to calculation results shown in Table 3, because the concentration of Ti is relatively high, when the specimen is held at high temperature, majority of Ti will be in solution, and the solution of Ti will suppress recrystallization by solution retardation. Fine TiC particles will precipitate during the following deformation process, and there further suppress recrystallization. Therefore, the solution of Ti and its precipitation prevent the austenite grain growth and even recrystallization. When the austenite recrystallization is suppressed, the deformation storage could be inherited by the microstructure after coiling process. This leads to the refinement of bainite during bainite transformation. Ti first forms TiN in the steel, coarse TiN is the precipitated phase in the liquid state or in the process of steel solidification process. Because of coarse and sparse distribution, this TiN cannot prevent grain growth validity. In this experimental steel, the content of nitrogen is also low, so the effects of TiN on microstructure and property can be ignored. Large quantity of Ti will form TiC, tiny precipitation of TiC plays an important role in the precipitation strengthening.

Figure 8 indicates the precipitates observed in specimen No. 3. Besides these, extremely tiny Ti compound precipitates are observed in Fig. 8, these may be TiC precipitates formed during the coiling simulation. It should be known that with the TEM used in this work it is difficult to observe very small particles due to its limited spatial resolution. Consequently, no tiny particle could be exhibited in the TEM macrographs clearly.

5. Conclusions

In this study, a new type of hot rolled high strength sheet steel with excellent elongation is successfully developed. The following results are obtained.

1. The newly develop hot rolled high strength steel in yield strength of 700 MPa grade can be produced in hot rolling process.
2. The hot deformation accelerates ferrite transformation and pearlite transformation, and retards bainite transformation under continuous cooling conditions.
3. Both the fine bainite structures and precipitation strengthening contribute to high strength. When the bainite composition is more than 70%, the yield strength of steel will be higher than 700 MPa, and simultaneously ratio of tensile of yield more than 1.07 and good mechanical performances are obtained. As a result of the presence of finely dispersed cementite particles which improve the work hardening capacity, the ductility of steel is improved, with the

<table>
<thead>
<tr>
<th>Table 3</th>
<th>The amounts of TiN and TiC precipitates at 1 200°C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiN</td>
<td>0.00146% as Ti</td>
</tr>
<tr>
<td>TiC</td>
<td>0.06% as Ti</td>
</tr>
</tbody>
</table>

Fig. 6. The result of XRD analyses.

Fig. 7. Relationship between yield strength and elongation.

Fig. 8. Electron micrograph of Ti compound precipitates in specimen No. 3.
steel’s elongation being about 19%.

Acknowledgments

This project is supported by High Technology Development Program of China (863) (No. 2001AA332020) and Project of National Natural Science Foundation of China (No. 50271015).

REFERENCES

3) N. Nakada and M. Matthias: ISIJ Int., 45 (2005), 82.

© 2006 ISIJ 758