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Effects of [S] and T[O] on strength and toughness of high purification low alloy steel plates

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Abstract: The effect of [S] on strength and toughness of low alloy steel plates in which sum of [P], [N], T[O] is less than 8×10^{-5} and the effect of T[O] on strength and toughness of the steel plates in which sum of [S], [P], [N] is less than 7×10^{-5} were investigated. It is found that the strength of the steel plates decreases with increasing [S] content when [S] is less than 4×10^{-5}. When [S] varies within the range of 4×10^{-5}-1.2×10^{-4}, [S] has no significant effect on strength of the steel. The strength of the steel plates increases with increasing T[O] content when T[O] is less than 30×10^{-6}, but decreases with increasing T[O] when T[O] is more than 3×10^{-5}. The difference between the LETT in plate length direction and LETT in width direction decreases with decreasing [S] content. However, even when [S] is decreased to 9×10^{-6}, the difference of the LETT is still 16℃. When T[O] varies between 1.8×10^{-5} and 5.2×10^{-5}, the low temperature impact toughness of the steel plates slowly decreases with T[O] increasing. When T[O] increases to more than 5.2×10^{-5}, the low temperature toughness of the steel rapidly decreases with increasing T[O] content.

Key words: low alloy steel; strength; toughness; sulfur; oxygen; tough-brittle transfer temperature (LETT)

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Harmful impurities of sulfur, oxygen, *etc.* exist in steel mainly in forms of non-metallic inclusions of oxides and sulfides. There have been many researches [1-5] on the influence of sulfur, oxygen, *etc* on properties of steel products as summarized by G.C. Jiang [6]. However, steel specimens used in most of previous researches were not very pure. For instance, in Y. Kozawa's research [2] which has been widely cited, although [S] was changed from a few 10^{-6} to about 2.50×10^{-4}, total contents of T[O], [N] and [P] of the steel tested were relatively high.

Increasing steel purity to meet the ever increased demand for property of steel products is an important tendency now in iron and steel production. In order to better understand the effect of [S] and T[O] on strength and toughness of the steel products with high purity, in this study, high purified steel specimens were prepared in laboratory, in which content of impurities like [P], [N], *etc.* were kept very low except for [S] and T[O] which were solely adjusted intentionally. Thus, the influence of [S] and T[O] on strength and toughness of low alloy steel plates with high purity were investigated.

1 Experimental methods

Purchased steel bars with high purity (([P]+[S]+[N]+T[O]$<8\times10^{-5}$) were melted and refined in a vacuum induction furnace. Sulfur and total oxygen contents of the steel were adjusted in the refining. The liquid steel was cast to 25 kg ingots. The ingots were machined to remove 1 mm thick surface layer and then forged into 50 mm thick slabs. The slabs were hot rolled into 8 mm thick plates through three passes. In the hot rolling, the slab reheating temperature was 1250℃ and the reheating time was 1.5 h. The slabs were rolled from 50 mm thick to 40 mm by the first pass, from 40 mm to 20 mm by the second pass and from 20 mm to 8 mm by the last pass. The finishing rolling temperature was 950℃. **Table 1** shows the chemical composition of the specimens among which specimens of S1~S5 were used for studying the influence of sulfur and O1~O7 for influence of total oxygen. It can be seen that, except for those impurity elements which were intentionally added for studying their actions, the purities of the specimens were very high.

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After rolling, the plates were cooled in air and no heat treatment was used. The microstructure of the plates was ferrites and pearlites and the grain sizes were around 8.5 of ASTM number. Rectangular shape short portion specimens (marked length: 75 mm) were used in the tensile tests. Specimens used for impact tests were standard Charp impact sample (5mmx10mmx55mm). The impact measurement temperature varied from 20℃ to −100℃.

Table 1 Chemical composition of the specimens

No.	[C] / %	[Si] / %	[Mn] / %	[Al] / %	[P] / 10^{-6}	[S] / $\times10^{-6}$	T[O] / 10^{-6}	[N] / 10^{-6}
S1	0.15	0.30	1.41	0.021	<20	9	28	38
S2	0.15	0.30	1.39	0.022	<20	20	20	35
S3	0.14	0.31	1.38	0.023	<20	37	19	35
S4	0.14	0.28	1.33	0.017	<20	50	21	37
S5	0.13	0.26	1.33	0.017	<20	110	19	35
O1	0.12	0.30	1.42	0.024	<20	11	12	40
O2	0.12	0.27	1.40	0.018	<20	12	18	38
O3	0.15	0.30	1.41	0.021	<20	9	28	38
O4	0.12	0.22	1.37	0.014	<20	10	42	37
O5	0.11	0.17	1.37	0.015	<20	12	52	37
O6	0.12	0.28	1.47	0.010	<20	6	73	32
O7	0.14	0.16	1.21	0.010	<20	8	100	36

2 Results and discussion

2.1 Influences of [S] and T[O] on strength

Figure 1 shows the influence of [S] in the steel on the yield strength (σ_s) and ultimate strength (σ_b) of the steel plates in which sum of [P], [N] and T[O] is less than 8×10^{-5}. It is seen that, when [S] is less than 4×10^{-5}, both the yield strength and the ultimate strength of the steel plates decrease with increasing [S] content. However, when [S] content is more than 4×10^{-5}, [S] has almost no significant effect on strength of the steel plates.

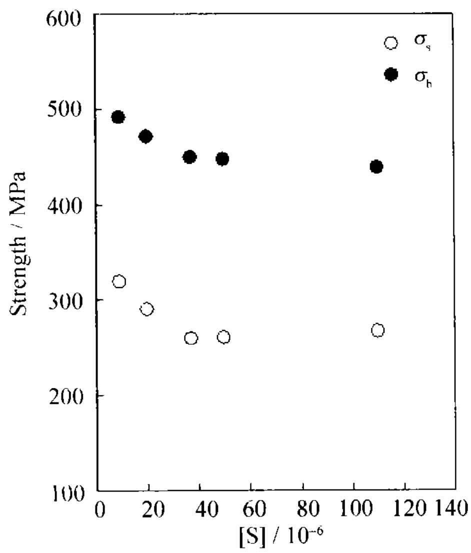

Figure 1 Influence of [S] on strength of the steel.

Figure 2 shows the influence of T[O] content on the yield strength (σ_s) and ultimate strength (σ_b) of the steel plates in which sum of [S], [P] and [N] is less than 7×10^{-5}. It can be seen that, when T[O] in the steel is less than 3×10^{-5}, both the yield strength and ultimate strength of the steel increase with increasing T[O] content. However, when T[O] is more than 3×10^{-5}, the strength of the steel plates decreases with increasing T[O] content. It is found in the study that there are mainly two types of oxide non-metallic inclusions in the steel. One is the single block shaped Al_2O_3 inclusions and another type is the Al_2O_3 clusters. The single block shaped Al_2O_3 inclusions are small and their sizes are usually around 2-4 μm (**figure 3** (a)). It is considered that fine non-metallic inclusions can increase the strength of steel products [8]. In this study, most of the oxide non-metallic inclusions are fine single block shaped Al_2O_3 in specimens which T[O] contents are less than 3×10^{-5}. These typed inclusions are uniformly distributed in the steel plates and can act as second phase particles to strengthen the steel. While, in steel plates containing more than 3×10^{-5} T[O], there exist more cluster typed Al_2O_3 inclusions which consequently results in the decrease of the steel strength with increasing steel T[O] content.

2.1 Influences of [S] and T[O] on impact toughness

It is found that, when [S] is changed within the range between 9×10^{-6} to 1.1×10^{-4} in the steel specimens in which sum of [P], [N] and T[O] is less than 8×10^{-5}, the impact toughness of the specimens is very good at room temperature and [S] has almost no effect on impact toughness at room temperature. However, at low temperature, the impact toughness of the plates decreases with increasing [S] content.

In the study, the tough-brittle transfer temperature (LETT) of the specimens is determined with side face swell measurement method. **Figure 4** shows the relation between [S] content and the tough-brittle transfer temperature of the steel specimens. It is seen that the LETT values both in the plate length direction and width direction of the steel plates increase with increasing [S] contents. The LETT values in width direction are higher than those in the length direction. The difference of the LETT values in different directions decreases with decreasing [S] contents. However, even when [S] is decreased to 9×10^{-6}, the difference of the LETT in different directions of the plates is still as high as 16℃.

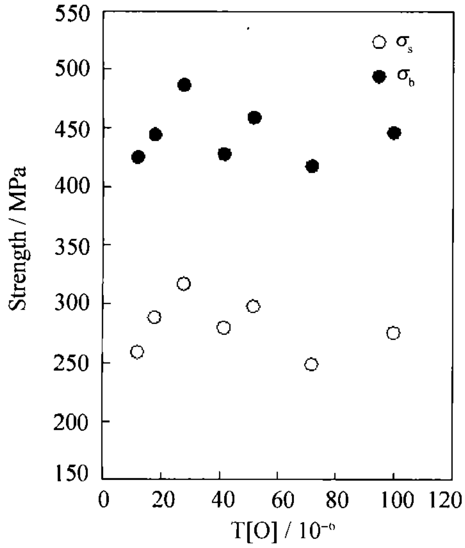

Figure 2 Influence of T[O] on strength of the steel.

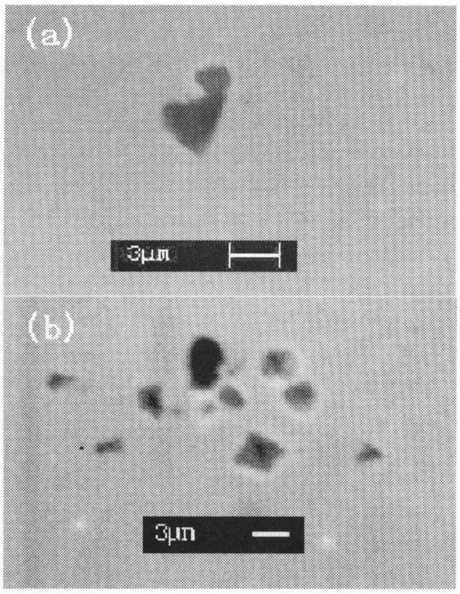

Figure 3 Single block shaped Al_2O_3 inclusion (a) and Al_2O_3 clusters in steel specimens (b).

It is found that sulfur in specimens exists mainly in form of MnS inclusions. MnS is of plastic typed nonmetallic inclusion. After hot rolling, MnS inclusions are deformed and exist in the plates in forms of catenarian shaped (**figure 5** (a)) or strip shaped (figure 5(b)) inclusions. The deformation of MnS inclusions along the length direction of the plates after rolling is the main reason why the LETT values in the length and width direction are different.

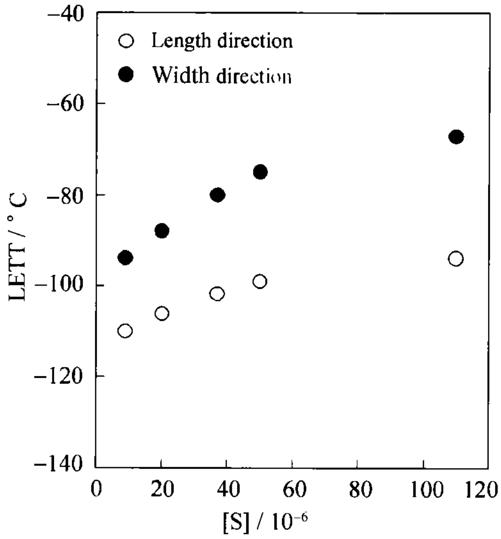

Figure 4 Influence of [S] on the LETT values.

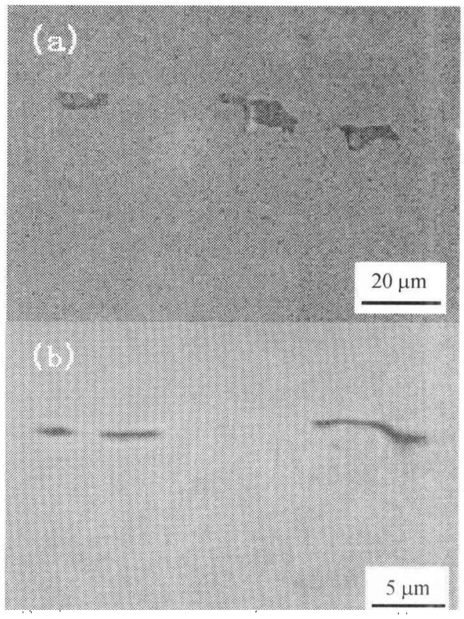

Figure 5 MnS inclusions observed in steel specimens, (a) catenarian shaped inclusions; (b) strip shaped inclusions.

It is also found that the impact toughness of the specimens is good at room temperature when T[O] is changed from 1.2×10^{-5} to 1×10^{-4} in the steel plates in which the sum of [S], [P] and [N] is less than 7×10^{-5}. T[O] has almost no effect on room temperature toughness of the steels.

Figure 6 shows changes of impact toughness of the steels respectively at −60℃ and −80℃ with steel T[O] contents. It can be seen that the low temperature impact toughness of the steel decreases with increasing T[O] contents. When T[O] varies within the range of 1.2×10^{-5}-1.8×10^{-5}, the low temperature toughness of the steel rapidly decreases with increasing T[O] contents. However, when T[O] contents are between 1.8×10^{-5}-5.2×10^{-5}, the decrease of the toughness of the steel with increasing T[O] becomes slow. When T[O] contents of the steels are between 7.2×10^{-5}-1×10^{-4}, the low temperature of the steel impact toughness again very rapidly decreases with increasing T[O] contents.

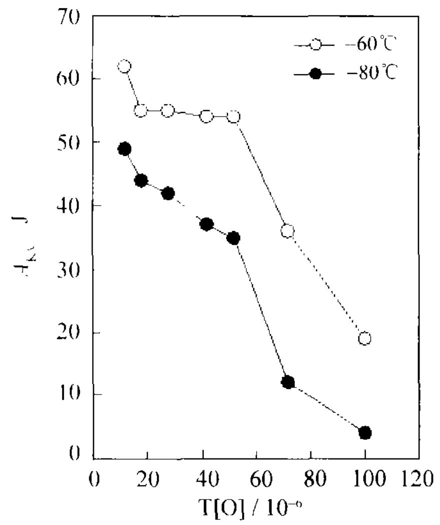

Figure 6 Influence of T[O] on impact toughness.

Figure 7 shows the effect of the T[O] contents on the tough-brittle transfer temperature of the steels (LETT). It is seen that T[O] contents have no significant effect on LETT values of the steels when T[O] contents are changed between 1.2×10^{-5}-5.2×10^{-5}. However, when T[O] increases to be more than 5.2×10^{-5}, the LETT values of the steel rapidly increase with increasing T[O] contents.

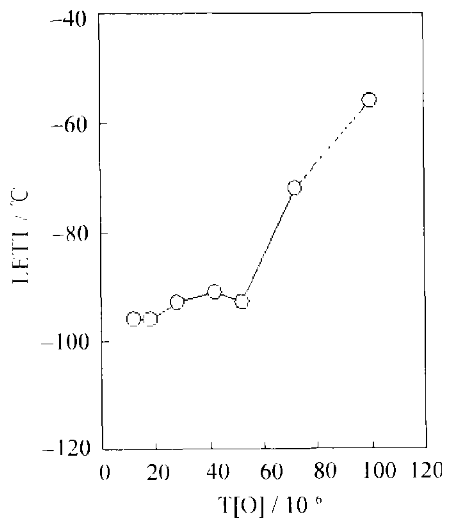

Figure 7 Influence of T[O] on LETT values.

3 Conclusions

(1) Both the yield strength and the ultimate strength of the steel plates decrease with increasing [S] contents when [S] is less than 4×10^{-5}. However, when [S] varies within the range of 4×10^{-5}-1.2×10^{-4}, [S] has no significant effect on strength of the steel.

(2) The strength of the steel plates increases with increasing T[O] contents owing to the strengthening action played by the fine oxide nonmetallic inclusions as the second phase particles in the steel when T[O] is less than 3×10^{-5}. When T[O] is more than 3×10^{-5}, the strength of the steel decreases with increasing T[O] contents.

(3) When [S] varies within the range 9×10^{-6}-1.1×10^{-4}, the impact toughness of the steel plates is very good at room temperature and [S] has almost no effect on room temperature toughness. The LETT values of the steel plates increase with increasing [S] contents. The difference of the LETT values in plate length direction and width direction decreases with decreasing [S] contents. However, even when [S] is decreased to 9×10^{-6}, the difference of the LETT in different direction of the plates is still as high as 16℃.

(4) When T[O] varies between 1.8×10^{-5} and 5.2×10^{-5}, with increasing T[O] contents, the low temperature impact toughness of the steel plates slowly decreases and the LETT value slowly increases. When T[O] increases to more than 5.2×10^{-5}, the low temperature toughness of the steel rapidly decreases and the LETT value rapidly increases with increasing T[O] contents.

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