The Effects of Alloying Elements on Thermal Fatigue and Thermal Shock Resistance of the HSLA Cast Steels

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(Received on April 19, 2000; accepted in final form on July 31, 2000)

The effects of alloying elements on thermal properties of the HSLA (High Strength Low Alloy) cast steels have been investigated by thermal fatigue, thermal shock, and tensile tests. The thermal fatigue resistances of the HSLA cast steels were superior to those of SC42 cast steels. Excellent thermal resistances of the HSLA cast steels were mainly caused by high thermal conductivity, elastic modulus and tensile strength. In case of the HSLA cast steels, the steels with both Nb and V had more excellent thermal fatigue life than those with Nb or V individually. Increment of C contents gave a harmful effect on thermal fatigue resistance. In case of Mn contents, HSLA cast steels with 1.2% Mn content had the highest thermal fatigue life among them and that with 1.5% Mn had lower thermal fatigue life than that with 1.2% Mn content. This result was attributed to rapidly increased bainitic acicular structure obtained by high Mn contents. Therefore, the optimum composition of HSLA cast steels to obtain the highest thermal fatigue resistance was 0.1%C–1.2%Mn–0.05%Nb–0.05%V, resulting in polygonal ferrite plus small amounts of bainitic microstructure. Thermal shock resistance of HSLA cast steels was also superior to that of SC42 cast steels. However, the difference between the HSLA cast steels with both Nb and V, and those with Nb or V individually has not been found.

KEY WORDS: thermal fatigue; thermal shock; HSLA cast steels; C–Mn cast steels; SC42; microalloyed steels; carbon; manganese; niobium; vanadium.

1. Introduction

Strength of C–Mn cast steels (SC42 etc.) used for structural steels and vessels like a slag pot subjected to thermal cycling conditions can be enhanced by raising the carbon contents. However, high carbon contents lead to adverse effects on toughness and weldability. C–Mn cast steels have low mechanical properties at elevated temperatures, so the steels can be substituted by highly alloyed cast steels to enhance mechanical properties at high temperature. However, high alloying induces not only cost up but decrease of weldability due to high carbon equivalent. HSLA (High Strength Low Alloy) cast steel can solve both of these problems. The known of physical metallurgy principle of HSLA wrought steel, which has improved mechanical properties by precipitation and fine ferrite grain size by adding small amounts of microalloying elements (usually Nb, V and Ti) may also be applied to cast steel, even though significant differences can be expected in the final compositions, microstructure and processing.11

Substitution of C–Mn cast steels with HSLA cast steels also leads to excellent weldability by lowering C content as well as weight and cost saving. In addition, excellent mechanical properties can be expected at elevated temperatures by stable precipitations.2 3 In spite of these potential applications where HSLA cast steels may be appropriate, at the present time, there has been only limited study with thermal fatigue,9 the use and specification of HSLA cast steel.11 Especially, there are no experimental and comparable data of thermal fatigue and thermal shock resistances under repeated thermal cycling between C–Mn cast steels and HSLA cast steels. In addition, the mechanism of thermal fatigue fracture of HSLA cast steels has not been reported yet.

Thermal fatigue and thermal shock tests were carried out to compare C–Mn cast steels with HSLA cast steels. Moreover, the effects of alloying elements such as Nb, V, C, and Mn contents on thermal fatigue resistance were investigated by thermal fatigue and thermal shock tests.

2. Experimental Procedure

2.1. Materials

Chemical compositions and heat treatment conditions used in this study are shown in Table 1. Specimens with different C and Mn contents and specimens microalloyed with Nb and/or V were designed for comparing thermal properties. C–Mn cast steel (SC42) and various HSLA cast steels were prepared by induction melting furnace. HSLA cast steels were prepared by heat treatments such as homog-
enization at 1323 K for 2 hr, austenitization at 1423 K for 4 hr and air cooling for grain refinement and precipitation hardening and tempering at 873 K for 4 hr.

2.2. Thermal Fatigue Test

The geometries of the thermal fatigue specimens are shown in Fig. 1. Specimens with 18 mm gauge length and 8 mm diameter were used for the first casting materials (HSLA 1-1 and HSLA 1-3) and specimens with notch of R16 as shown in Fig. 1 (b) were used for the second casting materials (HSLA 3-2–3-10). In this way, fatigue cracks will be created only at notched area of between extensometers tips (strain gage) enabling the observation of crack behavior. The thermal fatigue tests were carried out under thermal cycles which could be controlled by using induction heating device of 10 kW and compressive air spray from the nozzle of the circular coil with maximum heating temperature \(T_{\text{max}}\) of 773, 823, 873 and 923 K and minimum temperature \(T_{\text{min}}\) of 373 K. During the thermal cycles, temperature was measured by a thermocouple that was spot welded at a gauge portion of the sample and was controlled by a temperature controller.

After holding the sample at mean temperature \(T_{\text{mean}}\) for 1 min, thermal fatigue tests were performed in a thermal cycle sequence of \(T_{\text{mean}}\rightarrow T_{\text{max}}\rightarrow T_{\text{mean}}\rightarrow T_{\text{min}}\rightarrow T_{\text{mean}}\) under completely constrained condition to keep strain at zero. Therefore, compressive stress was acquired during thermal expansion while tensile stress was acquired during thermal contraction.

2.3. Thermal Shock Tests

Thermal fatigue tests were used to determine the effects of rapid change in temperature on the properties of cast steels. The geometry of the specimen for thermal shock is a hole of 2 mm diameter and 10 mm depth with notches at both side of the center of rectangular specimen with 100 mm width, 100 mm height and 20 mm thickness. Thermal shock test conducted to generate a large temperature variation in a short time. In case of water quenching, the hole of specimen was heated suddenly with a flame torch using oxygen and acetylene for 23 sec. Immediately, it was quenched in water through nozzle for 15 sec. This thermal shock cycles were repeated for 200 cycles for each specimen. In case of air cooling, compressive air was used to cool the hole instead of water for 300 cycles. Crack initiation and propagation behaviors caused by thermal shock were investigated at around hole.

3. Results and Discussions

3.1. Thermal Fatigue Properties

Relationship between temperature, stress, and time during the thermal fatigue test is shown in Fig. 2. When temperature was increased from \(T_{\text{mean}}\) to \(T_{\text{max}}\), compressive stress was generated for compensation of thermal expansion by temperature rise, and tensile stress was generated for compensation of thermal contraction by temperature drop. Finally, strain during the thermal cycle was held at zero. Maximum compressive stress \(\sigma_{\text{min}}\) was generated at \(T_{\text{max}}\) and maximum tensile stress \(\sigma_{\text{max}}\) was generated at \(T_{\text{min}}\). As shown in Fig. 2, however, the absolute value of \(\sigma_{\text{min}}\) is smaller than that of \(\sigma_{\text{max}}\). This reason can be explained by Eq. (1).

The Eq. (1) indicates thermal stress represented by \(E\), \(\alpha\), and \(\Delta T\).

\[
\sigma = E\alpha\Delta T \tag{1}
\]

\(E\) : Modulus of elasticity

Table 1. Chemical compositions and heat treatment of the C–Mn cast steels and the HSLA cast steels.

| Elements | Chemical composition (wt%) | Heat treatment |
|----------|---------------------------|----------------|
| SC42     | C 0.20, Mn 0.79, Nb -   | S/P < 0.02, Si 0.45 |
| HSLA 1-1 | 0.10, 0.65, 0.10        | Homogenization (1232 K, 2hr) + Air cooling |
| HSLA 1-3 | 0.10, 0.65, 0.05         | A austenitization (1423 K, 4hr) + Air cooling |
| HSLA 3-2 | 0.10, 0.66, 0.10        | Tempering (873 K, 4hr) |
| HSLA 3-3 | 0.15, 0.65, 0.10        |                |
| HSLA 3-4 | 0.10, 0.66, 0.05         |                |
| HSLA 3-6 | 0.10, 0.66, 0.05         |                |
| HSLA 3-8 | 0.10, 1.50, 0.05         |                |
| HSLA 3-10| 0.16, 1.50, 0.05        |                |

Fig. 1. Dimensions of the thermal fatigue test specimens. (unit:mm)

Fig. 2. Schematic diagram showing the relationships between temperature, stress, and time during the thermal fatigue tests.
Modulus of elasticity is decreased as temperature is increased, which indicates that the constrained stress level to keep the zero strain at high temperature is lower than that at low temperature. So, the absolute value of thermal stress in Eq. (1) at higher temperature range between the $T_{\text{mean}}$ and $T_{\text{max}}$ is smaller than that at lower temperature range between the $T_{\text{mean}}$ and $T_{\text{min}}$.

Variations of the maximum thermal stress during thermal cycles to failure with the number of cycles are shown in Fig. 3. The curves indicates that both maximum tensile stress and maximum compressive stress are increased as thermal cycles are in progress.

This cyclic hardening may be attributed to work-hardening caused by dislocation pile-up during thermal cycles. Figure 4 shows hardness of unheated and heated zones after thermal fatigue tests, in which cyclic hardening can be confirmed by the fact that hardness of heated zones is higher than that of unheated zones.

Absolute values of maximum tensile stresses and maximum compressive stresses of the HSLA cast steels were higher than those of the SC42 cast steel. This could be due to differences in thermal expansion coefficient and modulus of elasticity between HSLA cast steels and SC42. In case of materials with high thermal expansion coefficient, higher negative or positive thermal stress is induced than that with low thermal expansion coefficient by repeated thermal cycles. Moreover, the high elastic modulus materials need higher stress to constrain it to keep zero strain. Thermal expansion coefficient of SC42 and HSLA cast steels were similar in my previous work. Consequently, the difference of absolute value of maximum stress between SC42 and HSLA cast steels may be caused by higher elastic modulus of HSLA cast steels than that of SC42. The sudden drop of maximum thermal stresses with thermal cycling is attributed to crack initiation and propagation followed by failure.

Figure 5 shows the relationship between maximum heating temperature and number of cycles to failure for SC42 and HSLA cast steels with notched specimens. Thermal fatigue life of test specimens appears to be decreased as the maximum heating temperature is increased for all cast steels investigated. This is due to high thermal stress by large temperature difference ($\Delta T$) applied to specimens. Figure 5 also shows that HSLA cast steel has higher thermal fatigue resistance compared to SC42, which is significant as the maximum temperature is decreased.

Figure 6 shows the thermal fatigue life of the first cast specimens without notch. Test condition was $T_{\text{max}}$ and $T_{\text{min}}$.
of 873 K and 373 K, respectively. From comparison of the number of cycles to failure for various materials, thermal fatigue resistance of HSLA cast steels was superior to those of SC42. Among HSLA cast steels, the steels with both Nb and V had better thermal fatigue life than those with Nb or V individually. This result could be explained by the magnitude of Eichelberg quality factor as indicated in Eq. (2).

\[
\text{Eichelberg quality factor} = \frac{(1-v) \cdot K \cdot \sigma_u}{E \cdot \alpha} \quad (2)
\]

\(v\): Poisson’s ratio  
\(K\): Thermal conductivity  
\(\sigma_u\): Tensile strength at experimental temperature  
\(E\): Modulus of elasticity  
\(\alpha\): Thermal expansion coefficient

Eichelberg adopted the concept of quality factor as a measure of iron’s resistance to thermal fatigue. The quality factor incorporates various properties which can influence on thermal fatigue. Even though the use of quality factor to predict thermal fatigue resistance is limited, we could apply it to the cast steels. The Eichelberg quality factor increases as thermal conductivity and tensile strength increase. Figure 7 shows that tensile strength of HSLA cast steels is higher than that of SC42, and HSLA cast steel with both Nb and V (HSLA 1-3) shows high tensile strength compared to that with individual addition (HSLA 1-1). Table 2 indicates that HSLA cast steels have higher thermal conductivity than SC42 cast steels at all experimental temperatures. As mentioned above, thermal expansion coefficient of SC42 and HSLA cast steels were similar, but elastic modulus of SC42 was lower than HSLA cast steel. Poisson’s ratio is the same for most cast steels. From these data, it is possible to get the relative Eichelberg quality factor for each specimen. So, it was predicted that thermal fatigue life of HSLA cast steels was higher than that of SC42, and that of HSLA cast steel with both addition (HSLA 1-3) was higher than with individual addition (HSLA 1-1). The influences of C and Mn on thermal fatigue life of cast steels have been investigated. Figure 8 shows the results of thermal fatigue tests of the second cast materials. HSLA cast steels had ten times higher thermal fatigue life than that of SC42. HSLA 3-2 with 0.1% C contents had higher thermal fatigue life than HSLA 3-3 with 0.15% C contents. In case of HSLA 3-10 cast steel and HSLA 3-8 cast steel with 1.6% Mn content but having different C contents show the same results in terms of the C content effects. Consequently, as the C contents is increased, thermal fatigue lifes are decreased, that is, C had a detrimental effects on thermal fatigue resistance.

In case of Mn effects on thermal fatigue properties of HSLA cast steels with 0.1% C, 0.05% Nb, and 0.05% V, HSLA cast steels with 1.2% Mn content have the highest thermal fatigue life among 0.6, 1.2 and 1.6% Mn content. From this result, it is considered that HSLA cast steel with proper Mn content has the highest thermal fatigue life. According to Figs. 8 and 9, thermal fatigue life is, on the whole, proportional to tensile strength except HSLA 3-3, 3-8 and 3-10. HSLA 3-8 and 3-10 have low thermal fatigue life in spite of very high tensile strength by the increment of C and Mn contents. This can be explained by comparison.
of optical microstructures.

**Figure 10** shows the microstructures of HSLA 3-2 to HSLA 3-10 specimen. According to references, \(^2,^4,^5\) 0.4 % Mo containing Nb-V HSLA steel which is similar to our tested specimens in composition produces a microstructure which is predominantly low carbon bainite. 0.5 % Mo addition in tested specimens, namely, widen the bainite zone and shift pearlite nose to the left at CCT diagrams. So, it is expected that the microstructures of HSLA 3-2 to HSLA 3-10 specimen have the bainitic structure at air cooling condition. We recognized that the white areas represent a ferrite and the dark areas represent a bainitic structure in Fig. 10. The microstructures of HSLA 3-2 to HSLA 3-6 specimen have no significant difference in fraction of ferrite. However, fraction of ferrite for HSLA 3-8 and 3-10 is lower than that of HSLA 3-6 by transformation temperature decreases. Acicular bainitic structure has lower thermal conductivity than ferrite.\(^{14,15}\) Thus, it induces large thermal stresses compared to ferrite. There is a possibility that bainitic structure acts as stress concentration sites to initiate cracks. For this reason, HSLA 3-8 and 3-10 have lower thermal fatigue lifes in spite of very high tensile strengths. From the above results, the optimum composition of HSLA cast steels for excellent thermal fatigue resistance was 0.1%C–1.2%Mn–0.05%V with polygonal ferrite and small amounts of bainite.

**Figure 11(a)** shows the crosssectional microstructure of surface to see crack initiation by optical microscope. It is observed that only one among many microcracks propagates. Figure 11(b) shows the morphology of crack tip. This figure reveals the crack propagates in transgranular mode during thermal fatigue test, and this tendency is the same for all test specimens. **Figure 12** shows SEM fractographs for thermal fatigue test specimens showing the outline of striations which can be seen at typical fatigue test.

3.2. **Thermal Shock Properties**

Thermal shock properties are much affected by thermal conductivity and thermal expansion coefficient by a sudden temperature change. **Figure 13** shows crack growth of thermal shock specimens after water quenching 200 cycles and air cooling 300 cycles.

In both cases, SC42 with low thermal conductivity shows more extensive cracks than HSLA cast steels. These results are due to the fact that small thermal gradients for HSLA cast steels may be produced because HSLA cast steels have higher thermal conductivity than SC42, as shown in Table 2. However, HSLA 1-1 and HSLA 1-3 show no difference in crack size and number.

4. **Conclusions**

From the investigation of the effects of alloying elements on thermal fatigue and thermal shock properties of the cast steels, following conclusions were obtained.

1. Cyclic hardening has occurred as thermal cycles are repeated. Thermal fatigue life was decreased as the maximum heating temperature was increased because of increase of thermal stress.

2. Thermal fatigue resistance of HSLA cast steels was superior to that of C-Mn cast steels. The excellent thermal fatigue resistance of HSLA cast steels compared with C-Mn cast steel (SC42) was mainly caused by high thermal conductivity, elastic modulus and tensile stress. HSLA cast steels with both Nb and V have higher thermal fatigue life.
than with Nb or V individually.

3. Increment of C contents gave a harmful effect on thermal fatigue resistance.

4. In case of Mn contents, HSLA cast steels with 1.2% Mn content had the highest thermal fatigue life among them and that with 1.5% Mn had lower thermal fatigue life than that with 1.2% Mn content. This result was attributed to rapidly increased bainitic acicular structure obtained by transformation temperature decrease due to high Mn contents. Acicular bainitic structure acts not only as stress concentration sites but also lowering thermal conductivity. Therefore, the optimum composition of HSLA cast steels for the improved thermal fatigue property was 0.1%C –1.2%Mn–0.05%Nb–0.05%V with polygonal ferrite and small amounts of bainite.

5. Thermal shock resistance of HSLA cast steels was also superior to that of SC42 cast steels. However, the difference between the HSLA cast steels with both Nb and V, and those with Nb or V individually has not been found.

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