COMPARISON OF FATIGUE PROPERTIES OF WELDED TMCP STEEL AND NORMALIZED STEEL

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ABSTRACT

In this study, high cycle fatigue (HCF) and low cycle fatigue (LCF) properties of welded thermo-mechanically controlled process (TMCP) steel were investigated and compared with those of welded normalized steel. Microstructures of TMCP steel consisted of finer grains than normalized steels regardless of welding process. Tension test showed that welded TMCP steel revealed higher yield strength, but lower tensile strength as compared to those of welded normalized steel, resulting in the higher yield ratio (σ_{ys}/σ_{ts}). The fatigue limit (obtained by HCF test) was slightly higher in welded normalized steel than in welded TMCP steel. However, the fatigue ratio, represented by fatigue limit normalized by tensile strength, of welded TMCP steels was observed to be 0.84 much higher than that of welded normalized steel (0.78). Therefore, it was concluded that the HCF resistance of TMCP would be better than normalized steels with similar tensile strength. Both microstructures showed significant cyclic softening during the low cycle fatigue test, and cyclic strains were found to concentrate in the base metal resulting in the fracture. The LCF life of TMCP steels was less than that of normalized steels, which was explained by the difference of cyclic softening behavior of two steels.

KEYWORDS

TMCP steel; high cycle fatigue; low cycle fatigue; plastic constraint; fatigue ratio; cyclic softening

1. INTRODUCTION

During the last several decades, steel-making industries have focused their efforts to produce steels with higher toughness, better weldability and less expensive alloying elements. Concurrently, there has been a trend towards the use of higher strength steels to reduce structural weight and fabrication costs. This has been partly possible by introducing a thermo-mechanically controlled process (TMCP) which combines controlled rolling with on-line accelerated cooling [1]. The microstructures of TMCP steels are greatly refined as compares to those of conventional processed steels, resulting in a significant improvement in strength and toughness [2]. However, it is usually observed that fatigue strength does not exactly follow the trend of increasing strength, and the trend is rather reversed in the case of welded components [3].

A welded joint consists of three zones, i.e., weld metal, heat affected zone (HAZ) and base metal. In general, the HAZ is hardened after welding especially at the region adjacent to the fusion line. However, the softened zone is often generated in the HAZ adjacent to the base metal of TMCP steel, which is contrary to the case of conventional normalized high strength steel [4-5]. This softened zone has often been found to form when welding thick steels with high heat input, which greatly reduces the fatigue resistance of the weldment [6-7]. In this study, with the suppression of

softened zone by the optimization of welding heat input, cyclic fatigue (HCF and LCF) properties of TMCP steel were investigated and compared with those of normalized steel both in the as-received and welded conditions.

2. EXPERIMENTAL PROCEDURES

The materials used in this study were TMCP steel and normalized steel with a form of thick plate (t ≈ 25 mm), and their chemical compositions are listed in Table 1. For the welding process, the electro-gas welding was adopted and completed in a single pass with a heat input amount of a 150 kJ/cm. The welding direction was normal to the rolling direction of the base material.

Table 1 Chemical compositions of TMCP steel and normalized steel (wt. %).

Materials	C	Si	Mn	P	Al	Ti	C_{eq}
TMCP steel	0.093	0.262	1.31	0.008	0.049	0.011	0.329
Normalized steel	0.150	0.457	1.42	0.016	0.036	0.003	0.415

Tensile and fatigue tests were performed using cylindrical specimens (diameter of 9 mm and gage length of 25 mm) containing welds. Gage section included base metal, HAZ and weld metal, locating HAZ at the middle of the gage length [8]. Vickers hardness test was made under a 300 g load along a line crossing base metal, HAZ and weld metal. Tensile tests were performed at constant crosshead speed with the initial strain rate of 5×10^{-3} s^{-1}; three samples were tested for each condition. Here, tensile specimens with longer gage length (diameter of 9 mm and gage length of 50 mm) were also made and tested to estimate the effect of plastic constraint.

High cycle fatigue tests were conducted at room temperature under the following conditions; the frequency of 20 Hz, R = 0 and sinusoidal wave form. Then, S-N curves were drawn, and fatigue strength was measured when specimen did not fail at 10^7 cycles. Low cycle fatigue tests were performed in a fully reversed axial-strain controlled condition by varying total strain amplitude ($\Delta\varepsilon_t/2$) from 2×10^{-3} to 8×10^{-3}. Triangular wave was used with a frequency of 0.5Hz. The axial-strain was measured using an extensometer mounted on the specimen. Sometimes, two extensometers were utilized to observe strain difference between the base metal and the weld metal.

3. RESULTS AND DISCUSSION

3.1 Microstructures

Figure 1 shows the microstructures of the TMCP steel and the normalized steel both consisting of ferrite and pearlite phases. In both microstructures, pearlite (dark phase in Fig. 1) phase was formed as a band elongated to the rolling direction. It was also noted that the ferrite grain size (≈16μm) of TMCP steel was much smaller than that (≈23μm) of normalized steel. Also, the pearlite volume fraction was smaller in the TMCP steel (≈15%) as compared to the normalized steel (≈23%), which was due to the less carbon content in the TMCP steel. After welding two plates of each steel, microstructures were investigated at low magnification (Fig. 2) and also at high magnification (Fig. 3 and Fig. 4) along the line crossing weld metal, HAZ and base metal. The microstructures of weld

metal consisted of grain boundary ferrite and acicular ferrite. In the HAZ, the microstructure revealed coarse ferrite and bainite phases [9] and ferrite grains became coarser approaching the fusion line.

Microhardness distributions in various regions of the welded specimen are presented in Fig. 5. Due to the high hardness of the welding consumable used, the hardness of the weld metal was very high in both microstructures. However, normalized steel showed peak hardness in the HAZ region, and then dropped rapidly to become identical to that of base metal. This trend was somewhat different to the case of the TMCP steel, which was attributed to the higher amount of bainite formed in the HAZ of normalized steel as compared to the TMCP steel.
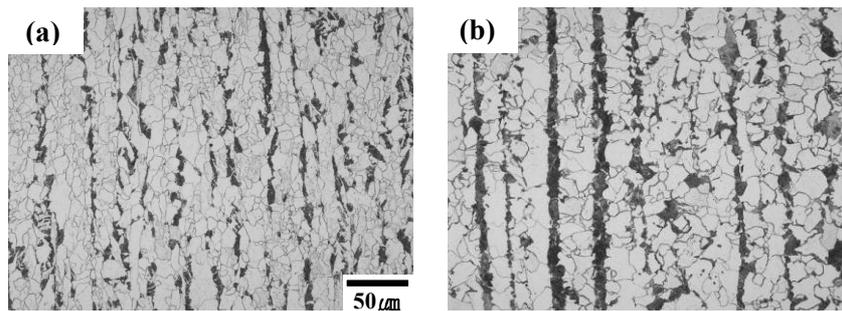

Fig. 1 Micrographs of the (a) TMCP steel and (b) normalized steel. Nital etched.
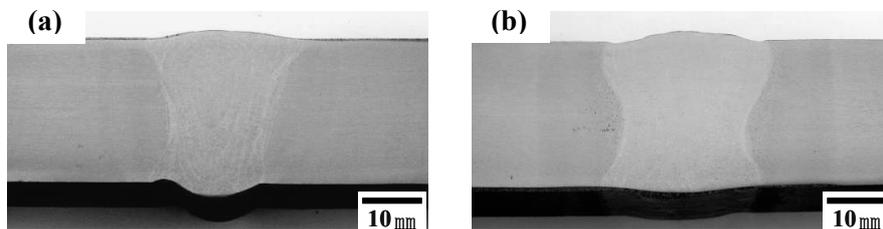

Fig. 2 Macrographs of the weld cross sections; (a) TMCP steel and (b) normalized steel.
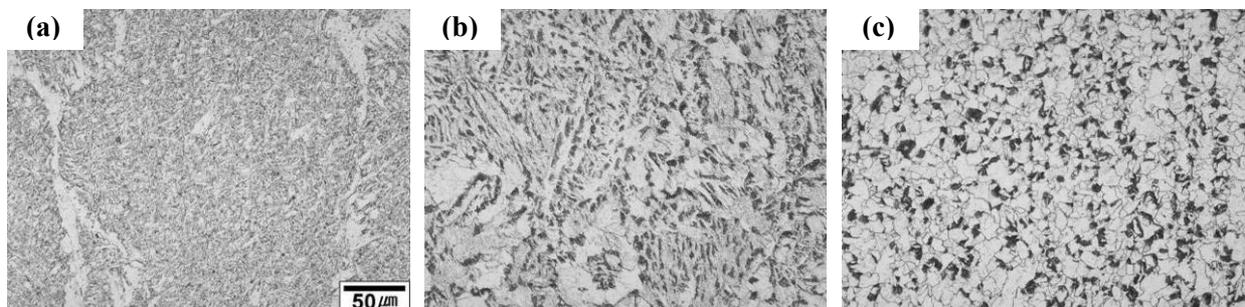

Fig. 3 Microstructures showing welded region of TMCP steel;
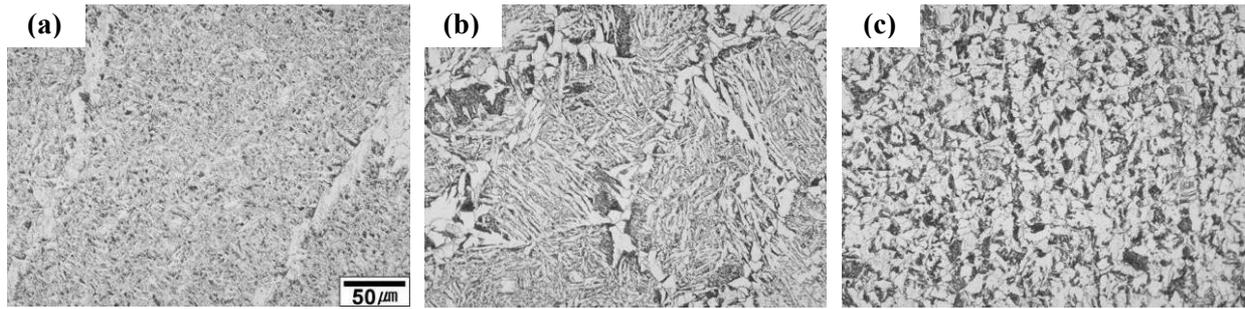(a) weld metal, (b) fusion line+1mm (c) fusion line+5mm.

Fig. 4 Microstructures showing welded region of normalized steel;
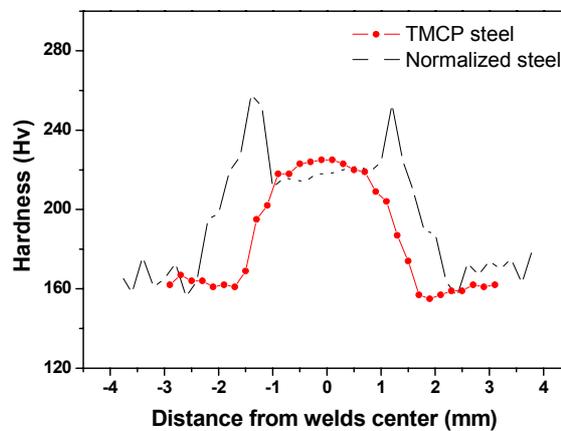(a) weld metal, (b) fusion line+1mm (c) fusion line+5mm.

Fig. 5 Hardness of welded specimens measured along the direction normal to the weld line.

3.2 Tensile properties

The tensile properties of the present steels are listed in Table 2. For the base metals, yield strength and elongation of the TMCP steel were higher than those of the normalized steel, while tensile strength of normalized steel was about 10% higher than TMCP steel. Accordingly, yield ratios (σ_{ys}/σ_{ts}) of the TMCP steel were higher than those of normalized steel. In the case of welded specimens, tensile strengths were slightly increased (and elongations were correspondingly decreased) as compared to the base metals, while yield strengths were remained constant.

Table 2 Nominal tensile properties of the steels used in this study.

Specimen		YS[*], MPa	UTS, MPa	El., %	Yield ratio
TMCP	Base metal	389	502	38.0	0.77
	As-welded (G[**]=25mm)	378	527	23.1	0.72
	As-welded (G=50mm)	385	517	25.4	0.74
Nor.	Base metal	370	548	36.1	0.68
	As-welded (G=25mm)	364	578	22.5	0.63
	As-welded (G=50mm)	369	553	23.2	0.67

[*]lower yield strength, [**]gauge length

The reason for the higher tensile strength of the welded specimens as compared to the base metal can be explained by the effect of plastic constraint between hard zone and soft zone. During the plastic deformation for the welded specimens, the base metal undergoes plastic deformation first due to its lower strength than HAZ and weld metal. The base metal adjacent to the HAZ becomes arrested by hard HAZ and weld metal with continued plastic deformation, resulting in the increase of tensile strength. This effect would be differentiated if the gage lengths of two specimens are markedly different. Table 2 shows that tensile strengths of 25 mm gage specimen were higher than those of 50 mm gage specimen, which evidences the effect of plastic constraint. In all specimens, tensile fracture occurred at the base metal adjacent to the HAZ.

3.3 High cycle fatigue properties

The S-N curves of base metals and welded steels are shown in Figure 6. Although there were slight differences in the fatigue life at high stress amplitude, the fatigue strengths (at 10^7 cycles) of TMCP and normalized steels were almost similar to each other both in the base metals and welded steels. It is noted that welded specimen represented higher fatigue strength than the base metal, which was attributed to the higher tensile strength of welded specimen (Table 2). In order to understand which microstructure represents better fatigue resistance, it is desirable to compare the fatigue strength of two steels having the identical tensile strength. Since tensile strengths of two steels used in this study were different, fatigue ratios (σ_f/σ_{ts}) were estimated and compared (Figure 7). It is important to note in Fig. 7 that fatigue ratios of TMCP steel (both in the base metals and welded steels) were much higher than those of normalized base metal, implying excellent high cycle fatigue resistance of TMCP steel as compared to the normalized steel.
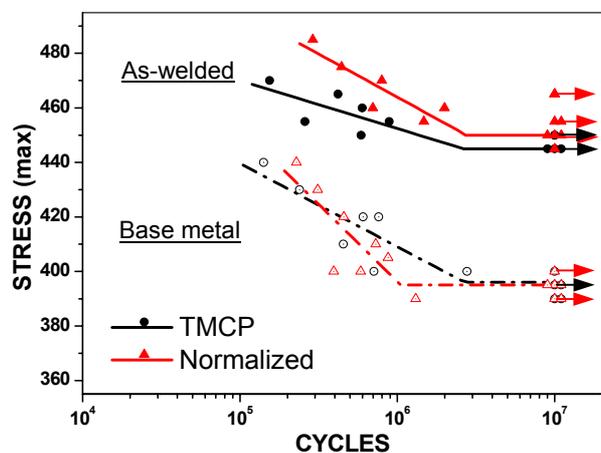

Fig. 6 S-N curves (R=0) of TMCP and normalized steels.

The significant increase of fatigue strength in welded specimens can be explained as follows. During the high cycle fatigue testing, cracks normally initiate at the specimen surfaces, especially at the location of high stress concentration such as grain/interface boundaries and at the slip band intrusions or extrusions. In the case ferrite and pearlite microstructure, ferrite and pearlite interfaces are the susceptible crack initiation sites. Therefore, TMCP steels containing less volume fraction of pearlite would represent better fatigue resistance than normalized steel. In addition, surface cracks usually start to initiate inside the soft phase [10]. Therefore, it is reasonably considered that the

welded specimens having smaller area of (soft) base metal would represent higher fatigue strength than the base metals comprised of soft phase only.
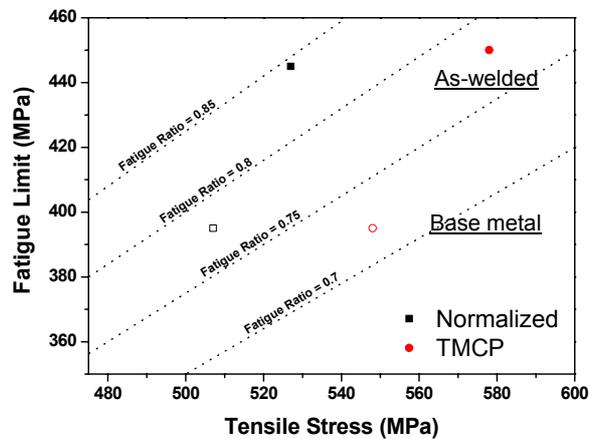

Fig. 7 Relation between fatigue strength and ultimate tensile strength of steels used in this study.

3.4 Low cycle fatigue properties

Figure 8 shows the total strain amplitude ($\Delta\varepsilon_t/2$) versus the number of cycles to failure ($2N_f$) for base metals and welded steels. In contrast to the case of high cycle fatigue, low cycle fatigue lives of welded specimens were much less than those of the base metals. Upon cyclic loading, plastic strains would be concentrated in the soft base metal, the effect of which would be more significant in the welded specimens. To estimate the strains imposed on the base metal and the weld metal, respectively, two strain gages were attached at the base metal and the weld metal of a specimen simultaneously, and corresponding strains were recorded with the cycles. Here, the strain of base metal was fixed at 0.5 and the strains in the weld metal of TMCP and normalized steels were compared as shown in Fig. 9. It is clearly demonstrated that the strain amount imposed on the base metal was much higher than that of weld metal in both steels. It is also interesting to note that strain in the weld metal of TMCP and normalized steels varied with increasing cycles; in the case of TMCP steel, the strain imposed
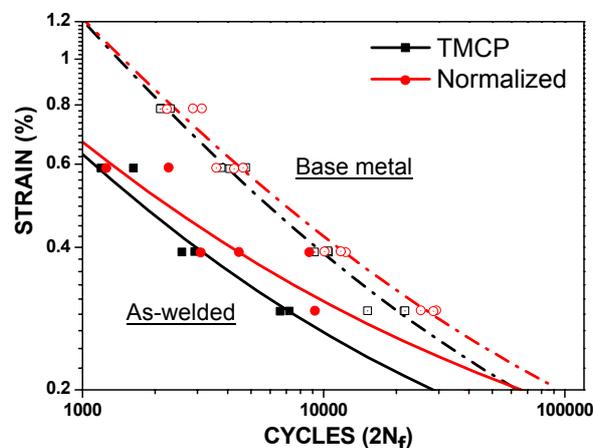

Fig. 8 Strain-life curves (R= -1) of the TMCP and normalized steels.

on the weld metal of TMCP steel decreased, while vice versa in the normalized steel. Therefore, it is believed that the inferior (low cycle) fatigue resistance of TMCP steel to the normalized steel results from the larger strain difference between weld metal and base metal during the cycling. In other words, it can be said that the TMCP base metal softens more than normalized base metal for the given strain amplitude [11]. To verify different cyclic softening behavior of TMCP base metal and normalized base metal, the variation of maximum stress at fixed strain amplitude ($\Delta\varepsilon_t/2 = 0.4\%$) was investigated as shown in Fig. 10. It is interesting to observe that the softening of TMCP steel continued until fatigue fracture occurred, while the normalized steel showed softening during 100 cycles and then slight hardening with continued cycling. This difference in cyclic softening behavior of two steels could well explain the different low cycle fatigue resistance of two steels.
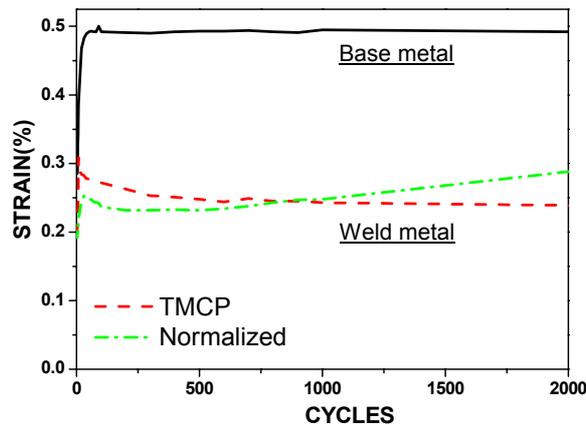

Fig. 9 Variation of strain in the weld metal of TMCP and normalized steels.
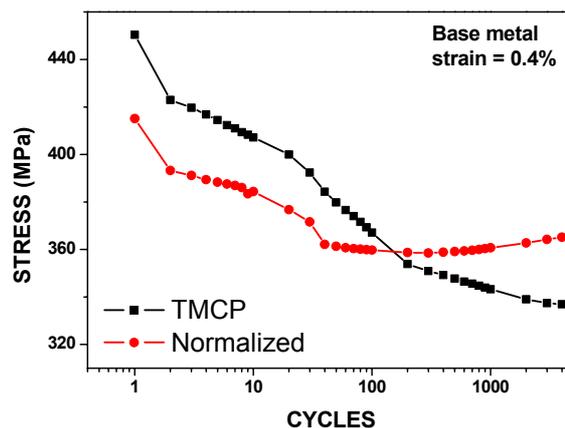Note that the strain of base metal was fixed at 0.5 with increasing cycles.

Fig. 10 Variation of maximum stress at a given strain amplitude ($\Delta\varepsilon_t/2 = 0.4\%$).

4. CONCLUSIONS

High and low cycle fatigue properties of TMCP steel and normalized steel were investigated in this study. The TMCP steels, both in the base metal and welded condition, represented higher fatigue ratios than those of normalized steels, indicating excellent high cycle fatigue resistance of TMCP

steel as compared to the normalized steel if the tensile strengths of two steels were similar to each other. On the other hand, the low cycle fatigue resistance of TMCP steel was similar to (in the case of base metals) or inferior to (in the case of welded conditions) the normalized steel resulting from the larger strain difference between weld metal and base metal during the cycling. This different low cycle fatigue resistance was well explained by considering different cyclic softening behavior of two steels.

ACKNOWLEDGEMENTS

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