Effect of Surface Treatment on Fatigue Strength Improvement of Martensitic Stainless Steel

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Abstract

Fatigue tests have been conducted on non-rolled and rolled martensitic stainless steel. Effects of roller-working and mean stress on fatigue strength improvement of plastically deformed and non-deformed specimens were evaluated. The fatigue limit is defined as the maximum nominal stress at the notch root where specimen endures by 1 x 10^7 cycles. Fatigue limit of ROL-05 and ROL-10 are 730 and 800 MPa, respectively. However, the fatigue limit of non-rolled specimen ROL-00 is 480 MPa. It is clarified that plastic deformation due to roller-working markedly increases the fatigue limit of notched specimens. Work-hardening, induced compressive residual stress and microstructure refinement are responsible for fatigue limit improvement. According to decrease of mean stress to yield stress ratio from +50, 0, and -50% the fatigue limit of these specimen increase to 290, 420, and 645 MPa, respectively. The results show that tensile mean stress is detrimental and compressive mean stress is beneficial on fatigue limit improvement. In general, when compressive mean stress increase the number of cycles to failure and the fatigue limit increase.

Keywords; Fatigue limit, roller-working, work-hardening, residual stress, mean stress, stainless steel.

Introduction

For a wide variety of applications, stainless steel competes with carbon steel supplied with protective coatings, as well as other metals such as aluminum, brass and bronze. The many unique values provided by stainless steel such as aesthetic appearance, heat resistance, and corrosion resistance, especially in view point of maintenance-free from corrosion, make it a powerful candidate in materials selection. With greater attention being made to achieving low long term maintenance cost, less environment impact and greater concern with life cycle cost, the using of stainless steel continues to increase. When this material used in dynamic structural components, its fatigue properties is one of the most important characteristic have to be evaluated to achieve the overall service performance requirements, since about 87% of mechanical failures directly or indirectly caused by fatigue process [1].

Most basic fatigue data collected in the laboratory are for completely reversed alternating stresses, that is, zero mean stresses. Most service applications involve nonzero mean cyclic stresses. It is, therefore, very important to evaluate the influence of mean stress on fatigue properties of structural steels for limitation miscalculation in design. The effects of mean stress on fatigue strength of metals were reported in several papers [2-10]. For high cycle fatigue strength of metals, the mean stress effect is usually predicted by either the Goodman equation, the Gerber equation or modified versions of these equations [11-14]. Others papers explained that mean stress could be treated as residual stress and both have similar effects on fatigue strength improvement [15-17].

Notch effects on fatigue strength of structural steels have been a key problem in the study of fatigue since more than 100 years ago. Although, it is well known that fatigue cracks are initiated from stress concentrated parts but notches can not be avoided in mechanical components due to structural requirements. While it is well known, these conventional methods, such as hard-facing ones and heat-treatment, are effective to increase fatigue strength of plain specimens but sometimes they deteriorate fatigue strength of notched specimen. Roller-working can be applied to stress-concentrated parts and considered as an effective and low cost method to improve fatigue strength of bar shape components [2-4]. The purposes of this research are to evaluate effect of roller-working and mean stress on fatigue strength of martensitic stainless steel SUS410.

Experimental procedure

Material

The chemical compositions and the mechanical properties of martensitic stainless steel SUS410 which were used in the experiment are listed in Tables 1 and 2, respectively. Details of the specimens could be seen in Figures 1 and 2.

Heat treatments given to SUS410 were 1030C×2hrs→AC→200C×2hrs→AC, and expressed by MEAN (specimen under mean stress) and ROL (rolled specimen), respectively. The suffix behind the specimens` symbols express percentage of applied mean stress to yield stress ratio. In case of rolled specimens, the suffix behind the specimens` symbols express plastic deformation value in mm due to roller-working.

As shown in the Figures 1 and 2, each specimen has a small v-shape circumferential notch in order to provide small stress concentration part for limitation crack initiation area. The notch will a little bit decreases the fatigue limit due to stress concentration. After machining MEAN specimen was polished with emery paper from # 400 to # 3000 to improve the surface layer. In addition, about 30 μm of the specimens` surface layer was removed by electro-polishing, in order to reduce the work-hardened layer. Finally, in order to make more convenience in observing the specimens` surface state during fatigue test it was etched in some solution of distilled water and sulfuric acid.

The minimum cross sectional diameter after machining for ROL-05 and ROL-10 are 11 and 12 mm, respectively and then their surface layer were plastically deformed by roller-working to a final diameter of 10 mm, which is the same as the minimum cross sectional diameter of the non-rolled specimen. After roller-working, rolled specimen was polished with emery paper from # 400 to # 3000 and diamond paste for limitation the effect of surface defect due to rolling fold, and then a little bit of the their surface layer were removed by electro-polishing. Afterward the specimens` surface layer was etched with solution of distilled water and sulfuric acid in order to observe the state of specimens` surface during the fatigue test, with successively taken replica method.

Fatigue test

The fatigue tests have been performed on a tensile-compressive fatigue testing machine under the frequency of 10 Hz. The compressive mean stresses applied to MEAN specimens are specified at 0, 50 and -50 % ratio of yield stress, by nominating as MEAN-0, MEAN+50, MEAN-50, respectively. In case of rolled specimen, the fatigue tests have been performed on a rotating-bending fatigue testing machine under the frequency of 3600 rpm. The hardness distribution was evaluated with a Vickers hardness tester under the load of 0.49N, measured longitudinally across the diameter and indented every 50 μm from the surface to its centre. Fracture surfaces were studied by a scanning electron microscope. The crack propagation properties were observed by surface replica method. The crack lengths were measured using an optical microscope equipped with a digital measurement system

Table 1: Chemical composition [mass %]

Material	C	Si	Mn	P	S	Ni	Cr
SUS410	0.117	0.35	0.55	0.03	0.015	0.38	11.77

Table 2: Mechanical properties

Material	Heat treatment	S_u (MPa)	S_y (MPa)	Hardness (0.49N)
SUS410	1030C 2 hrs.-AC, 200C 2 hrs.-AC	1372	1060	397

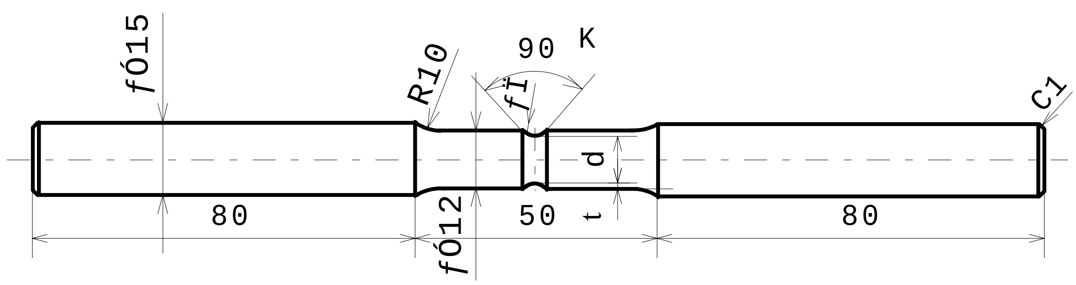

Figure 1. Details of rolled specimen under rotating-bending fatigue stress

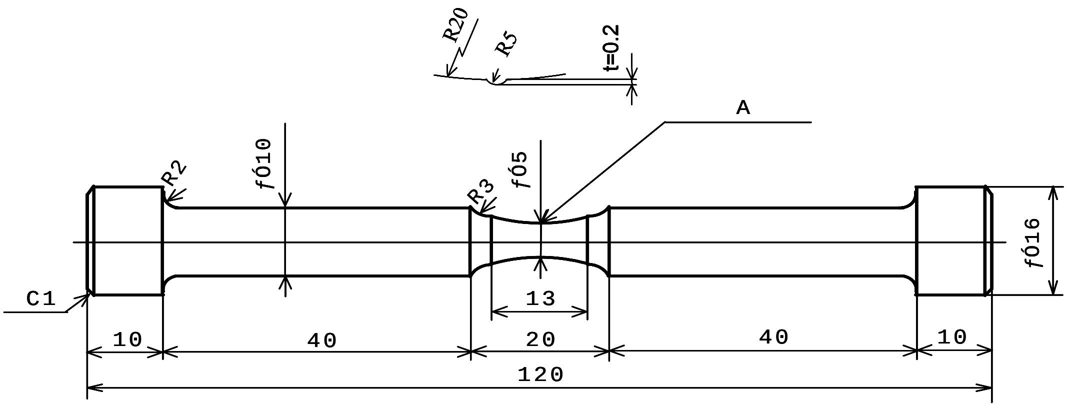

Figure 2. Details of non-rolled specimen under compressive-tensile fatigue stress

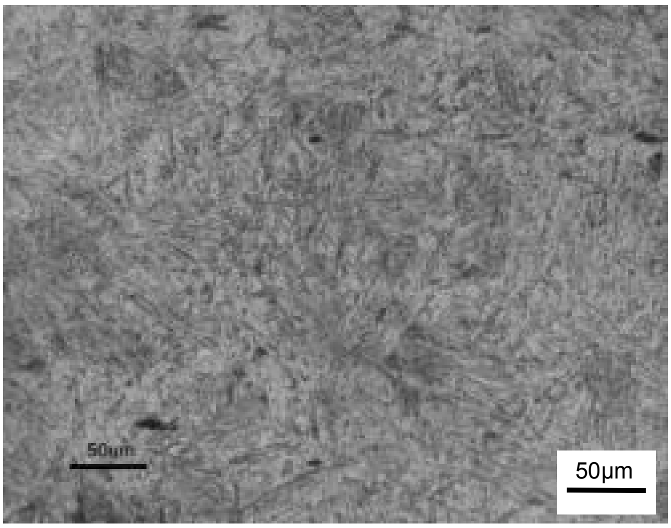

Figure 3. Microstructure of specimen

Results and discussion

Tensile testing

Figure 3 and 4 show microstructure of SUS410 and stress-strain diagram, respectively. As shown in figure 4, Martensitic stainless steel has high tensile and yield strength but low ductility. Yield and tensile strength of SUS410 are 1060 and 1372 MPa, respectively. Complete mechanical properties SUS410 are listed in Table 2.

Fatigue strength of rolled specimen

Figure 5 shows the S-N curves of MRB under rotating bending fatigue stress. The rotating bending fatigue tests were performed on the specimen ROL-00, ROL-05 and ROL-10. The degree of plastic deformation could be seen on the suffix of each specimen’s symbol. The fatigue limit is defined as the maximum nominal stress at the notch root where specimen endures by 1 x 10^7 cycles. As shown in Figure 5, the fatigue limit of ROL-05 and ROL-10 are 730 and 800 MPa, respectively. However, the fatigue limit of non-rolled specimen ROL-00 is 480 MPa. As shown in Figure 5, fatigue limit of ROL-10 is 165% higher than that of ROL-00. From the above results, it is clarified that plastic deformation due to roller-working markedly increases the fatigue limit of notched specimens.

Work-hardening and residual stress

Figure 6 shows the micro-Vickers hardness distribution. As shown in the figure, the micro-Vickers hardness of rolled specimens is higher than that of non-rolled one, especially at the surface layers. As shown in these Figures, the effect of plastic deformation due to roller-working is directly enhance hardness of roller-worked specimen, especially at the surface layer. Generally, fatigue cracks are initiated at the surface layer of the mechanical component due to higher stress distribution than that of its center axis. High surface hardness value may affect crack tip opening behavior and delay crack initiation. Therefore, fatigue strength will be improved due to increasing of surface hardness value.

Actually, mechanical failures are very sensitive to the structure and the properties of the material surface, and in most cases material failures are initiated at the surface of notched components. Optimization of the surface structure and properties especially at notched parts may effectively improve the global behavior of materials. Therefore surface treatment technology such as shot peening and roller-working have been developed in order to improve fatigue and wear properties of mechanical components. Among other surface treatments, cold rolling is considered as a simple and low cost method to improve fatigue strength of notched bar shape components. Residual stress and its distribution generated by surface treatment play an important task on fatigue strength improvement. If a crack lies in a region of compressive residual stress, a tensile applied load must overcome this stress before the crack can propagate. Unfortunately, in this experiment residual stress due to rolling was not observed.

Effect of mean stress

Figure 7 shows stress-cycle relationship of SUS410. The suffix behind the specimens` symbols express applied mean stress to yield stress ratio. The negative and positive marks mean compressive and tensile mean stress, respectively. As shown in Figure 7, according to decrease of mean stress to yield stress ratio from +50, 0, and -50□ the fatigue limit of these specimen increase to 290, 420, and 645 MPa, respectively. The above results explain that tensile mean stress is detrimental and compressive mean stress is beneficial on fatigue limit improvement. In general, when compressive mean stress increase the number of cycles to failure and the fatigue limit increase.

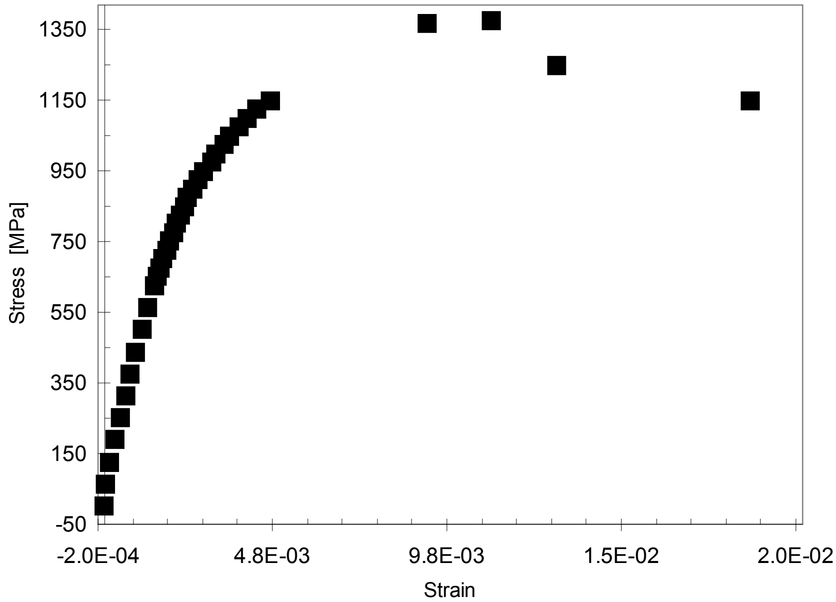

Figure 4. Stress-strain curve of SUS410

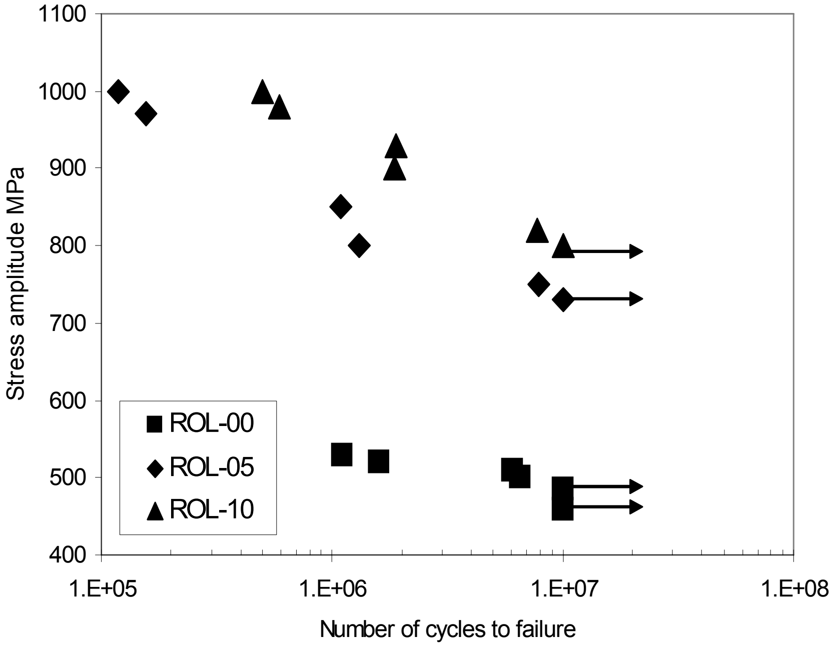

Figure 5. S-N curves of rolled specimen

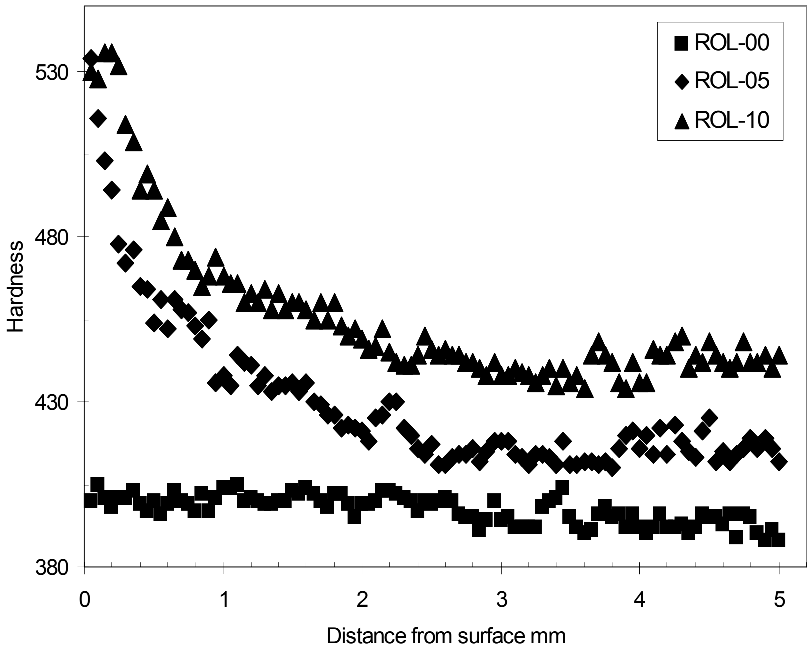

Figure 6. Hardness distribution of rolled specimens

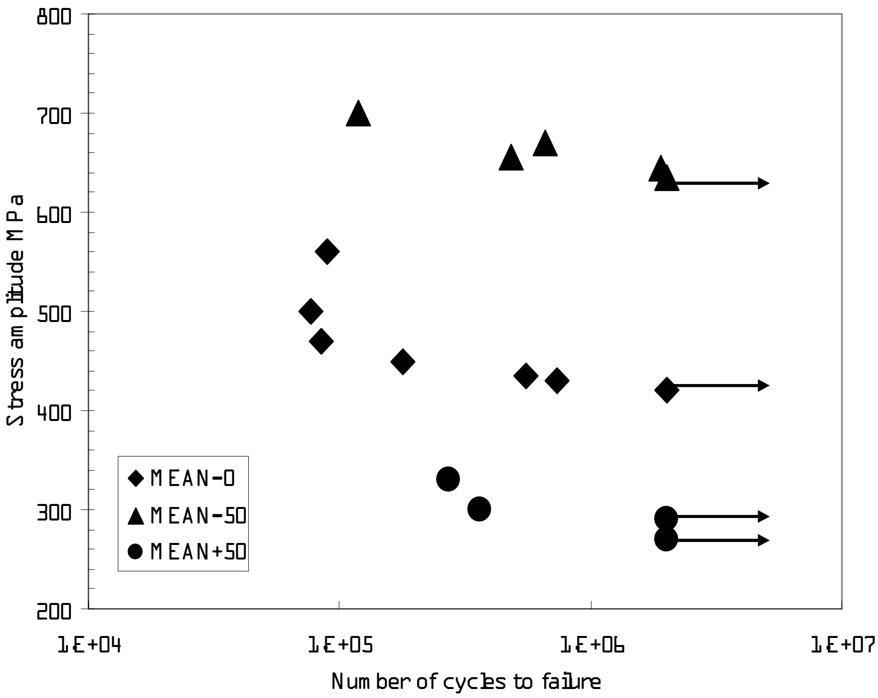

Figure 7. S-N curves of SUS410 under mean stress effect

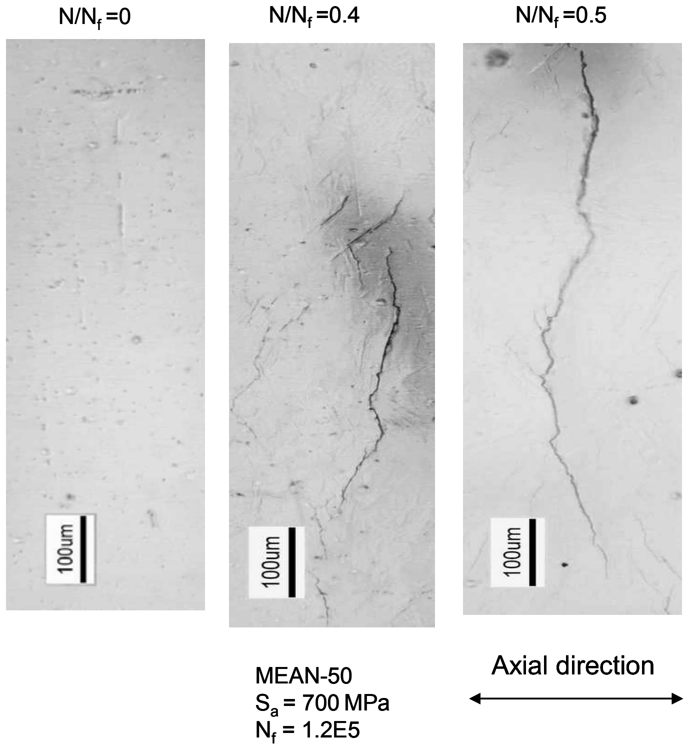

Figure 8 An example of fatigue crack growth

Conclusion

The results in this test could be summarized as follows;

1. Fatigue limit of all specimens increase with increasing compressive mean stress and decrease with increasing tensile mean stress.
2. Compressive mean stress responsible on delaying of fatigue cracks initiation by affecting crack tip opening behavior and suppresses fatigue crack growth rate.
3. Plastic deformation due to roller-working markedly increases the fatigue limit of notched specimens.
4. Work-hardening, induced compressive residual stress and microstructure refinement are responsible for fatigue limit improvement.

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