# Fatigue Limit Prediction of AISI4140 Steel with Compressive Residual Stress Considering the Local Yielding of Compressive Residual Stress Layer

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**Abstract**
The effect of compressive residual stress on the fatigue limit was investigated using fatigue tests on specimens with and without compressive residual stress. The results demonstrated that the fatigue limit of AISI4140 steel with compressive residual stress can be predicted using the fatigue limit diagram, considering the local yielding of the compressive residual stress layer.

## 1. Introduction

Surface treatments such as shot peening, induction heating, and carburizing are widely used in industry to improve the fatigue properties of metals. Compressive residual stress is one of the most important parameters that affects the fatigue limit of surface-modified metals. However, evaluating the effect of the compressive residual stress on the fatigue limit is challenging because it is relaxed during the fatigue process. It is widely accepted that relaxation of the compressive residual stress occurs because of compressive yielding owing to the superposition of the compressive applied and residual stresses. Therefore, it is important to reveal the yielding behavior of the compressive residual stress layer to determine its effect on the fatigue limit. This study investigated the local yielding behavior of the compressive residual stress layer and a prediction method for the fatigue limit considering its effect.

## 2. Results

AISI4140 chromium-molybdenum steel with the following mechanical properties: 0.2% proof stress of 1044 MPa; ultimate tensile strength of 1133 MPa; and Vickers hardness of 335HV was used. The steel was machined into an hourglass-type fatigue specimen, and the smallest diameter section was polished using emery paper (#100-600). Two different specimens, the EP and FPP+EP series, were prepared. The EP series was electrically polished (EP) after emery polishing, and the FPP + EP series was electrically polished after fine particle peening (FPP) to generate compressive residual stress. The EP series had no residual stress on the specimen surface, whereas the FPP+EP series had a compressive residual stress of −460MPa. In addition, the two specimens exhibited almost the same surface roughness.

The results of the axial loading fatigue tests with a stress ratio of −1 are shown in Fig. 1. The figure shows that the fatigue limit of the FPP + EP series (525 MPa) was higher than that of the EP series (425 MPa). In this study, the fatigue limit was defined as the average of the maximum stress without specimen failure at $N = 10^7$ cycles and the minimum stress at which the specimen fractured [1]. Fig. 2 shows the fatigue limit diagram for AISI4140 steel drawn based on a previous study [2]. The black and red lines indicate the yield limit line, and fatigue limit line according to the modified Goodman line based on the fatigue limit of the EP series and ultimate tensile strength, respectively. The equation for the fatigue limit line is as follows:

$$\sigma_{\mathrm{w}} = -(\sigma_{\mathrm{m}} + \sigma_{\mathrm{r}}) + 1044 \qquad (991 \leq \sigma_{\mathrm{m}} + \sigma_{\mathrm{r}} \leq 1044) \qquad \ldots(1)$$

$$\sigma_{\mathrm{w}} = -0.378(\sigma_{\mathrm{m}} + \sigma_{\mathrm{r}}) + 428 \qquad (-447 \leq \sigma_{\mathrm{m}} + \sigma_{\mathrm{r}} \leq 991) \qquad \ldots(2)$$

$$\sigma_{\mathrm{w}} = 597 \qquad (-1044 \leq \sigma_{\mathrm{m}} + \sigma_{\mathrm{r}} \leq -447) \qquad \ldots(3)$$

where $\sigma_{\mathrm{w}}$, $\sigma_{\mathrm{m}}$,and $\sigma_{\mathrm{r}}$ are the fatigue limit, mean stress, and residual stress, respectively. Based on the equation and residual stress of the FPP+EP surface (−460 MPa), the fatigue limit of the FPP+EP series was predicted to be 597 MPa (△ symbols in Fig. 2). The predicted fatigue limit was considerably higher than the experimentally determined fatigue limit (525 MPa), although the effect of the compressive residual stress relaxation was estimated from the yield limit line. The relaxation of the compressive residual stress occurred because of the local compressive yielding of the compressive residual stress layer. Therefore, the prediction error was attributed to the difference between the macroscopic yield strength obtained from the tensile test and microscopic yield strength of the compressive residual stress layer.

To elucidate the difference in yield strength, the local yielding behavior of the compressive residual stress layer of the FPP+EP series under compressive loading was investigated using in-situ X-ray stress measurements [3]. The green squares in Fig. 2 indicate the measured local yield line of the compressive residual stress. The fatigue limit of the FPP+EP series predicted from the modified Goodman and local yield limit lines of the compressive residual stress layer was 540 MPa (◇ symbols in Fig. 2) which was approximately equal to the experimental value (525 MPa). Consequently, the fatigue limit with compressive residual stress could be predicted using the modified Goodman diagram considering the local yielding behavior of the compressive residual stress layer.

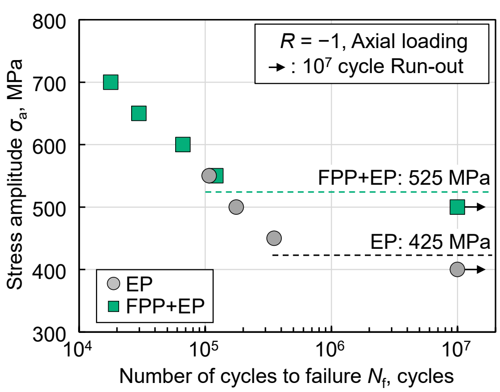

Fig. 1 S-N diagram of AISI4140 steel

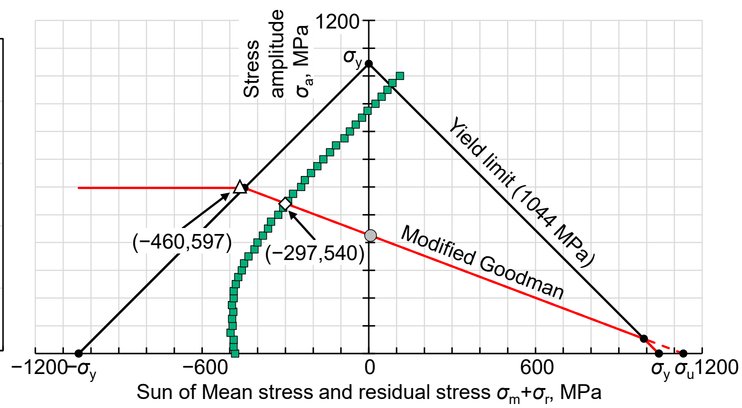

Fig. 2 Fatigue limit diagram of AISI4140 steel considering the local yielding of the compressive residual stress layer

## 3. Conclusions

The predicted fatigue limit of the FPP+EP series based on the fatigue limit of the EP series and the initial residual stress of the FPP+EP surface was considerably higher than the experimental results because of the difference between the macroscopic yield strength of the material and microscopic yield strength of the compressive residual stress layer. The predicted fatigue limit considering the local yielding of the compressive layer, which was investigated by in-situ X-ray stress measurements, provided a reasonable value of the fatigue limit of the FPP+EP series. This implies that the local yielding behavior of the compressive residual stress layer should be considered in predicting the fatigue limit of steel with compressive residual stress.

## Reference

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