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304L stainless steel fatigue evaluation using dynamic mechanical analysis

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Abstract: In order to evaluate the fatigue effects on 304L Stainless Steel, the internal friction or damping of the material have been investigated by means of dynamic mechanical analysis (DMA), using single cantilever test modes. Before DMA measurement, the 304L plates are loaded with different cycle number and stress amplitude to simulate different fatigue condition. The amplitude dependant internal friction (ADIF) of 304L small sample is measured. It shows that the ADIF curves of DMA are associated with the pre-fatigue loading. One ADIF peak is observed near the critical strain amplitude. The DMA data of different pre-stressed samples (cyclic stress amplitude from ±80MPa to ±200MPa) show that the height of ADIF peak increases with the pre stress value. The mechanism of the peak is discussed in the paper. The results indicate that a clear correlation exists between fatigue condition and internal friction curve, so that the fatigue behaviour of 304L stainless steel can be evaluated from DMA measurements.

Keywords: Dynamic mechanical analysis (DMA); Fatigue; Amplitude dependant internal friction; 304L stainless steel

1. Introduction

Type 304L stainless steel, as its corrosion resistance and excellent mechanical properties, has always attracted attention of manufacturing industries, and it is widely used in industry of chemistry and nuclear energy. As one of main structure material, the 304L components are often exposed to severe conditions such as cyclic fatigue stresses, thus a detailed research on the fatigue behavior and fatigue life of the material is required.

Materials subjected to cyclic loading absorb energy, some of which may be stored as potential energy within the structure of the material, but most of which is dissipated as heat to surroundings. Energy dissipation in materials, termed damping or internal friction (IF), is caused by a wide range of physical mechanism, depending on the material, temperature, strain amplitude, and frequency of cyclic loading involved [1]. Dynamic Mechanical Analysis (DMA) methods have been widely used in the characterizations of viscoelastic materials, particularly in the polymer science. The DMA can determine changes in sample properties resulting from changes in five experimental variables: temperature, time, frequency, force, and strain. It can measure many properties of material, including: modulus (storage modulus and loss modulus), internal friction or damping, creep, stress relaxation, glass transitions, and softening points. Many studies have been performed on the effect of prior deformation on internal friction. To characterize the internal friction peak in cold deformed A316L stainless steel, the specimens with prior tensile strain 5% or 20% were used by Ivanchenko et al[2]. Liu et al explored the effects of cold working deformation on the internal friction of the 2.25Cr-1Mo steel [3]. The prior deformation was performed also on tensile loading and results show that the internal friction of the steel increases with the magnitude of cold working deformation. Li et al has been studied the internal friction of Fe-Ni based austenitic alloy with prior tensile deformation [4]. The IF of the austenitic alloy was explained by planar and wavy slip of dislocation. Mechanical spectroscopy of Co-Ni-Cr super-alloy was investigated by Cosimati et al[5]. The internal friction of cold worked and annealed Co-Ni-Cr super-alloy samples were interpreted based on the G-L theory. These research were based on the tensile loading or roll milling to produce cold working or prior deformation. However, structural materials failure due to fatigue loading is very common phenomenon. Therefore, it is of great importance in many engineering problems to measure the changes of the materials after fatigue. Few works are available on the internal friction of austenite steel after fatigue loading. In this study, type 304L stainless steel samples, which have been cyclic loaded, were tested on DMA. The amplitude-dependent internal frictions (ADIF) of different pre-stressed samples were measured. The relationship between the ADIF and cyclic stress amplitude was discussed.

2. Materials and Methods

304L plates are machined to dog-bone shape indicated in figure 1. To simulate the effect of fatigue or cyclic loading, the 304L plates are cyclic loaded on material testing system MTS810. The plates are loaded with stress control mode and the loading involves completely reversed (R= -1) cycling between constant stress limits.

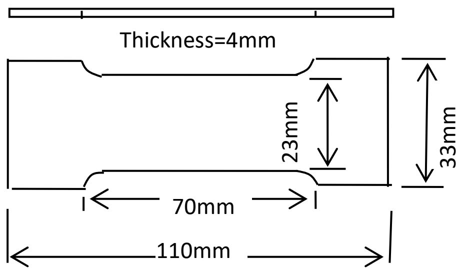

Figure 1. 304L plate with prior fatigue loading.

After cyclic loaded the dog-bone plates are cut in half. The small samples of DMA are extracted along length of the plate using electric spark cutting (figure 2) . Then the small sample surfaces are grinded and polished by hand. The final size of DMA small sample is shown in the right side of figure 2.

Figure 2. The 304L plate and the small sample of DMA extracted.

(a) **(b)**

Figure 3. (a) DMA2980 dynamic mechanical analyzer and **(b)** the single cantilever test mode.

Internal friction measurement is made on the Mechanical Analyzer type DMA 2980 of TA Company. The single cantilever test mode is used. The small sample undergoes a flexural deformation between the fixed clamp and floating clamp, see figure 3. During DMA testing the storage modulus E' (elastic response) and loss modulus E'' (viscoelastic/anelastic response) of 304L samples are measured as a function of strain/stress amplitude as the samples is deformed under an oscillatory load (stress) at a controlled frequency (f=1Hz) and temperature in a specified atmosphere. The storage modulus is related to stiffness, and the loss modulus to internal friction and energy dissipation. The relative amount of internal friction or energy loss in the material is given by the loss tangent, $\tan\delta$ [6]

$$E''/E' = \tan\delta \quad (1)$$

Anelastic deformation is the term used to describe the time-varying, hysteretic elastic behavior of metals. Anelasticity of metal can lead to mechanical hysteresis manifested by strain not being in phase with an oscillatory stress. The resulting energy loss or internal friction ($\tan\delta = Q^{-1}$) is related to the internal structure of the materials [7]. The internal structures of 304L samples change after cyclic loading and the DMA testing results may show the internal friction difference of samples which subjected to different cyclic loading amplitude and time.

3. Results and discussion

Figure 4 shows the amplitude-dependent internal friction of four samples which have been subjected to different number of cyclic loading while the prior fatigue stress amplitude of the samples is 150MPa. The ADIF of four samples are almost the same when the strain is below 0.1% and the ADIF increase with the increasing of strain. Cyclic number of prior fatigue has little influence on the ADIF or damping values. However, when the strain amplitude approach 0.2%, the effect of fatigue time (cyclic number) appears. The internal friction of original sample without pre stressed increase steadily as the plastic deformation increase. But the ADIF curves of the pre-stressed samples have a hump when strain amplitude is 0.2%, which agree with the yield strain of the samples. The more prior fatigue cycle the higher the ADIF curve hump. The plastic deformation is significant when the strain amplitude approach 0.2%, therefore, the hump is associated with the extent of plastic strain during DMA.

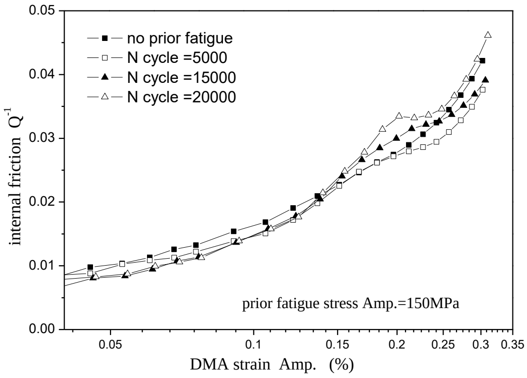

Figure 4. ADIF of four samples with different cyclic pre-stress number.

The ADIF of samples which have been loaded with different amplitude of loading are measured on DMA2980.The cyclic pre-stress amplitude is from ±80MPa to ±200MPa and the number of loading cycle is 10000. Five internal friction curves are shown in figure 5.

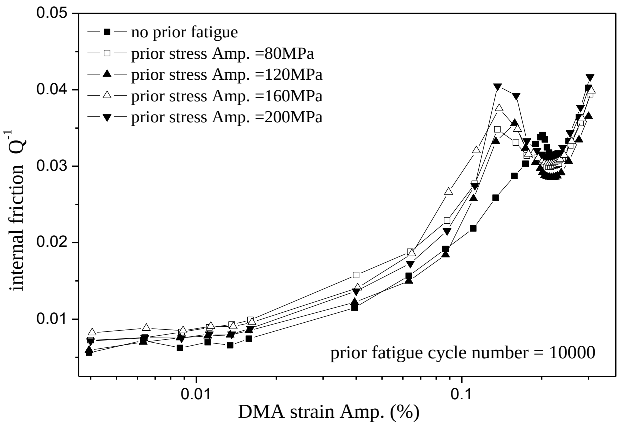

Figure 5. ADIF of samples with different pre-stress amplitude.

Figure 5 shows all ADIF curves have a peak when the strain amplitude is about 0.2%. The peak is not mentioned in many ADIF related literatures because the maximum strain amplitude is generally less than 0.1% during ADIF testing with DMA [8,9,10]. The peak in figure 5 shows an apparent association with the prior fatigue stress amplitude. The height of the ADIF peak increase with an increase of the prior fatigue stress amplitude. The relationship between the ADIF peak and the prior fatigue stress amplitude indicate that the fatigue history of the 304L SS may reflect by the internal friction curves, thus, the fatigue life of the 304L SS may be predicted with the peak value of internal friction.

The ADIF curves can be explained by the Granato-Lucke mode (G-L) [11]. According to the mode, a crystal contains a network of dislocation lines. The network nodes are considered to be strong pinning points: under the small strain conditions during DMA testing, dislocation will oscillate between these nodes, but will not be torn loose from the dislocation intersections, therefore, the ADIF is low when the oscillation amplitude is small. Once the strain is over critical level, the attractive force between dislocation and point defect is overcome and the dislocation moves away from the pinning point. At still higher strain, long-range dislocation motion will result in dislocation multiplication and drastically alter the internal friction behavior [12]. An internal friction peak occurs which relates to the plastic deformation of the materials. Samples subjected to higher cyclic loading amplitude (pre-stress amplitude) have heavier dislocation density and the ADIF peak is higher. The agreement between G-L mode theory and the ADIF curves is obtained.

4. Conclusions

The study shows that dynamic mechanical analysis equipment can be applied for the internal friction or damping characterization of 304L SS. The fatigue history of 304L SS can be reflected by the internal friction curves. The ADIF of 304L SS samples are insensitive to the DMA strain amplitude when the strain amplitude is less than 0.1%. There is a peak in ADIF curves when the strain is about 0.2% which relates to the damping and plastic deformation. ADIF curves may indicate the dislocation pinning and unpinning from pinning point and dislocation multiplication, which are compliance with the Granato-Lucke mode. As the prior fatigue stress or cyclic loading is a strong influence on the distribution and density of dislocations, this work provides a means for the evaluation of fatigue status and residual life of 304L SS.

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