INFLUENCE OF RESIDUAL STRESS ON FATIGUE LIFE OF HOT FORGED AND SHOT BLASTED STEEL COMPONENTS

G. H. Farrahi

School of Mechanical Engineering, Sharif University of Technology
Tehran, Iran, farrahi@sina.sharif.ac.ir

D. J. Smith

Department of Mechanical Engineering, University of Bristol
Bristol BS8 1TR, UK, David.Smith@bristol.ac.uk

W. X. Zhu

BAe Systems, Bristol, UK

C. A. McMahon

Department of Mechanical Engineering, University of Bristol
Bristol BS8 1TR, UK Chris.Mcmahon@bristol.ac.uk

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Abstract Hot forging is a common manufacturing process for the production of large quantities of engineering components. Residual stresses are developed in forged components as a result of various aspects of the manufacturing process, including subsequent cooling, and heat treatment. Residual stresses can significantly affect the deformation and fatigue failure of materials. Hot forged EN15R steel bars were studied. Four batches of specimens representing different stages of the forging process were employed. Residual stresses introduced by the process were measured by X-ray diffraction technique. Fatigue tests were carried out on fourteen specimens from each batch. Weibull distribution for fatigue data was considered. It was found that compressive residual stress had no benefit under low cycle fatigue (LCF) because the residual stresses were completely relaxed due to the large plastic deformation but had a beneficial effect on high cycle fatigue (HCF).

Key Words Fatigue, Residual Stresses, Hot Forging, X-Ray Diffraction

چکیده آهنگری گرم یکی از فرآیندهای تولید قطعات مهندسی در تعداد زیاد است. تنشهای پسماند در قطعه در مراحل مختلف تولید از جمله سرد شدن و عملیات حرارتی بوجود می آیند. تنشهای پسماند می توانند به طرز قابل توجهی در تغییر شکل و از کار افتادگی در اثر خستگی اثر گذارند. آهنگری گرم فولاد مورد مطالعه قرارگرفت. چهار گروه نمونه معرف مراحل مختلف فرآیند مورد استفاده قرارگرفت. تنشهای پسماند ناشی از فرآیند توسط پرتو ایکس اندازه‌گیری شد. آزمایشهای خستگی بر چهارده نمونه از هر گروه انجام شد. توزیع ویبال برای نتایج خستگی منظور شد. نتایج نشان داد که تنشهای پسماند فشاری هیچگونه اثر مفیدی در خستگی سیکل کوتاه ندارند؛ زیرا تنشهای پسماند تحت تغییر شکلهای پلاستیک بزرگ کاملا رها می‌شوند. ولی تنشهای پسماند اثری مفید در خستگی سیکل بالا دارند.

INTRODUCTION

Hot forging is a common manufacturing process for the production of large quantities of engineering components. With their reputedly superior performance, forgings have been used for safety critical parts such as components operating under conditions of high dynamic stress or impact loading [1]. The largest material fraction of a typical car is made up of 25% forged steel [2].

The majority of failures in machinery and structural components can be attributed to fatigue processes. Such failures generally take place under the influence of repeated loadings whose peak values are considerably smaller than the safe loadings estimated on the basis of static analyses. Fatigue is now one of the major considerations in design.

There is little doubt that residual stresses exist in engineering components. These may be induced from manufacturing processes or mechanical loading. They play an important role in integrity and reliability of components and their design optimization [3]. In the operation of forging, tensile stresses may develop in the process of changing shape and failure can often be traced to the occurrence of these stresses [1]. Tensile residual stresses that often exist in welded and forged components decrease the fatigue strength of the components.

Compared with work on residual stresses in welded components, there is little work on residual stress in forged components available. Experiments have been the best way to study residual stress in forged components. Bashun et al. [4] studied the distribution of residual stresses in drop forging using X-ray diffraction method. Their study indicated that the forging process introduces residual stresses in components. Furthermore Appleton et al. [5] studied the residual stress caused by the indentation phase of rotary forging also using X-ray diffraction method. The beneficial effect of compressive residual stresses on fatigue life is often used for improving fatigue performance of components [6-8]. Shot pining process which produce surface compressive residual stress has been used for extending fatigue life of components subjected to cyclic loading [7, 8].

Deterministic methods have been normally used to assess structural reliability or safety. The parameters in the methods, such as the fatigue strength, stress range and residual stresses have been typically based on average values. In some industries, the values used for strength and stress range are chosen as the worst-case quantities. This then results in unrealistically conservative assessments of safety. In general, the statistical distributions of these parameters have been ignored in the deterministic models.

It has been generally recognized that most design parameters of engineering structure and system have statistical variations. The use of statistical methods in the planning and interpretation of fatigue experiments has become a necessity in modern technology. Many distribution functions have been proposed for the description of the statistical variations of fatigue [9-11]. The most frequently used distributions are the logarithmic normal and Weibull distributions. In this paper, results from tests on four batches of specimens representing different stages of the forging process, are examined. Surface residual stresses were measured using the X-ray method; fatigue tests were carried out on each batch. The effect of residual stress on high cycle and on low cycle fatigue life was studied.

EXPERIMENTAL PROCEDURE

Material Hot forged round EN15R steel bars of composition (wt%) 0.4 C, 0.17 Si, 1.59 Mn, 0.07 Cr, 0.17 Ni, 0.02 Mo, 0.004 S, 0.022 P remainder Fe were used in the experiments. The forging process used in the production of these bars simulated the manufacture of wheel suspension arms for automobile components. The process consists of an initial induction heating of a steel billet to about 1200 to 1250 °C then molding in a hot forging press, followed by finish pressing. After clipping the excess material, the forged bars were allowed to cool in air to room temperature. Then the components were heat treated (harden and tempered), followed by shot blasting to clean the surface of oxide scale and to introduce compressive residual stresses.

Four batches of specimens, AF, HT, FS, and HTS, were used and represent the different stages of the forging process. Figure 1 shows hot forged round specimens. The diameter of the bars was 8.2 mm. Young's Modulus E and Poisson's ratio

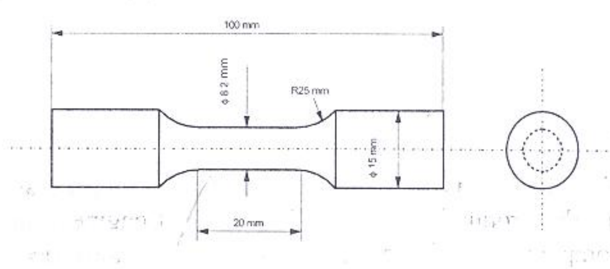

Figure 1. Hot forged steel bar specimen.

v of the material are 208 GPa and 0.28, respectively.

AF = as forged, without heat treatment and shot blasting
HT = heat treated without shot blasting
FS = forged and shot blasted without heat treatment
HTS = subjected to the complete process

Residual Stress Measurements Residual stress measurements were carried out on the surface of all specimens by X-ray diffraction. This method is well known and is described elsewhere [12].

A Philips horizontal diffractometer with a chromium X-ray source ($\lambda_{K\alpha}$ = 0.22895 nm; 40 kV, 40 mA) was employed to examine the 211 peak ($2\theta = 156^{o}$). A computer monitored all measurements and analyzed the experimental data.

Before carrying out the residual stress measurement, the accuracy and reproducibility of the X-ray measurements were checked. The magnitude of residual stresses on a stress free sample at seven random positions was -30$\pm$15 MPa. Repeat measurements at one location of a bar showed that the value of the axial stress was -300$\pm$15 MPa. These results showed that the measurements were accurate and adequately reproducible.

Fatigue Tests Prior to fatigue testing, surface roughness measurements were obtained using a Talysurf measuring device for each bar in each batch.

Fatigue tests of tension-compression were carried out on fourteen specimens from each batch, Figure 1 shows the specimens. In each group, two cyclic strain ranges were chosen for the fatigue tests, one ($\Delta\varepsilon/2$ = 2200 $\mu\varepsilon$) was for high cycle fatigue (HCF) tests and the other ($\Delta\varepsilon/2$ = 6000 $\mu\varepsilon$) was for low cycle fatigue (LCF) tests.

RESULTS AND ANALYSIS

Residual Stresses X-ray diffraction has been used to measure residual stresses. The forging process introduced the residual stresses. Because in the manufacture of large batches of forged components there were statistical variations in the geometry of the components, material properties and surface roughness, the residual stresses in the forged components would be expected to have inevitable variability from component to component.

Figure 2 shows the histograms of the distribution of axial residual stresses for AF, HT, FS and HTS that represent different forging processes. There were fourteen specimens in each group and two measurements on each one. From this figure, the difference among the residual stress distributions for each group specimens can be seen approximately. The statistical methods are expected to be used in the interpretation of the distributions.

Fatigue Both Normal and Weibull distributions have been found to be applicable to the materials and testing conditions. From the Figures 3 and 4 we can see there is no real difference between these distribution functions. The Weibull distribution may be preferred because it leads to more realistic reliability analysis.

In the following analysis it was assumed that the fatigue results could be described using a Weibull cumulative probability function P, where

$$P = 1 - \exp\left[-\left(\frac{N - N_0}{N_a - N_0}\right)^{\beta}\right] \qquad N > N_0 \qquad (1)$$

N_0 and N_a are the assumed minimum life and characteristic life respectively and β is the Weibull slope.

The fatigue lives of the specimens for each batch are shown in Figure 5 for HCF tests and for LCF tests results are shown in Figure 6.

Fitted curves, using Equation 1 are also shown in Figures 5 and 6, assuming that N_0=0. The material parameters N_a and β are given in Table 1 for each batch and each strain range.

The cumulative probabilities of failure using equation and the fitted material parameters are shown in Figures 7 and 8. The results in Figures 6 and 8 illustrate that the different manufacturing processes for low cycle fatigue conditions largely influenced the fatigue lives of the various batches. In contrast for high cycle fatigue the largest fatigue lives were obtained for the HTS batch, Figures 5 and 7.

For a given batch of material, the degree to

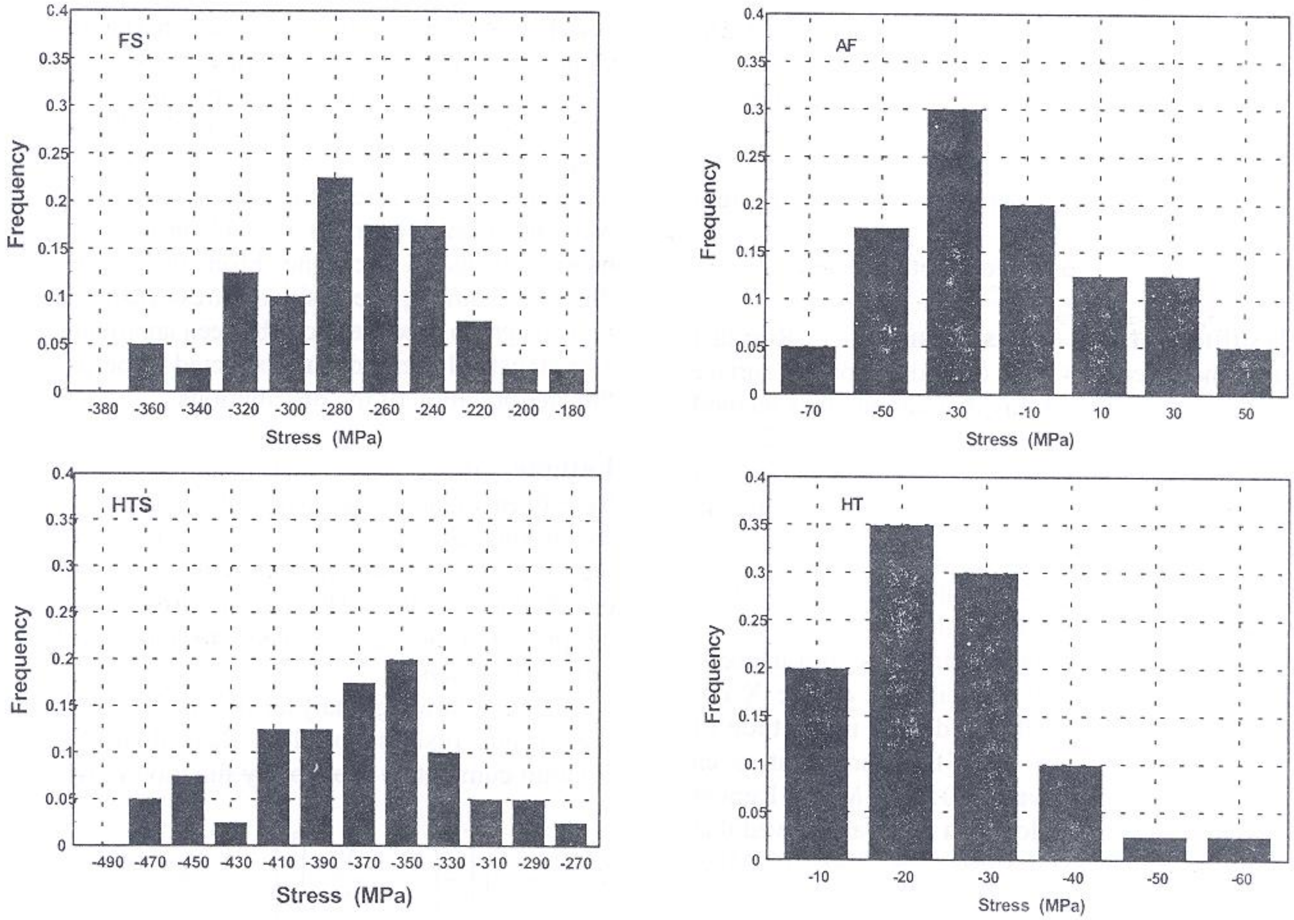

Figure 2. Axial residual stress distribution.

which residual stresses and also surface roughness influence fatigue life was explored. For example, for the HTS batch, Figure 9 illustrates the relationship between measured surface residual stress and fatigue life. The curves shown in each figure correspond to a linear on least squares fit to the experimental results with 90% confidence intervals. For LCF conditions there was essentially no evidence that residual stresses influenced fatigue life. For HCF conditions there was a limited correlation with longer fatigue lives occurring for lower surface residual stresses.

Figure 10 shows how surface roughness influenced fatigue life for both LCF and HCF conditions. Longer fatigue lives were obtained for lower surface roughness. However, the largest influence of surface roughness on fatigue life occurred for HCF conditions.

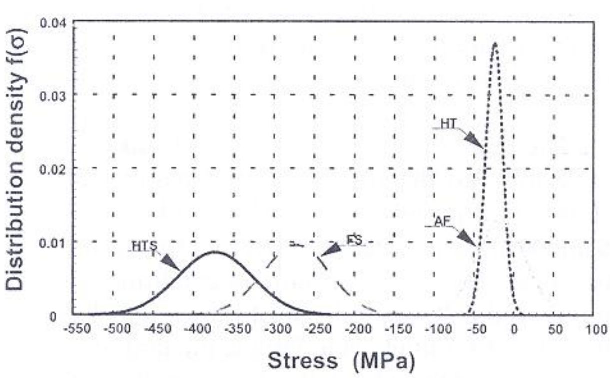

Figure 3. Normal distribution of axial residual stress for hot forged specimens measured by X-ray diffraction.

DISCUSSION

For high cycle fatigue at a half strain range of 2200 $\mu\varepsilon$, the effect of manufacturing process on fatigue

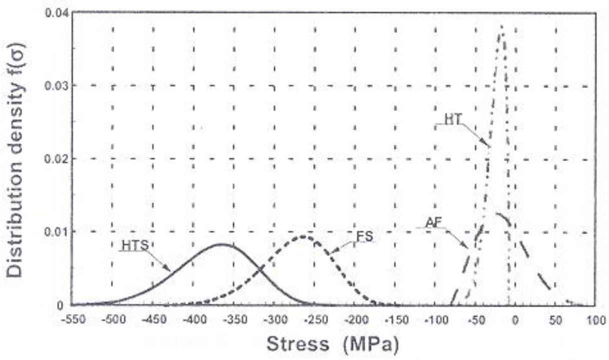

Figure 4. Weibull distribution of axial residual stress for hot forged specimens measured by X-ray diffraction.

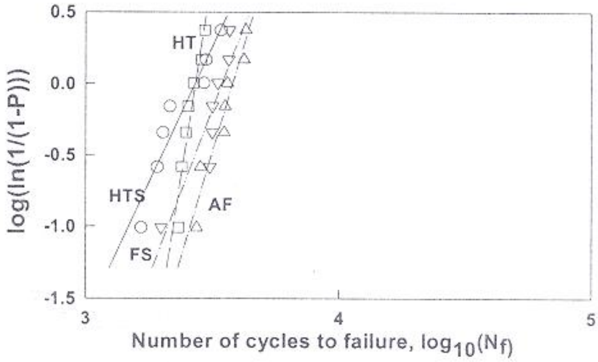

Figure 6. Probability of low cycle fatigue failure ($\Delta\varepsilon/2=6000$ $\mu\varepsilon$).

lives can be seen from Figures 5 and 7. The HTS batch, which had been subjected to the complete manufacturing process (forged plus hardening & tempering plus shot-blasting), had the best fatigue behavior, whilst AF group, which had been subjected to only the forging process, had the shortest fatigue lives. Comparing the HT and AF batches, the heat treatment reduced the scatter without changing the mean life. The shot blasting treatment improved the fatigue life but also increased the scatter.

In contrast at a high strain range the difference between the various batches was not so pronounced, as shown in Figures 6 and 8. Nevertheless, it was evident that the complete forging process had a complete opposite effect for LCF conditions compared with HCF conditions. The HTS batch had the shortest fatigue lives, while the AF batch had the longest. However, under LCF conditions the heat treatment reduced the scatter as well.

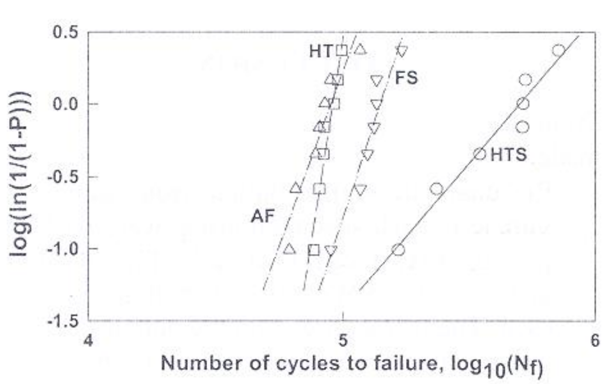

Figure 5. Probability of high cycle fatigue failure ($\Delta\varepsilon/2=2200$ $\mu\varepsilon$).

The following points could explain these experimental results:

- The heat treatment increased the elastic limit, which may enhance fatigue lives for HCF. However, the heat treatment reduced the ductility of the material, which was detrimental to LCF because plastic deformation dominated during LCF. Nitriding, which is a thermochemical surface treatment that is often utilized to improve the fatigue strength of mechanical elements, showed a similar effect. It has been shown that increasing the duration of nitriding, strongly increased the high-cycle strength but decreased the fatigue behavior for high applied strains [13].
- Shot blasting has been shown to introduce

TABLE 1. Fitted Parameters of Weibull Distribution for Fatigue Tests.

Batch	Weibull Slope β	Characteristic Life, Cycles N_a
$\Delta\varepsilon/2=2200$ $\mu\varepsilon$		
AF	4.82	89809
FS	5.36	140271
HT	11.27	91378
HTS	2.04	500453
$\Delta\varepsilon/2=6000$ $\mu\varepsilon$		
AF	5.97	3820
FS	4.69	3470
HT	11.44	2724

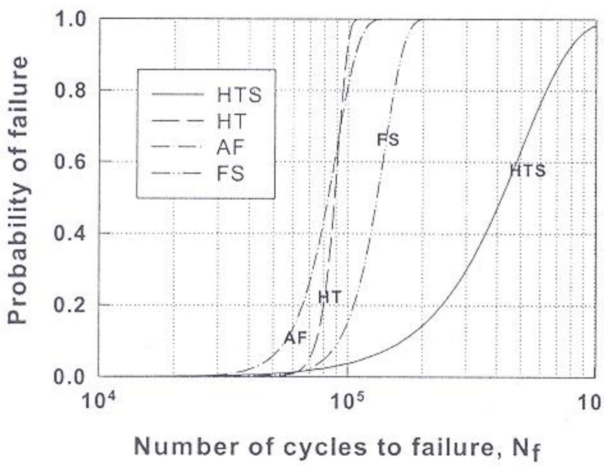

Figure 7. Probability of failure of forged specimens ($\Delta\varepsilon/2$ = 2200 $\mu\varepsilon$).

compressive residual stresses and increase specimen surface roughness. Generally compressive residual stresses increase fatigue life and surface roughness has an opposite effect.

- For HCF conditions, most of the residual stresses are not relaxed during fatigue. The positive effect provided by compressive residual stresses on fatigue is much more than the negative effect caused by surface roughness. Thus, the fatigue life increased for HCF conditions. Consequently, shot blasting increased

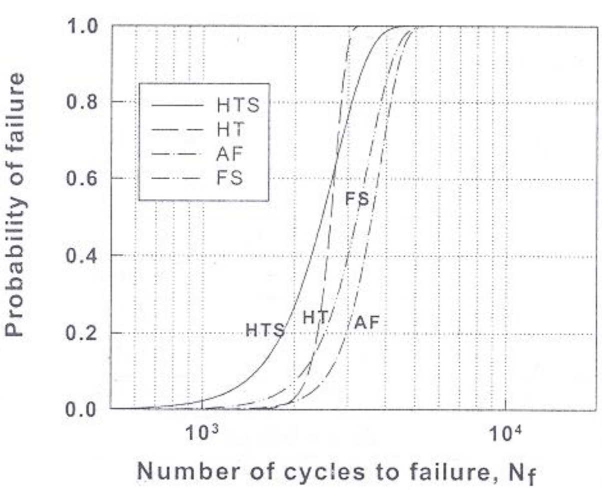

Figure 8. Probability of failure of forged specimens (De/2 = 6000 me).

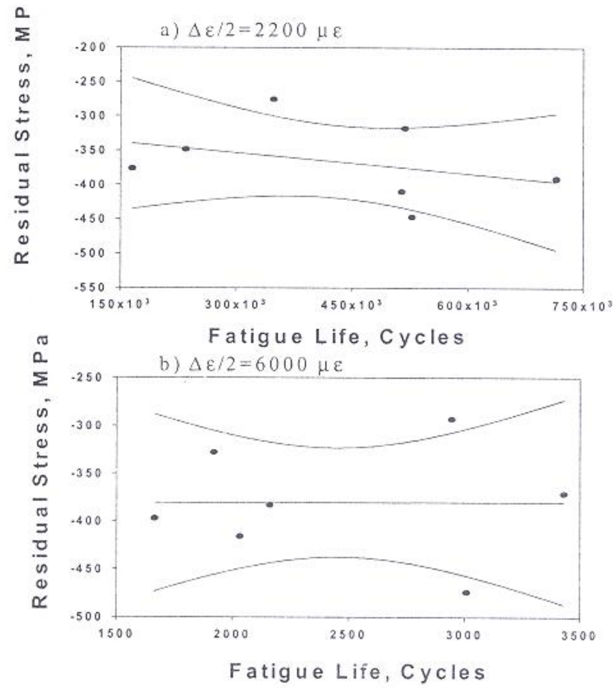

Figure 9. Correlation between residual stresses and fatigue lives for HTS batch.

the fatigue life under HCF conditions just as shown in Figures 5 and 7.

Large plastic deformation dominated under LCF and therefore residual stresses are completely relaxed in a few fatigue cycles, which has also been revealed by both experiments and finite element analysis [14]. Therefore, residual stresses introduced by shot blasting will have no effect on fatigue life. However, surface roughness caused by shot blasting decreased the fatigue life, as shown in Figures 6 and 8.

CONCLUSION

From this work the following conclusions may be made:

1. Residual stress distribution from sample to sample in each specimen group were analysed using statistical method. The normal distribution and Weibull distribution were both used. The histograms from the both histograms were compared with those from X-ray measurement results. It was found that there was no much difference between the two distributions.

2. Residual stresses, surface roughness and fatigue behavior for each batch were different.
3. Fatigue test data from four batches, AF, HT, FS and HTS were analyzed. The failure probability for two strain ranges, 2200$\mu\varepsilon$ and 6000$\mu\varepsilon$, for each batch was obtained using the Weibull distribution.
4. The shot blast treatment was shown for high cycle fatigue conditions to improve fatigue lives significantly but increase scatter and for low cycle fatigue to reduce fatigue lives and also increase scatter.
5. The heat treatment slightly enhanced fatigue in HCF and reduced fatigue lives in LCF, and reduced scatter in both cases dramatically.

It was found that compressive residual stress had no benefit under LCF because the residual stresses were completely relaxed due to the large plastic deformation.

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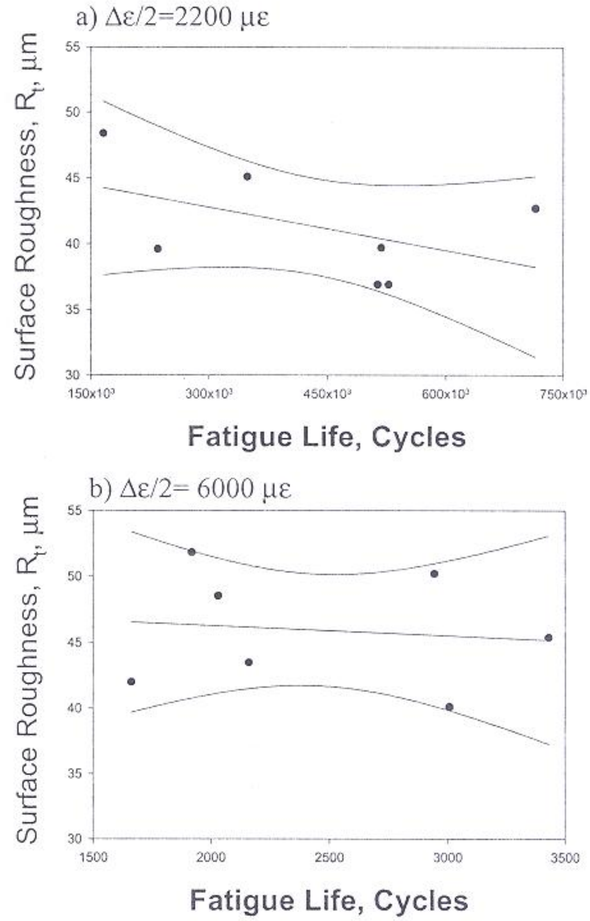

Figure 10. Correlation between surface roughness and fatigue lives for HTS batch.

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