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THE EFFECT OF SURFACE FINISH ON THE LOW CYCLE FATIGUE OF MEDIUM CARBON STEEL.

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Abstract

As fatigue cracks initiate predominantly at the free surface of a material, the condition of the surface can be assumed to be critical with regards to fatigue strength. The features of a mechanically prepared surface which are considered to be major factors affecting fatigue strength are stress concentration (a shape factor), dimension (a scale factor), and surface finish (a technological factor). This paper investigates the effect of surface finish on the fatigue life of AISI/ SAE 1040 (medium carbon steels). A compositional analysis was performed to ascertain the percentage of carbon in the materials. The specimens were machined to a precise gauge length and diameter and exposed to various surface finishes mainly; polishing and grinding machining surface conditions. A fatigue test was performed with the use of Avery Dennison and bending stress was obtained using the curve supplied with the machine. The results from the machine were converted to Mega Pascal (MPa) and the values used to plot S-N curves. The fatigue resistance for the specimens at various surface finishes of the different carbon steels was thus established. The results show that the polished surface with surface roughness ($Ra = 0.20$ microns) has the longest fatigue life.

Keywords: Surface finish; Machining; Fatigue, Medium Carbon Steel.

1. Introduction

Due to market pressures for improvements in productivity, reliability, ductility, wear resistance and profitability of mechanical systems, manufacturers are placing increasing demands on available materials. In order to enhance the surface properties of today's engineering materials, producers of components are turning to different surface finish and treatments. There are several techniques available for improving a component's surface properties, such as polished, ground, machined, hot rolled, forged, cast, etc. Some of these techniques produce improved surface by plastic deformation of surface irregularities (Hassan and Momani, 2000). Engineering components and structures are regularly subjected to cyclic loading and consequently are prone to fatigue damage, which in most cases start at the surface due to localized stress concentrations caused by machining marks, exposed inclusions or even the contrasting movement of dislocations. Fatigue is an important parameter to be considered in the behaviour of components subjected to constant and variable amplitude loading (Torres and Voorwald, 2002). Fatigue is a big problem of components subjected to cyclic stresses; particularly where safety is paramount, examples include free piston linear generator engine components etc. Components of machines, vehicles and structures are also frequently subjected to cyclic loads, which in some cases may lead to their failure due to fatigue. It is estimated that fatigue is responsible for 80% to 90% of all engineering failures (Fatemi and Yang, 1998). According to Bannantine et al. (1989) Fatigue failure involves a multi-stage processes that begins with crack initiation, followed by a progressive crack growth across the part with continued cyclic loading, and finally the sudden fracture of the

component or specimen. A machining process can be obtained from a profile scan and is often expressed as the centre line average R_a value. The R_a value might vary from 0.2 microns for a good polish to 8 microns for a rough turned finish (Gunnberg et al., 2006). Fatigue cracks initiate predominantly at the free surface of a material, the condition of the surface can be assumed to be critical with regard to fatigue crack initiation (Sasahara, 2005). Since the surface finish of the engineering materials can be controlled during machining, it is often considered by manufacturers in order to increase the life of the products (Javidi, 2008). Low-cycle fatigue tests subject specimens to repeated stress or strain until failure occurs at a relatively small number of cycles (Kuroda and Marrow, 2007). The upper limit in low-cycle life has generally been selected arbitrarily by individual investigators to lie in the range of 10^2 to 10^5 cycles. On the other hand, the lower limit of life is the static test which has been represented by various investigators as one cycle, two cycles, three cycles, four cycles and five cycles. Investigations in low-cycle fatigue are conducted either to provide information concerning a particular problem, or to obtain fundamental information. In this paper, the effect of surface finish on the low cycle fatigue life of medium carbon steel is examined using a variety of surface finishes.

2. EXPERIMENTAL PROCEDURES

In this work, 0.40 % carbon steel was selected to study the effect of surface finish on fatigue strength. Composition of the alloy is summarized in Table 1. Standard fatigue specimens were prepared according to Avery Dennison machine 7305 Fatigue Testing Machine standards. From the material used, hour-glass shaped smooth specimens were turned to shape with surface roughness of $R_a \approx 1.58 \mu\text{m}$. These conditions were selected from the response surfaceto obtain surface finishthat were close the average roughness required (Kuroda and Marrow, 2008).The population of specimens with this surface roughness is later referred as series F. Three additional series were created out of series F. Another one was grinded to an average surface roughness of $R_a \approx 1.38$ (series G). Series T were added also $R_a \approx 0.86$. The last series (series P) were additionally polished after the grinding process using emery paper of 400 grit size. Surface roughness of the specimens was measured using Surface Roughness Tester (TR100). Standard readings taken were average surface roughness (R_a) and maximum profile height (R_z).

Table 1. Chemical composition of Medium Carbon Steel

| AISI No. | UNS No. | Carbon (%) | Manganese (%) | Phosphorus (%) | Sulfur (%) |
|----------|---------|------------|---------------|----------------|------------|
| 1020 | G1020 | 0.4045 | 0.5993 | 0.0317 | 0.0444 |

Source: Spectroanalysis done at Universal Steel Company, Lagos



Figure 1: Fatigue testing machine specimens.

2.1 Fatigue Test

The fatigue test was done using Avery Denison machine (Avery model 7305). The bending moment was measured. The revolution counter fitted to the motor records the number of stress cycles to failure (N). The calibration curve supplied with the machine was used to show the relationship between dial gauge reading and the imposed torque. The essence of this is to determine the actual load the material in question can withstand before failure in service.

The following equation was used to calculate the bending stress.

$$\sigma_s = \frac{M_{max}}{W}$$

Where;

σ_s = Bending stress (MPa)

M_{max} = bending moment read from the machine in Kgcm

W = section modulus = $\frac{\pi d^3}{32}$

The stair case method was used in applying the moment. The applied bending moment was increased by a fixed increment and the next specimen was tested with the new bending moment. That was done to each specimen at a particular surface finish.



Figure 2: Avery Dennison fatigue testing machine.

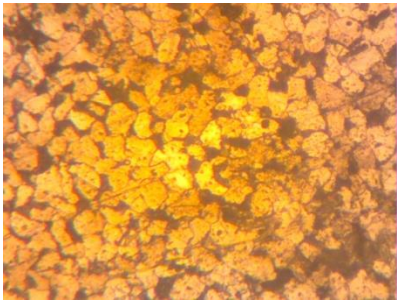
The fatigue test of the material in air was done for the as-received materials A1 (i.e. the medium Carbon steel). The bending moments imposed were 55, 110, 165, 220, and 275 Kgcm which was converted to 396.3, 792.6, 1188.9, 1585.3, and 1981.6 KN-m for various Surface finish.

The bending test was performed at a frequency of 50Hz (1400rpm) for each specimen. It was a complete reversed cycle of stress range (R) and is equal to minimum stress divided by maximum stress which is equal to a negative value (-1) in fatigue tests.

3. RESULTS AND DISCUSSION

3.1 Effect of machined surface on fatigue strength

The micrograph of the specimen prior to surface finish is presented in Fig. 3, which shows that the microstructure is composed of pearlite and ferrite. Machining influences the conditions of the subsurface microstructure, which was examined under a confocal scanning laser microscope in etched condition. Selections of the etched subsurface microstructures generated after machining are illustrated in Fig. 4. The scanning electron microscope image of the layer underneath the machined surface shows that the grain boundaries tend to deform in the direction of feed due to the high temperature and force generated during hard turning. Region A indicates that the original grains are no longer discernible. Clearly, the observations indicate that high plastic deformation was generated after machining.



(a) Medium carbon steel

Figure 3. Photomicrograph: specimens of medium carbon steel prior to surface finish



Figure 4. Photomicrograph: specimens of medium carbon steel after machining

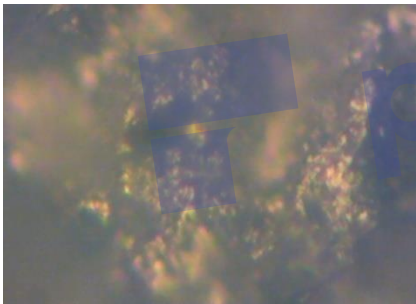


Figure 5. Photomicrograph: Tip of fractured specimen of medium carbon steel



Figure 6. Tip of fractured specimen of medium carbon steel

Figure 5 which represents photomicrograph of steel specimen tips which has failed under fatigue loading, show a fast fracture region and crack initiation region. Brittle fracture shows a bright granular appearance in micrographs. The examinations of the specimen show a brittle fractured surface with inter-granular facets. These inter granular facets are grain surfaces that have been exposed by crack propagation along grain boundaries. They are characterized by incremental propagation of crack, the cross section has been reduced to where it can no longer support the maximum applied load and fast fracture occurs. Considerable evidence of plastic deformation was apparent from the necking and cup–cone fracture surface of the LCF specimens ($N \leq 10^4$ cycles). The origin of failure was clearly evident at the machined surface and a finite portion of the fractured surface was oriented normal to the applied cyclic tensile stress with clear indication of crack initiation and cyclic growth. Microscopic observations clearly indicated that fatigue failure of the specimens initiated at surface defects that resulted from machining, regardless of the magnitude of surface roughness. This is consistent with previous observations by Kuroda et al. (2006).

The Effect of Surface Finish on Fatigue strength of Medium Carbon Steel

The fatigue life diagram representing the results from fatigue testing of the medium carbon steel specimens are shown in Figures 7 and 8. As evident in these figures, there was a notable difference in fatigue strength amongst the two groups of specimens, although high plastic deformation and the machined surface finish continued to contribute to fatigue damage accumulation. The failure process in the low-cycle fatigue shows no differences in the fracture surfaces apparent between the two groups of specimens. Nevertheless, results from the fatigue testing indicated that there was a significant difference in the LCF life between grinded and polished specimen with $1.29 \mu\text{m}$ and $0.20 \mu\text{m}$ roughness respectively.

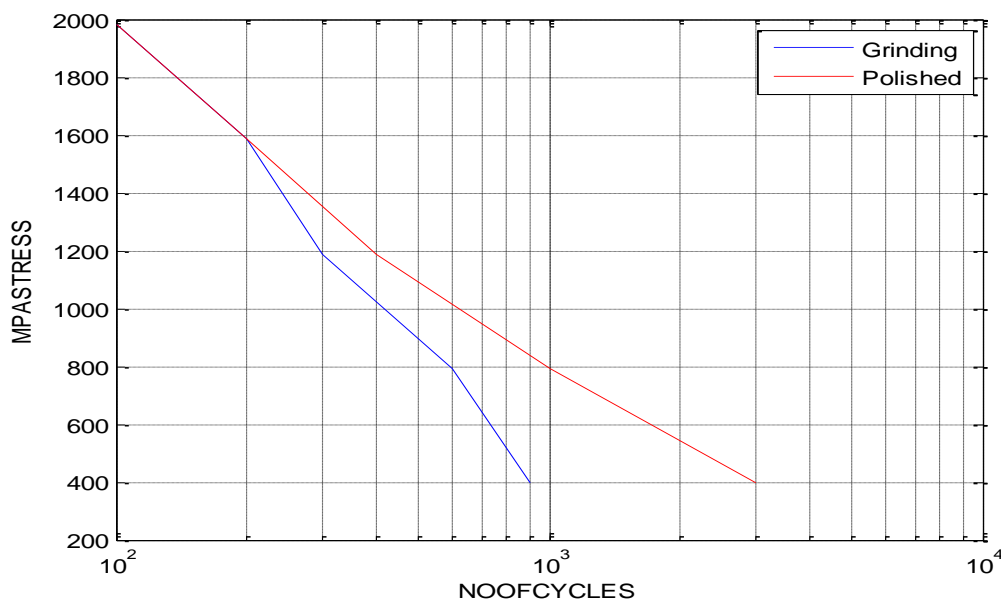


Figure 4.6 The S-N curve for grinded and polished surface finish of medium carbon steel.

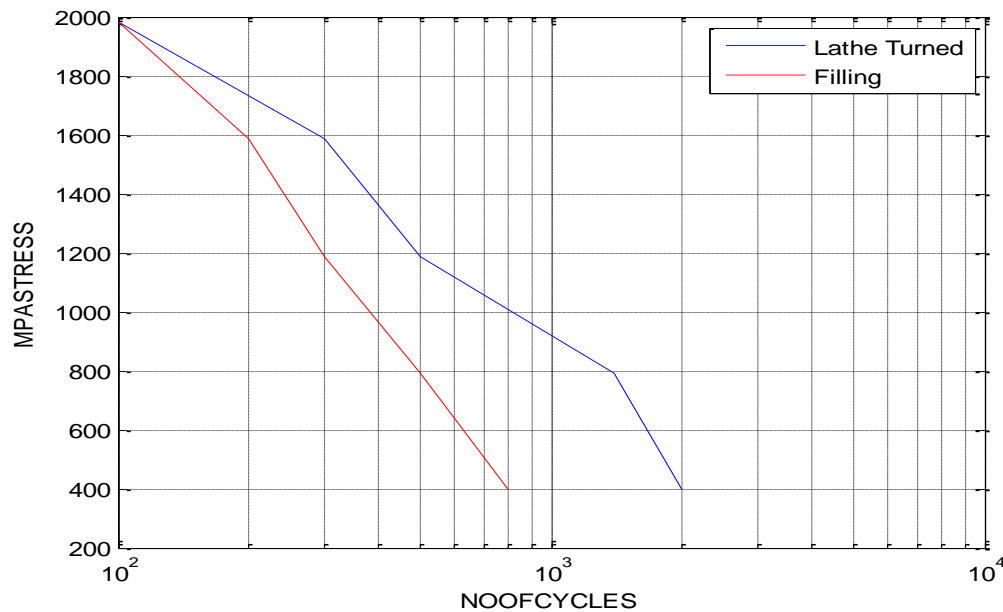


Figure 4.7 The S-N curve for Lathe turned and filled surface finishes of medium carbon steel.

The rate of damage accumulation and corresponding contribution of surface finish to fatigue failure of the medium carbon steel specimens with largest roughness were suppressed. The increase in low-cycle fatigue life of the medium carbon machined steel with increasing surface roughness resulted from retardation in damage accumulation at the machined surface due to its higher hardness value. In this manner, the machined surface integrity of specimens with R_a equal to $1.69 \mu\text{m}$ contributed less to the damage accumulation process than within those specimens with the lowest roughness (polished $0.20 \mu\text{m}$). These findings considering the limited experimental results require additional investigation for verification.

For polished surface finishes better than $0.20 \mu\text{m}$, the fatigue life increases as the surface finish improves. This life increases steadily with improving surface finish and approaches a minimum of $0.10 \mu\text{m}$.

Results from fatigue testing of the medium carbon steel indicated that the magnitude of surface roughness affected the material's fatigue strength. A reduction in fatigue life occurred with increasing roughness of the steel specimens under LCF and undoubtedly occurred due to the stress concentration occasioned by the surface roughness.

5.0 Conclusion

Fatigue life of the medium carbon steel specimens after surface finish process was determined using the bending type fatigue testing machine. The results showed the fractured

surface of the fatigue tested specimen and the location of the fracture along the specimen. S-N curves were drawn to assess the effect of machined surface quality (i.e. surface finish) on the fatigue life of the two grades of steel specimens with varying surface roughness. The Number of cycles to failure was plotted against the bending strength. It was observed that the fatigue life increases as the bending load subjected on the specimen decreases. It was found that the surface with lower surface roughness ($Ra = 0.20 \mu\text{m}$) has larger fatigue life.

However, surface with higher roughness ($Ra = 3.99 \mu\text{m}$) shows relatively lower fatigue life. Thus it can be concluded that the polished surface increases the fatigue life of the machined components compared to ground, lathed turned and filled specimens because rough surfaces are stress concentration areas, thus leading to decreasing endurance limit. Fatigue strength was impaired for low-cycle regime ($<10^4$) of medium carbon steel, because ductility is the more important factor. This can be explained as lower ductility and toughness, with higher hardness values, will lead to smaller strain-hardening values and redistribution of surface stresses, but higher local stresses will encourage crack propagation at low cycle regime. The higher the ultimate tensile strength and hardness, the greater the degradation of fatigue limits.

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