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Influence Of Surface Roughness On Ultra-High-Cycle Fatigue Of Aisi 4140 Steel.

Daniel Januário Cordeiro Gomes; Ernani Sales Palma; Pedro Américo Almeida Magalhães Júnior.
Mechanical Engineering, Pontifical Catholic University of Minas Gerais (PUC - MG) – Brazil

ABSTRACT
Low and high-cycle fatigue life regimes are well studied and are relatively well understood. However, recent fatigue studies on steels have shown that fatigue failures can occur at low amplitudes even below the conventional fatigue limit in the ultra-high-cycle fatigue range (life higher than 10^7 cycles). Fatigue life in the regime of 10^6 to 10^8 cycles-to-failure in terms of the influence of manufacturing processes on fatigue strength is examined. Specifically, the influence of surface roughness of turned surfaces of AISI 4140 steel specimens on fatigue strength in the giga cycle or ultra-high-cycle fatigue range is evaluated. The fatigue experiments were carried out at room temperature, with zero mean stress, on a rotating-bending fatigue testing machine of the constant bending moment type. The fatigue strength of the specimens were determined using the staircase (or up-and-down) method.
***Keywords*:** Giga cycles, ultra-high-cycle fatigue, super long life regime, very high cycle regime, fatigue limit, surface roughness, surface integrity.

I. INTRODUCTION

Fatigue is a major cause of the failure of mechanical components during service. Fatigue cracks usually nucleate on the surface of these components. Thus, the fatigue life of a machine component strongly depends on its surface layer condition. Fatigue crack nucleation and propagation, in most cases, can be attributed to impaired surface integrity, which includes surface roughness, structural and stress conditions of the surface layer. The importance of surface integrity increases with increasing lives, loads, environment and temperature.
The surface layer is determined by manufacturing processes and by finishing treatments. Machining is a competitive alternative process for producing a wide range of mechanical components, such as gears, cams, shafts and axles. The process of machining steel is complex and the surface generated is influenced by several variables: steel properties (elastic and plastic deformations), tool material and geometry, cutting tool vibrations, cutting speed, feed, depth of cut, lubricant, etc. Previous studies have demonstrated that machining processes produce damage to the surface of metals, thus the properties of the surface differ from those of the bulk of the material (BENARDOS; VOSNIAKOS, 2003; BAILEY; JEELANI; BECKER, 1976; ZAHAVI; TORBILO, 1996) e.g., the surface layer is subjected to elastic-plastic deformation and heating, which results in structural changes, strain hardening, residual stresses and irregularities that may cause surface roughness.
The influence of machining parameters on the fatigue limit of AISI 4140 steel was studied in detail by Lopes 2006 and Lopes, Sales e Palma (2008). A relationship between surface roughness and machining parameters with a fatigue limit at $2x10^6$ cycles was determined. Residual stresses, strain hardening and roughness surface play a dominant role in determining material fatigue behavior.
Many structural components now are working beyond 10^7 cycles. This required has increased the number of research on ultra-high-cycle fatigue life regime (MARINES; BIN; BATHIAS, 2003). Studies on fatigue lives greater than 10^7 cycles began to emerge in the late 1980s. In the 1990s, several consistent reports demonstrated that steels could fail beyond ten million cycles due to fatigue (BATHIAS et al., 1991; BATHIAS; NI, 1993; ; MASUDA; TANAKA, 1994; MURAKAMI; ENDO, 1994; WU; NI; BATHIAS, 1994; BATHIAS, 1996; KANAZAWA; NISHIJIMA, 1997; STANZL-TSCHEGG, 1999). Bathias and co-workers performed fatigue tests on steel and other metals and concluded that these materials do not have an infinite life under cyclic loading. (BATHIAS, 1999; BATHIAS; DROUILLAC; FRANÇOIS, 2001; BATHIAS; PARIS, 2005). According to these researchers, the S-N (stress/ cycles) curves obtained up to 10^{10} cycles did not have a typical horizontal level, i.e., it was not possible to determine fatigue limit for these materials. Several other authors have presented the same conclusion (BAYRAKTAR; GARCIAS; BATHIAS, 2006; SHIMIZU; TOSHA;

TSUCHIYA; 2010). Sadananda, Vasudevan and Phan (2007) showed that the fatigue strength of steel is more sensitive to the presence of stress inducers at a giga cycle life than at shorter lives. Finally, some researchers have shown that S-N curves exhibit more than one type of failure (PYTELL; SCHWERDT; BERGER, 2011; SONSINO, 2007; BOMAS; BUKART; ZOCH, 2011). In general two knees can be observed: one associated with surface crack nucleation, for high fatigue life and inner crack initiation observed at giga cycle lives (WANG *et al*., 2002; CHAPETTI, 2011). Subsurface cracks may be associated with microscopic defects (inclusions, pores) but sometimes these failures can occur in defects free materials like microstructural heterogeneities (BAYRAKTAR; GARCIAS; BATHIAS, 2006; ZUO; WANG; HAN, 2008).

The recent studies have shown that fatigue tests on super long life have shown that metallic materials exhibit a decrease in fatigue strength after 10^7 cycles. Therefore, the concept of life-safe based on infinite life criterion should not be used because the S-N curves do not have a horizontal level as previously thought.

In Low and high-cycle fatigue life regimes the crack nucleation arises primarily from surface defects. Recent researches have shown that the nucleation in ultra-high-cycle fatigue tends to occur within the material from inclusions, pores, microstructural heterogeneities and other internal defects. However, there are not conclusive studies on the mechanisms of failure and methods of predicting fatigue life in this life range.

Tanaka and Akiniwa (2002) obtained interesting results in the very high cycle regime of specimens submitted to shot peening. These authors noted that all fatigue cracks appeared within the material due to compressive residual stresses on the surface layer. Furthermore, when compared with grinding test specimens, the shot peening specimens showed a decrease of fatigue strength because of tensile residual stresses being inside the material.

Bayraktar *et al*. (2009) carried out a research about the surface conditions in mechanical components in order to understand the fatigue behavior in super long life regime. These authors analyzed the influence of carburizing thickness and of surface roughness. This study did not show evident effect in fatigue strength for the two cases of carburizing thickness. Furthermore, the three cases of surface roughness investigated did not present noticeable effect on the S-N curves.

The importance of both surface roughness and integrity is well recognized, with several studies relating these characteristics with fatigue life (MCKELVEY; FATEMI, 2012). Few reports in the literature, however, describe the influence of machining cutting parameters on the very high cycle fatigue life of commercial steels. In the present study, the influence of feed rate on the fatigue strength of turning specimens of commercial AISI 4140 steel at lives above 10^7 cycles is examined.

II. MATERIAL, SPECIMENS AND EXPERIMENTAL METHOD

In this investigation the AISI 4140 steel was used as raw material. The average chemical composition (wt%) of this steel is shown in Table 1.

Table 1: Chemical composition of the AISI 4140 steel

Element	**C**	**Mn**	**Si**	**Cr**	**Mo**	**Fe**
wt (%)	0,40	0,87	0,25	0,95	0,20	balance

The microstructure of this steel is composed of ferrite and pearlite. A micrograph of the virgin specimen of the investigated steel is shown in Figure 1.

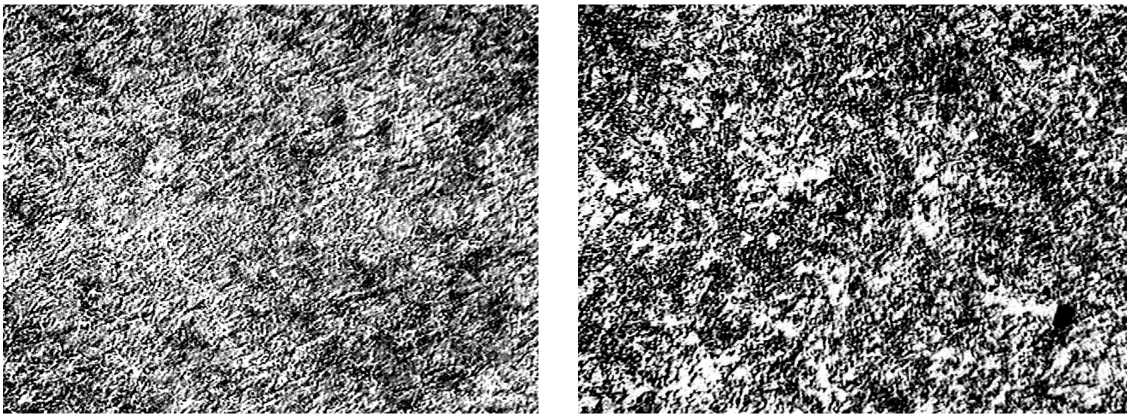


Figure 1: Micrograph of the AISI 4140 steel in virgin specimen. Expansions of 200 and 500 times respectively

This material was supplied as laminated cylindrical bars about 3,000 mm long with a diameter of 16.88 mm (5/8 in). These as-received materials were normalized and fatigue specimens were turned to the configuration shown in Figure 2.

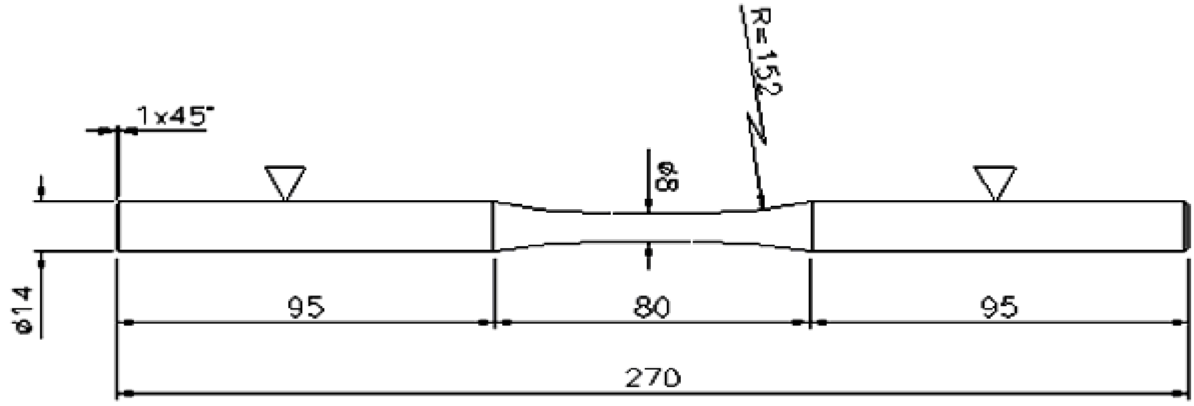


Figure 2: Geometry of the specimens used in rotating-bending fatigue testing – Dimensions in mm

The test specimens were turned with the following cutting parameters: Cutting velocity (V_c) = 60m/min, depth of cut (a_p) = 1.2 mm and two feed rates [(f) = 0.12 and 0.25 mm/rev]. These test specimens were grouped according to the surface finish induced by cutting parameters.

The turning process was carried out using a CNC lathe model Romi Centur 30D with a 6% concentration emulsion as the cutting fluid (Esso, specification Kutwell 40). The selected cutting tool was cemented carbide (WC+Co+TiC+TaC), with a specification of DCMT 11 T 304 – PM05, WAM-20 and coated by TiN. The geometry of the tools used was as follows: rake angle □ = 6^0, clearance angle □ = 5^0, approach angle $□_r$ = 60^0 and inclination angle $□_s$ = 0^0. The tool-holder used for machining the specimens was the PDJCR2020. All tests were performed using cutting tools with fresh edges (without wear). An optical microscope was used to observe and control the cutting tool wear.

Other specimens were cut and their surfaces were finished by grinding to achieve a surface finish less than Ra = 30 µm in the gauge length. These specimens are hereafter designated as grinded and were used to generate reference mechanical properties.

The specimen turning procedures are summarized in Figure 3. These specimens are hereafter designated according to their condition number.

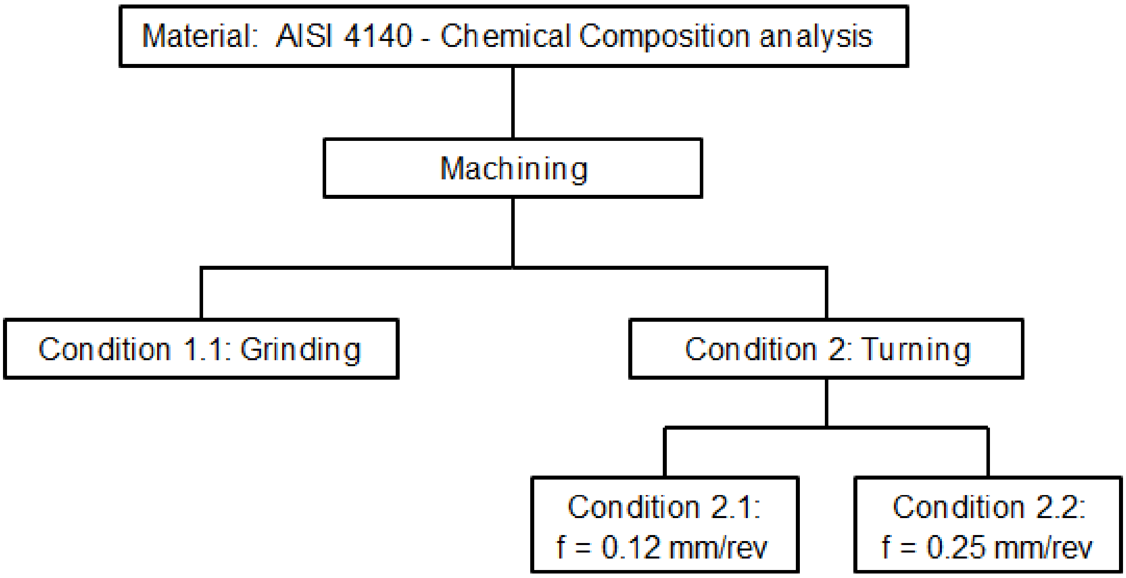


Figure 3: Flow chart of specimen production procedures

After turning with each combination of cutting parameters, the surface roughness was measured before performing the fatigue tests. A surface evaluation system (Surtronic, Taylor Hobson) was used to measure the roughness of the turned surfaces. The surface perfilometer was set for a 0.8mm cut-off length. Surface roughness was evaluated using the arithmetic mean value (R_a), the root mean square (R_q) and the peak to valley height or maximum height roughness parameter (R_t) over a gauge length of 80 mm (Fig. 2) for all specimens. Surface roughness of each specimen was measured four times. The mean values of all specimens of each condition were used for analysis.

1.1. Fatigue Tests

Fatigue tests were performed at room temperature, applying a cyclical frequency of 58Hz, with mean stress equal to zero (R= -1), on a rotating-bending fatigue testing machine with a constant bending moment. The specimens were subjected to a constant bending moment along the gauge length (80 mm according to Figure 2) between the inboard bearings. The specimens were cooled to maintain a constant temperature of 23±2^{o}C during the test.

The test specimens were grouped according to the machining parameters in the turning process. These specimens were separated under conditions determined in accordance with the specific parameters of cutting (Figure 3). These conditions made it possible to measure the influence of machining parameters on the fatigue strength.

The staircase or up-and-down method was used to determine the fatigue strength of each specimen's condition. In these fatigue tests were used $1x10^8$ cycles as the run out criterion. For each test group, if the specimen failed before reaching the run out criterion, the stress level was decreased by a preselected increment and the second specimen was tested at this new lower stress level. If the first specimen ran out, the stress level was increased by the preselected increment and the second specimen was tested at this new higher stress level. The tests were continued in this sequence, with each successive specimen being tested at a stress level that was above or below that of its predecessor. The experimental data were statistically analyzed, using staircase method (COLLINS, 1993; LEE *et al*., 2005).

1.2. Microhardness Test

Because of its wide use and acceptance in scientific research, the Vickers microhardness method was adopted to measure material's hardness. This method utilizes a pyramid-shaped diamond indenter with a square base and inside angle of 360^0 between their opposing faces. In these tests, was used a load of 1.0 kgf and a time of 30 seconds to obtain printing.

In each machining condition were taken two hardness test sample of virgin specimens (i.e., test specimens not examined by fatigue) and four hardness test sample of specimens tested by fatigue. Of these, two samples were taken of specimens failed by fatigue before attaining the prescribed life (1.0×10^8 cycles) and the other two samples of test specimens that ran out (i.e., reached the prescribed life without occurrence of fatigue failure). The microhardness measurements were carried out radially and equally spaced of 500 µm from the surface toward the center of the sample.

The objective of this analysis was to evaluate the behavior of microhardness in super long lives regime (ultra-high-cycle fatigue), before and after fatigue tests.

2. EXPERIMENTAL RESULTS AND DISCUSSIONS

Surface roughness of several specimens was measured in each machining condition according to Figure 3. The surface roughness parameter R_a and R_t increased with an increase in the feed rate, as shown in Table 2.

Table 2: Mean roughness of each machining condition

Machining condition	V_c (m/min)	a_p (mm)	f (mm/rev)	R_a (µm)	R_t (µm)
1.1	**	**	**	**0.22 ± 0.08**	**2.65 ± 0.99**
2.1	60	1.2	0.12	**1.29 ± 0.14**	**7.75 ± 0.53**
2.2	60	1.2	0.25	**5.10 ± 0.88**	**26.70 ± 3.44**

The mechanical properties of AISI 4140 steel are summarized in Table 3. Tensile tests were performed in each machining condition, using de same test specimens utilized in fatigue tests. The monotonic mechanical properties were similar for all conditions.

Table 3: Mechanical properties of AISI 4140 steel

Machining Condition	1.1 - Grinding	2.1 - Turning (f = 0.12 mm/rev)	2.2 - Turning (f = 0.25 mm/rev)
$\sigma_{0,2}$ (MPa)	479.35 ± 39.45	522.26 ± 17.54	490.43 ± 28.55
σ_u (MPa)	624.90 ± 28.82	670.11 ± 9.24	638.47 ± 6.39
σ_r (MPa)	450.71 ± 10.39	484.61 ± 3.97	475.13 ± 6.63

2.1. Fatigue Test Results

The fatigue strength of each specimen's condition was determined using the staircase method. In these fatigue tests were used $1x10^8$ cycles as the run out criterion. Thus, the staircase tests of all condition are shown in figure 4 to 6.

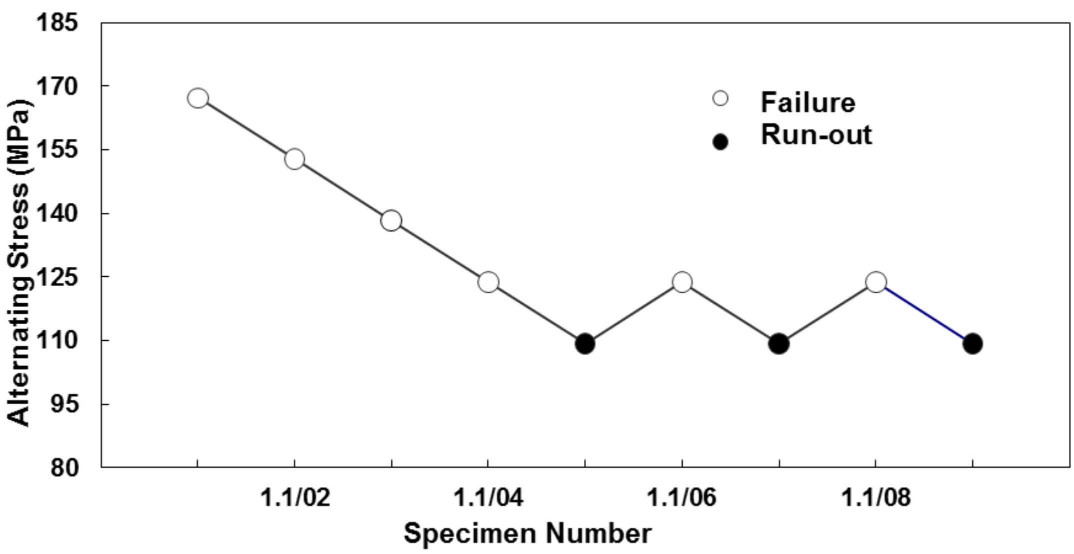


Figure 4: Stair case fatigue test - Condition 1.1 (grinded)

In the condition fatigue tests 1.1, referring to the grinding specimens, the mean fatigue strength was determined as 116.5 ± 7.7 MPa.

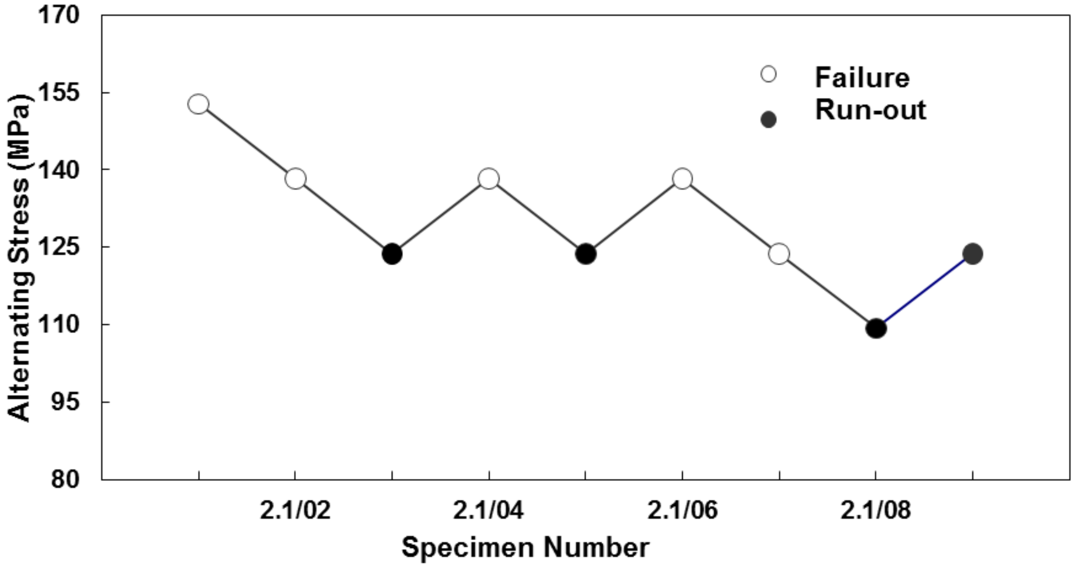


Figure 5: Stair case fatigue test - Condition 2.1 (turned, f = 0.12 mm/rev)

In the condition fatigue tests 2.1, referring to the turning specimens with V_c = 60m/min, a_p = 1.2 mm and f = 0.12 mm/rev, the mean fatigue strength was determined as 127.4 ± 7.7 MPa.

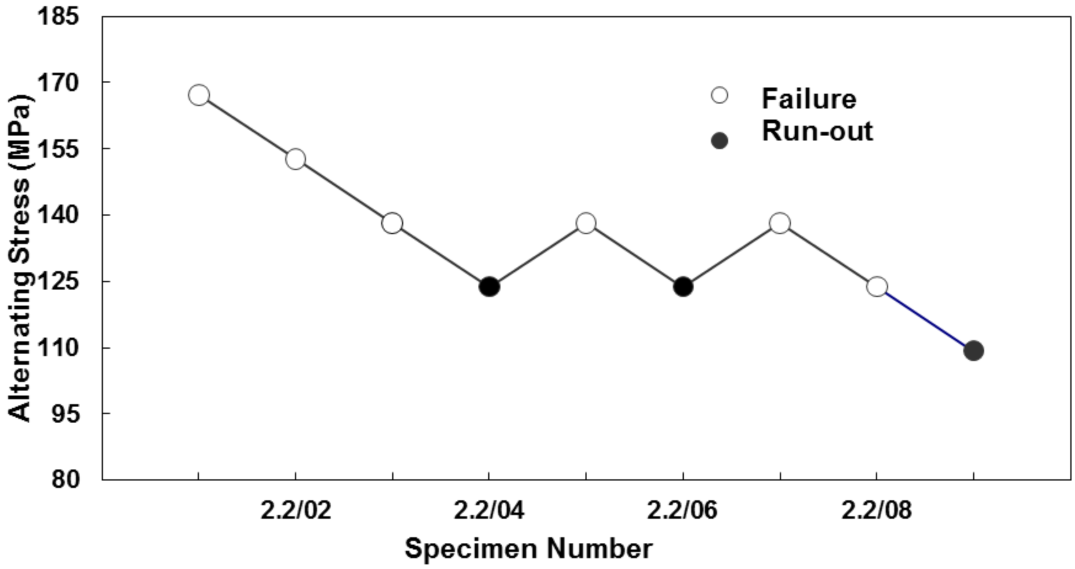


Figure 6: Stair case fatigue test - Condition 2.2 (turned, f = 0.25 mm/rev)

In the condition fatigue tests 2.2, referring to the turning specimens with V_c = 60m/min, a_p = 1.2 mm and f = 0.25 mm/rev, the mean fatigue strength was determined as 126.2 ± 7.7 MPa.

Comparing the fatigue strength results for the three machining conditions, it is noted that the surface roughness did not have a noticeable influence on the fatigue strength of AISI 4140 steel in ultra-high-cycle fatigue. Despite the mean fatigue strength of each machining condition being different, the results are very close. Thus, it can be said that the surface roughness has a smaller effect on fatigue strength for larger numbers of cycles.

The Figures 7 and 8 shows, for each machining condition, the results of mean surface roughness and mean fatigue strength respectively.

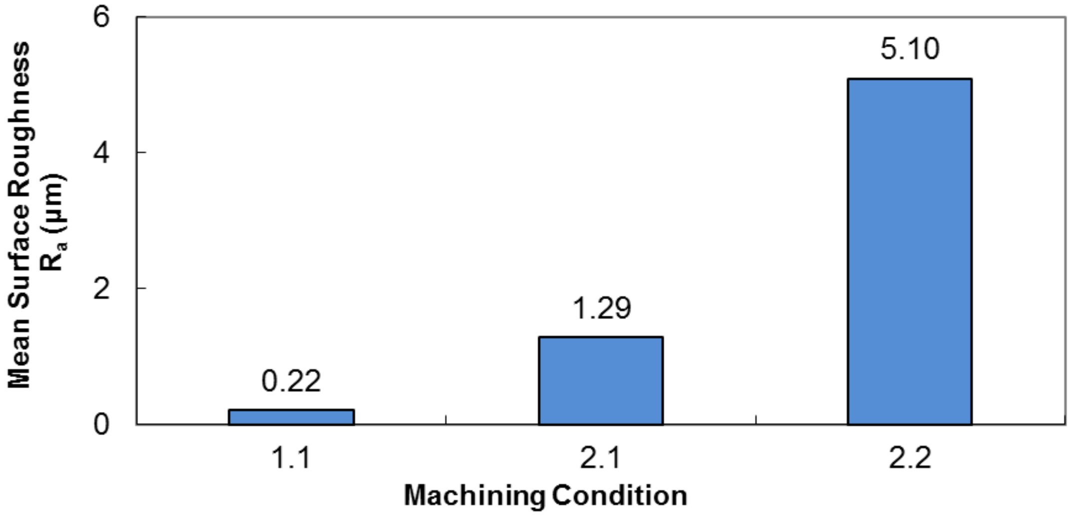


Figure 7: Mean surface roughness for each machining condition.

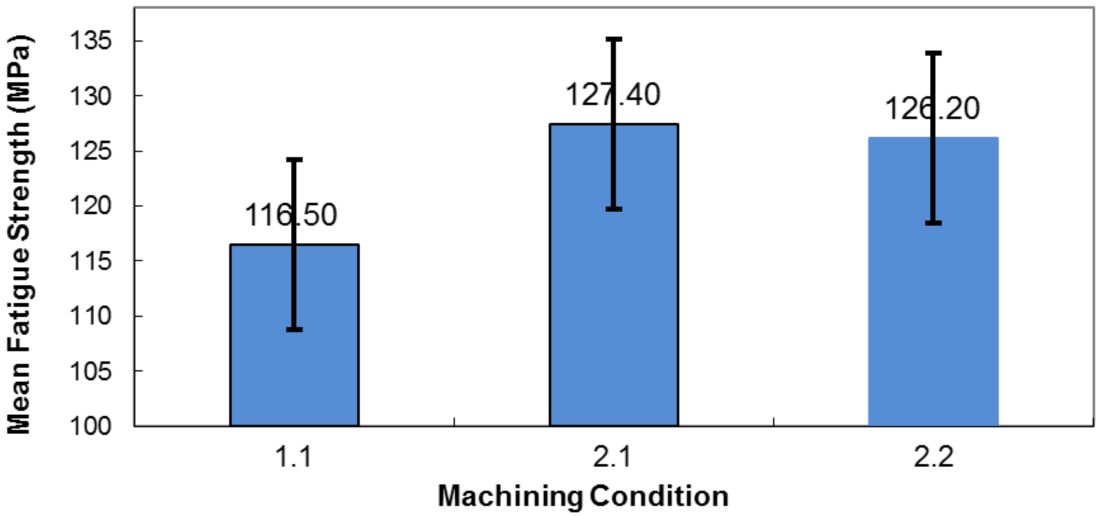


Figure 8: Mean fatigue strength with standard deviation for each machining condition.

The grinded test specimens (condition 1.1) there was lower fatigue strength, despite its lower surface roughness. This behavior is due to the presence of residual stresses in the surface layer of test specimens. The machining causes irregular elastic-plastic deformations, which contributes to the appearance of compressive residual stresses in the surface layer. Despite the grinding decrease the surface roughness also eliminates compressive residual stresses and causes the onset of tensile residual stresses when no proper cooling is used. Thus, the residual stresses have greater influence on fatigue strength than the surface roughness in ultra-high-cycle fatigue.

2.2. Microhardness Test Results

Figures 9 to 11 shows microhardness profile of virgin specimens and specimens tested by fatigue in each machining conditions.

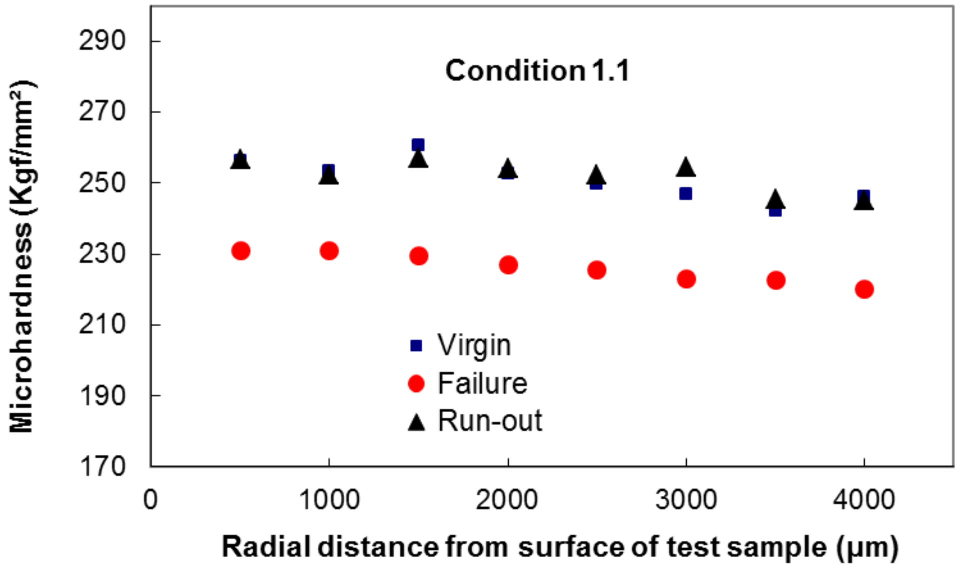


Figure 9: Microhardness profile of the condition 1.1 before and after fatigue tests.

In the condition 1.1 there was a mean cyclic softening of 9.84 ± 1.16% between virgin specimens and specimens that failed by fatigue. This percentage represents a mean cyclic softening of 24.74 ± 3.34 kgf / mm².

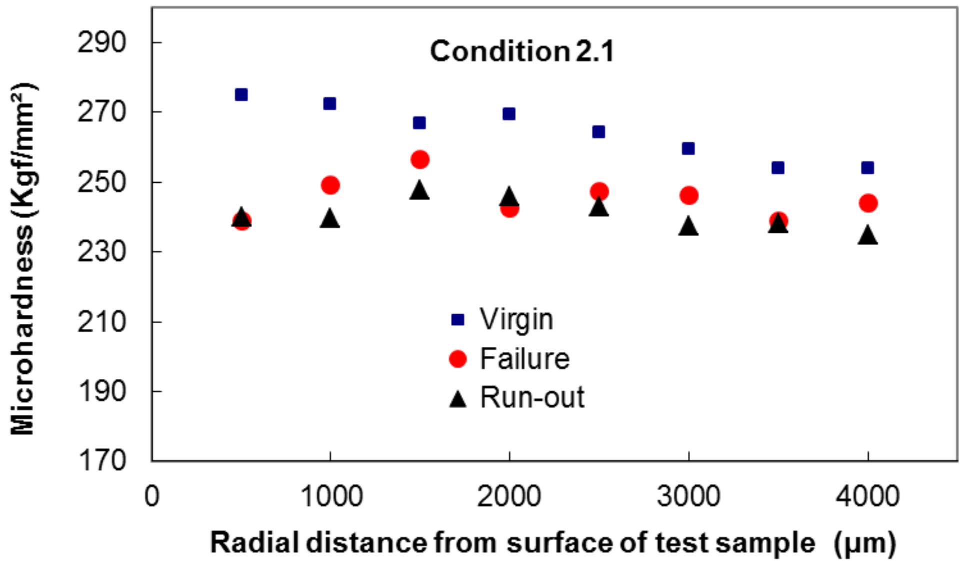


Figure 10: Microhardness profile of the condition 2.1 before and after fatigue tests.

In the condition 2.1 there was a mean cyclic softening of 7.11 ± 3.27% between virgin specimens and specimens that failed by fatigue. This percentage represents a mean cyclic softening of 18.96 ± 9.24 kgf / mm².

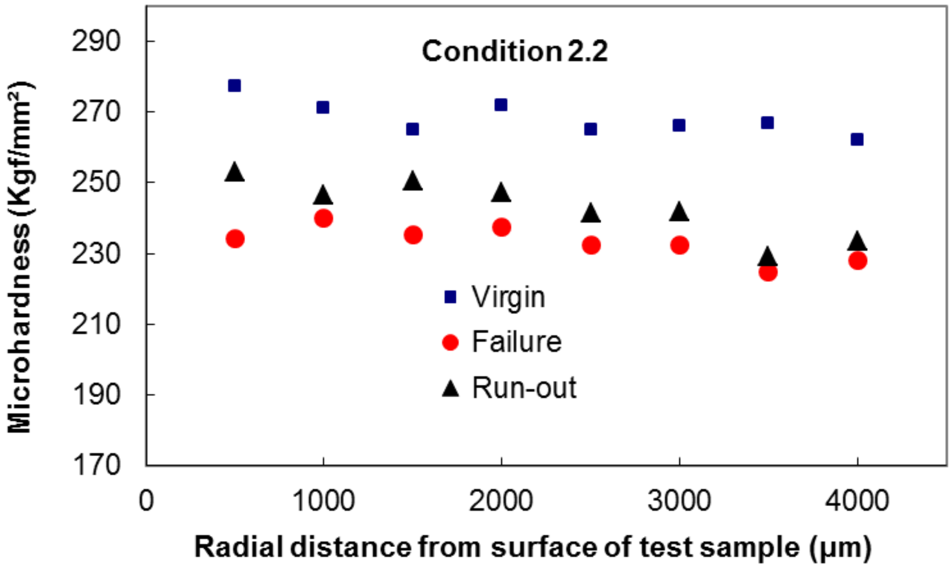
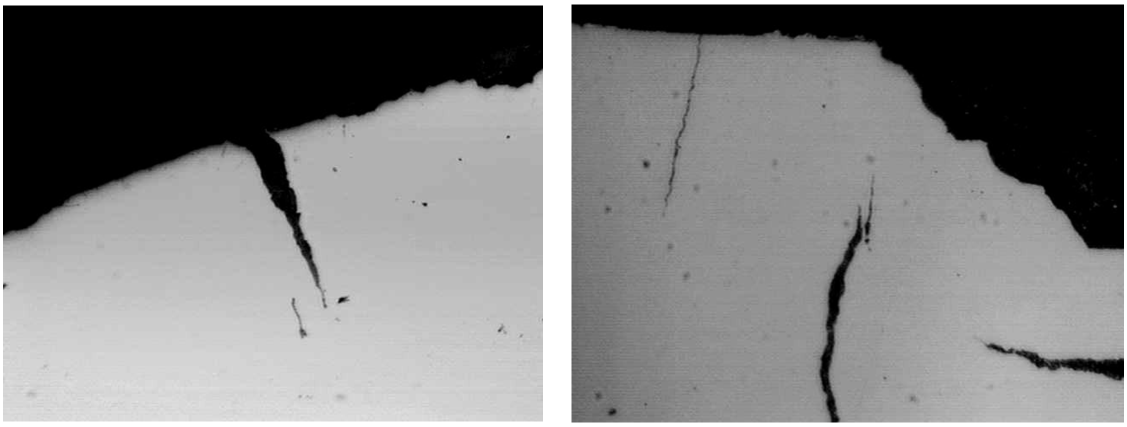


Figure 11: Microhardness profile of the condition 2.2 before and after fatigue tests.

In the condition 2.2 there was a mean cyclic softening of 13.05 ± 1.68% between virgin specimens and specimens that failed by fatigue. This percentage represents a mean cyclic softening of 35.02 ± 4.84 kgf / mm².

2.3. Microstructural analysis

Micrographic analyzes were also performed on specimens tested by fatigue that did not fail until reaching a life at $1x10^8$ cycles (see figure 12a and 12b for representative example).



a) Condition 1.1 b) Condition 2.1

Figure 12: Cracks in specimens tested until $1x10^8$ cycles. 500 time expansion.

Cracks were observed on the surface and the inner of several specimens. Thus, if the tests were not interrupted, the specimens could fail. Therefore, there isn't infinite fatigue life, because the material could break by fatigue even in the super long life regime.

III. CONCLUSIONS

Analysis of results of the influence of machining parameters on the fatigue strength of AISI 4140 steel in very high cycle regime is presented. The results are summarized as follows:

- An cyclic softening was observed in the specimens tested by fatigue, i.e., there was a decrease in the hardness of AISI 4140 steel after it is subjected to cyclic stresses of the order of giga cycles.
- Surface roughness did not have a noticeable influence on the fatigue behavior of AISI 4140 steel in super long life regime. Thus, the surface integrity has a smaller effect on fatigue strength to lifetime beyond 10^7 cycles.
- In the grinding specimens the fatigue strength was lower than in the machining specimens. This effect was not caused by the finish surface, but the absence of compressive residual stresses in the surface layer.

- Even tests which reached the prescribed life without breaking fatigue cracks were detected by micrographics analyze. Therefore, if the test specimen was not interrupted the fracture would occur. So, there isn't infinite fatigue life in ultra-high-cycle fatigue.

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