# INFLUENCE OF TURNING PARAMETER (FEED RATE) ON ULTRA HIGH FATIGUE LIMIT OF AISI 4140 STEEL

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***Abstract.*** *Classical fatigue limit of ferrous metals is a consequence of testing materials at a constant range of cyclic stress and determining the cyclic stress range below which fatigue failures do not occur. However, recent fatigue studies on steels have shown that fatigue failures can occur at low amplitude stresses even below this conventional high cycle fatigue (HCF) limit in the ultra-high-cycle fatigue range (life higher than* $10^6$ *cycles). This paper examines fatigue life above* $10^6$ *cycles in terms of the influence of manufacturing process on fatigue strength. Specifically, the purpose of this research is to study the influence of feed rate of turned surfaces of AISI 4140 steel specimens on fatigue strength in the ultra-high-cycle fatigue (UHCF) range. In some specimens, the residual stresses were eliminated by heat treatment. As expected, the fatigue limit decreases with increasing surface roughness. Besides, the influence of surface roughness on fatigue limit depends of the run out test criterion. Stress relief heat treatment caused a sharp increase of fatigue limit of machined specimens with high roughness parameters. This influence becomes more evident with increasing the number of cycles used to stop the test.*

***Keywords****:* Gyga cycles, Ultra high cycle fatigue, Fatigue limit, Fatigue damage, Surface roughness, Surface integrity

## 1. INTRODUCTION

It is well known that fatigue is a major cause of failure of mechanical components during service. Fatigue cracks usually are nucleated at the surface of these components. Thus, fatigue life of a machine component depends strongly on its surface layer condition. Fatigue crack nucleation and propagation, in most cases, can be attributed to surface integrity, which includes surface roughness, structure 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 mainly, by finishing treatments. Machining is a competitive alternative process for producing a wide range of mechanical components, such as gears, cams, shafts, axles and others. 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, vibration of cutting tool, cutting speed, feed, depth of cut, lubricant, etc. Besides, previous works have shown that in the machined surface of metals a damage region is produced that is different from the bulk of the material (Benados and Vosniakos, 2003, Bailey, Jeelani and Becker, 1976 and Zahavi and Torbilo, 1996). During machining, the surface layer is subjected to elastic-plastic deformation and heating, which result in structural changes, strain hardening and residual stresses, while irregularities may appear, creating surface roughness.

The influence of machining parameters on fatigue limit of AISI 4140 steel was studied in detail by Lopes el al (Lopes, 2008). A relationship between surface roughness and machining parameters with fatigue limit at $2x10^6$ cycles was determined. Residual stresses, strain hardening and roughness surface plays a dominant role in determining material fatigue behavior. Stress relief heat treatment causes an increase of fatigue limit of machined specimens with high roughness parameters and a decrease in polished specimens.

Nowadays, many structural components are working beyond $10^7$ cycles. Consequently, from the end of the eighties, began to emerge some studies on fatigue lives greater than $10^6$ cycles, and the fatigue limit in these ultra-high-cycle fatigue range is well studied. However, only in the nineties have come to light several consistent results showing that the steels may fail due to fatigue after reaching ten million cycles (Bathias, 1993, Kanazawa and Nishijima, 1997 and Kanazawa and Nishijima, 1999). Bathias (1999) and Bathias et al (2001) showed results of fatigue tests on steel and other metals and concluded that there is no infinite life under cyclic loading for these materials. According to this author, the S-N curves obtained until $10^{10}$ cycles did not have a typical horizontal level, that is, there was not possible to determine fatigue limit for these materials. Several authors showed the same conclusions (Marines et al, 2003, and Bayraktar et al (2006)). Finally, Sadananda, Vasudevan and Phan (2007) showed that the fatigue limits of steel in giga-cycle life are more sensitive to the presence of stress raisers than in short lives.

As shown, the importance of both surface roughness and integrity is well recognised, with many studies relating these characteristics with fatigue life. Besides, run out criteria during fatigue test are important to define fatigue strength. However, there are few results in literature that show the influence of machining cutting parameters on ultra high fatigue life of commercial steels. In the present study, the influence of feed rate on the fatigue endurance of turned specimens of commercial AISI 4140 steel in lives above $10^6$ cycles is analyzed.

## 2. EXPERIMENTAL PROCEDURE

In this investigation the AISI 4140 steel was used as raw material whose chemical composition (wt%) is given in Table 1. The microstructure of this steel is comprised of ferrite and perlite. This material was supplied as laminated cylindrical bars about 3,000 mm long with a diameter of 16.88 mm (5/8 in).

Table 1. Chemical composition of the AISI 4140 steel

| Element | C | Mn | Si | Cr | Mo | Fe |
|---|---|---|---|---|---|---|
| wt% | 0,40 | 0,88 | 0,28 | 0,95 | 0,20 | balance |

The as-received materials were normalized and fatigue specimens were turned to the configuration shown in Fig. 1.

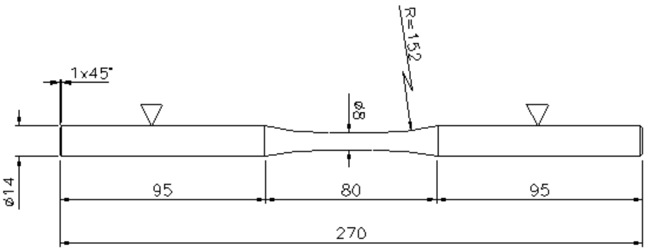

Figure 1. Test specimens – Dimensions in mm..

The as-received bars were turned with the following cutting parameters: Cutting velocity ($v_c$) = 60m/min, deph of cut (a) = 1.2 mm, and feed rates (f) = 0.12, 0.18 and 0.25 mm/rev. The turning process was carried out using a CNC lathe model Romi Centur 30D with emulsion as a cutting fluid (Esso, specification Kutwell 40) at concentration of 6%. The selected cutting tool was cemented carbide (WC+Co+TiC+TaC), specification of DCMT 11 T 304 – PM05, WAM-20 and coated by TiN. The used tool geometry was as follows: rake angle $\gamma_0 = 6^0$, clearance angle $\alpha_0 = 5^0$, approach angle $\chi_r = 60^0$ and inclination angle $\lambda_s = 0^0$. The tool-holder used for machining the specimens is PDJCR2020. Both, cutting tool and tool-holder were produced by Walter do Brasil. All tests were carried out with fresh edges (without wear) on cutting tools. An optical microscope was used to control the cutting tool wear.

After turning with each combination of cutting parameters, the surface roughness was measured. A surface evaluation system (Surftest SJ–400 perfilometer, Mitutoyo) was used in the surface roughness measurements over the turning surfaces. The surface perfilometer was set for a 0.8 mm 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 the gauge length of 80 mm (Fig. 1) of all specimens. The surface roughness measurements on each specimen were repeated four times. The average values of all specimens of each condition have been used as a data point.

### 2.1 Fatigue Tests

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

The staircase or up-and-down method was used to determine the fatigue limit of the specimens (Collins, 1993 and Lee et al., 2005). Several specimens were used for determining the fatigue limit, as follow: The first specimen was tested at a stress level higher than the estimated fatigue limit until it either was failed or was ran out. Three run out criteria were chosen: $2X10^6$, $2X10^7$ and $5X10^7$ cycles. For each test group, if the specimen failed before reaching the run out criterium, the stress level was decreased by a pre-selected 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 pre-selected increment and the second specimen was tested at this new higher stress level. The tests were continued in this sequence, with each succeeding specimen being tested at a stress level that was above or below its predecessor. The obtained experimental data were statistically analyzed according to Lee et al. (2005), using the Dixon-Mood method (Lee et al., 2005 and Lin et al., 2001).

## 3. EXPERIMENTAL RESULTS

Surface roughness of all specimens was measured according to item 2. The surface roughness parameters ($R_a$, $R_q$ and $R_t$) increase almost linear with increasing feed rate, as shown in Fig. 2.

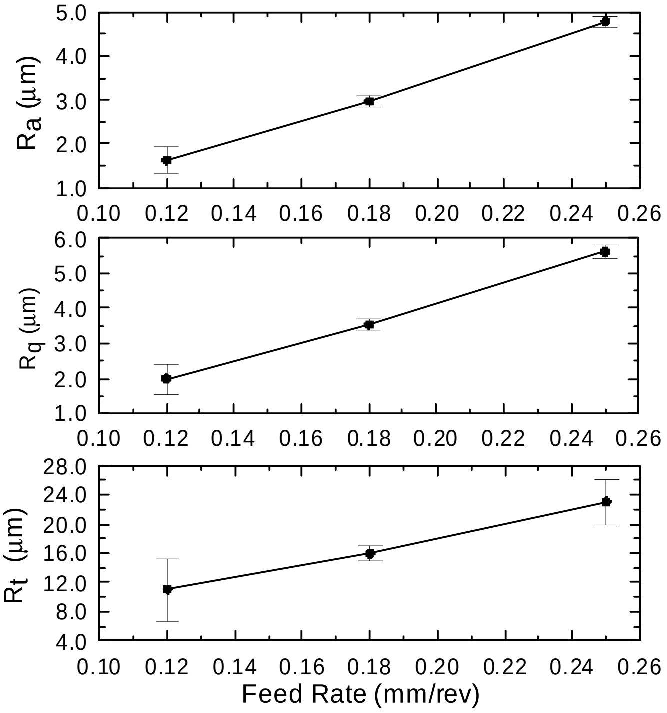

Figure 2. Influence of feed rate on surface roughness parameters (Lopes et al, 2008)

The fatigue limits of the specimens machined were determined using the stair case method. Since all experiments are similar, in this paper it will be showed only the results of one of these tests. Thus, the stair case tests with run out criterion of $2x10^7$ cycles and feed rate equal to 0.12 mm/rev are showed in Fig. 3. The fatigue limit for this test was found to be equal to 356.33 ± 17.21 MPa.

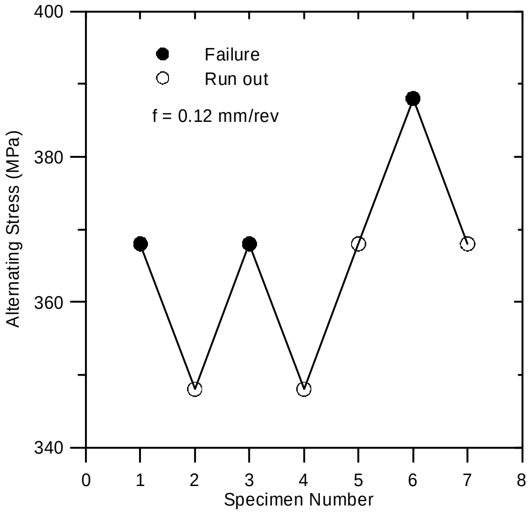

Figure 3. Stair case fatigue test – Run out criterion = $2x10^7$ cycles

The influence of feed rate on fatigue limits with all run out criteria is showed in Fig. 4. The fatigue limit of the AISI 4140 steel is only slightly influenced when the feed rate (f) is increased from 0.12 to 0.18 mm/rev, with run out criterion equal to $2x10^6$ cycles. For tests with higher run out criteria, the fatigue strength values decrease more sharply than before. A sharp decrease in fatigue limit is observed when the feed rate is further increased to 0.25 mm/rev for all run out criteria. It was previously shown that surface roughness increased almost linear with increasing feed rate. It was expected a similar behavior between fatigue limit and feed rate. However, the decrease in fatigue strength is more pronounced that the increase of roughness surface with feed rate. It becomes evident that fatigue limit is determined not only by roughness values. Residual stresses originated by machining are also important.

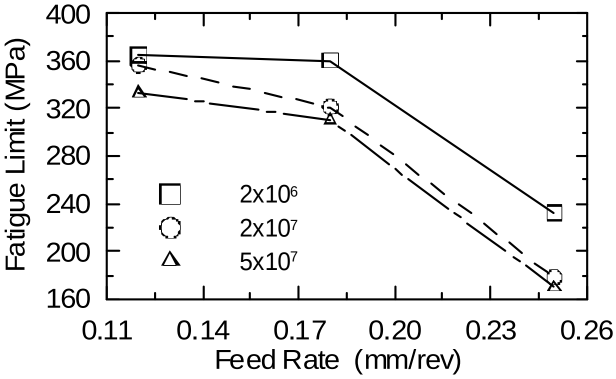

Figure 4. Influence of feed rate on fatigue strength

To analyze the influence of residual stresses on fatigue limit, several specimens machined with feed rate equal to 0.25 mm/rev (with the greatest roughness values) were submitted to a stress relief heat treatment. After that, these specimens were submitted to fatigue tests, with identical test parameters as before. As shown in Fig. 5, the fatigue limit of these heat treated specimens increased when compared to the fatigue limit of non heat treated specimens. It was not observed a tendency in this increase. The heat treatment after mechanical turning excluded the effects of residual stresses and cold work of the machined surface of the specimens. These factors have opposite effects on fatigue limit of the tested specimens: Tension residual stresses decrease and cold work increases fatigue strength. The heat treatment eliminated both, strain hardening and residual stress. As in this study the residual stress values could not be measured, it was not possible to determine a tendency of the influence of heat treatment.

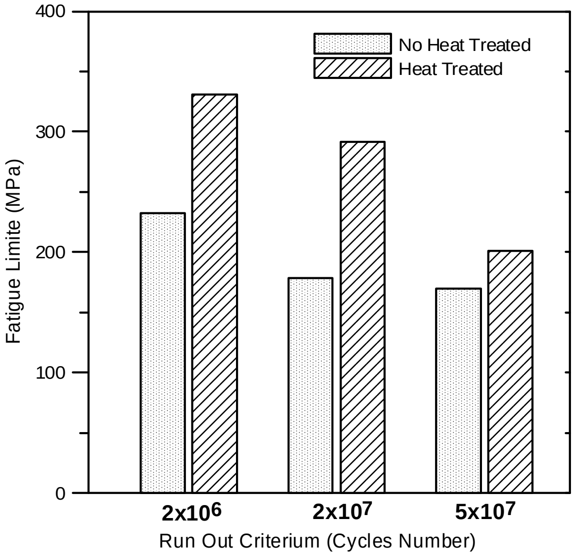

Figure 5. Influence of residual stress relief on fatigue limit – f = 0.25 mm/rev

## 4. CONCLUSIONS

Smooth specimens of AISI4140 steel were fatigued up to $5x10^7$ cycles under rotating-bending test loading. The influence of feed rate during machining on fatigue limits of AISI 4140 steel in very high cycle regime is presented and fatigue strength was investigated. The results are summarized as follows:

- Fatigue limit decreases with increasing both feed rate and run out criteria values.
- Stress relief heat treatment causes an increase of fatigue limit.
- The influence of feed rate on fatigue limit increases with increasing run out criterium values.
- The fatigue limit decreases by 150 MPa in heat treated conditions, and 70 MPa in specimens without residual stress relief.

## 5. ACKNOWLEDGEMENTS

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## 7. RESPONSIBILITY NOTICE

The authors Ernani S. Palma, Karina S. S. Lopes, Daniel J. C. Gomes and Wisley F Sales are the only responsible for the printed material included in this paper.