Cyclic Durability Modeling of Parts During Finish-Turning

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Abstract

In this paper, it is studied the relationship between cyclic durability of parts and their finish-turning modes. An analysis of the influence of various factors on the fatigue resistance of parts was carried out. It is shown that it is advisable to use turning as the final stage for surface machining, which allows to obtain high-quality parts with smooth surface finish, and therefore, with good operational properties. It is provided experimental results of fatigue tests for the specimens made of 40X steel (DSTU 7806:2015). The specimens were machined by turning with a cutting speed range 80 and 180 m/min; a federate range of 0.08 and 0.12 mm/rev and a cutting depth of 0.3 mm. Based on the experimental result, a mathematical model of the cyclic durability of parts made of 40X steel was obtained by the method of multifactorial regression analysis considering turning modes and stress amplitude.

Keywords

Cyclic durability, fatigue strength, turning, surface roughness, cutting mode, mathematical model.

1. Introduction

More than 70% of all failures of structural elements of machines are related to failure from fatigue. Local processes of nucleation and initial growth of a crack do not have a visible effect on the deformation of the part, and the accelerated development of the crack, as a rule, is short-lived. As a result, the destruction of parts often occurs suddenly and becomes the cause of emergency situations.

The main characteristic of fatigue resistance is cyclic durability - the number of stress or strain cycles (or hours of operation) endured by the loaded object to the limit state (destruction).

The fatigue resistance of parts is affected by three main groups of factors [1]: design: geometry, stress concentration, fits, margin of safety, nature and application of loads:

- geometry, stress concentration, fits, margin of safety, nature and application of loads;
- operational: conditions (temperature, humidity, physical and chemical properties of the external environment, etc.), quality and periodicity of lubrication and repair, compliance with the rules of product operation;
- manufacturing: the process of obtaining the necessary metal, the method of manufacturing the workpiece, methods of further processing of parts and assembly of the product.

Dimensions, stress concentration, external environment, frequency of alternating stresses, and surface condition influence on the fatigue resistance of a part [2-4].

The influence of surface roughness on fatigue resistance is explained by the mechanism of fatigue failure, which is based on the formation and development of microcracks during cyclic loading.

The machining (turning, milling, grinding, polishing, etc.) is the main method of manufacturing parts. This process is accompanied by plastic deformation, heating and structural transformations of the

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surface. In this regard, during the manufacturing process of the part, irregularities are formed on its surface, the structure, phase and chemical composition changes, and residual stresses arise.

The production of many important parts usually requires grinding, polishing, or even some specific machining after roughing, semi-finishing, and finishing transitions in turning or milling.

Thus, the production of such parts is quite expensive. One of the possible ways to reduce the cost [5] is to exclude one or more finishing operations. Usually, the use of turning or milling as a final finishing operation is often problematic due to the need to required tooling.

Finishing of parts made of hardened steels (for example, AISI 52100 steel for bearings and 16MnCr5 steel for automotive gears and shafts) by turning with tools made of ultra-hard cutting materials (PCNB, ceramics, etc.) has increased industry application [5]. Turning is considered an alternative to traditional fine grinding due to its high flexibility, the ability to use higher metal removal rates, the ability to work without the use of coolants, and the ability to achieve the same quality of the machined surfaces of the part.

It is possible to obtain slander and residual compressive or tensile stresses of different intensities and depths during turning and grinding [6]. High-speed cutting gives compressive residual stress, and power cutting gives tensile stress, grinding with corundum wheels - tension, and diamond - compression. In addition, during turning, as during mechano-ultrasonic, electro-erosion, and laser processing, it is possible to obtain so-called "white" layers on the surface of the metal, which significantly increase corrosion-mechanical strength, wear resistance, and other operational characteristics. With such types of processing, pulsed heating occurs at significant rates of heat removal and diffusion of carbon, chromium, nickel, and other elements from the inner layers of the metal to its surface, which leads to a change in its mechanical properties and an increase in fatigue resistance.

The results of the use of super hard tool material hexane-R [7, 8] in the turning of HCVS steel (HRC 54...56) in comparison with the grinding of samples with an abrasive wheel showed that the fatigue limit is 30% higher for the samples after turning hexane-R. This is because this tool material has high thermal conductivity, which contributes to the formation of residual compressive stresses.

It was found that micro-uniformities with a depth of up to 5 μm after turning can be compensated due to the formation of residual compressive stresses for stainless steel machining [9, 10]. In this regard, turning becomes more favorable than grinding in relation to the fatigue resistance of parts.

Considering the above, it can be stated that turning allows to obtain parts with high-quality surface, and therefore, with good operational properties.

Therefore, to ensure the necessary cyclic durability of parts, it is required to control technological heredity which corresponds to surface roughness during turning [11, 12].

The purpose of the work is to determine the influence of turning finishing modes and stress amplitude on the cyclic durability of parts.

The processes of gradual accumulation of damage in the material, which arise because of applying cyclic loading to the specimens obtained under different modes of turning finishing processing, are considered.

2. Experimental study

To study the cyclic durability of parts during turning finishing made of structural material, the fatigue tests of specimens were carried out under different turning modes.

Structural alloyed chromium steel 40X DSTU 7806:2015 was chosen for this study. Parts subjected to vibration and dynamic loads are usually made from this material, and requirements for increased strength, viscosity and durability are imposed on them.

To study the influence of technological conditions of turning processing on the fatigue properties, smooth specimens of round cross-section type I were used (Fig. 1).

The specimens were tested for fatigue failure on a machine MUI-6000 on the basis of $N = 2 \cdot 10^7$ cycles with 20°C temperature and rotation frequency of 2000 rev/min.

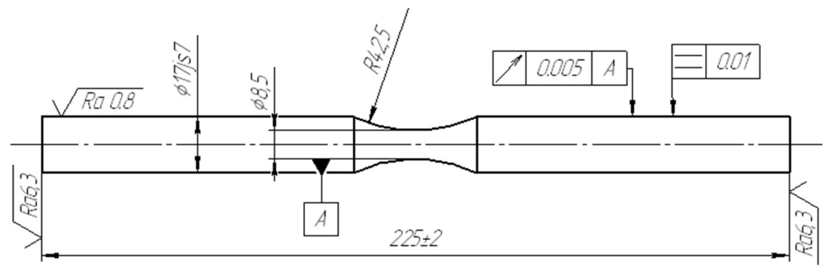

Figure. 1. Sketch of a specimen for fatigue failure tests

Turning of specimens was performed on a HAAS ST20 CNC machining center with a PVVNN 2525M-16Q cutter with a VBGW 160404T00815SE cutting plate without cooling. The cutting modes of turning are given in Table 1.

Table 1
Turning Modes

№	V, m/min	S, mm/rev	t, mm
1	120	0.12	0.3
2	80	0.08	0.3
3	180	0.08	0.3

The machining of the gage region of the specimens was carried out in several stages. First, turning processing of the surface of the specimens was performed with an allowance for the final finishing turning transition.

At the next stage, in order to remove scratches on the surface of the specimens from previous turning, the grinding and polishing operation were used. Finally, the specimens were subjected to heat treatment.

The heat treatment of the specimens was carried out in a shielding gas environment to prevent oxidation of the surfaces under the following regime: heating to a temperature of 450 ºC, exposure for 2 hours and cooling in the oven. The results of experimental studies are given in the Table 2-4.

Table 2
The value of the stress and the number of cycles to failure for specimens machined in the cutting mode: V=120 m/min; S=0.12 mm/rev; t=0.3 mm

σ, GPa	N, cycles
0.672556	3700
0.384167	248700
0.248973	2186800
0.298608	79500
0.499964	27600
0.229996	2787000
0.224723	241050
0.299336	291200

The fatigue curves are shown in Figure 3, Figure 3, and Figure 4 respectively.

The analysis of high-cycle fatigue curves demonstrates the influence of machining modes on the fatigue life. Thus, the lowest fatigue life was observed for the regime of V=80 m/min; S=0.08 mm/rev; t=0.3 mm, and the maximum one for the regime of V=120 m/min; S=0.12 mm/rev; t=0.3 mm. At the same time, the scatter factor is getting higher for decreased stresses.

At a stress of 500 MPa, the number of cycles to failure for specimens machined under the regime V=80 m/min, S=0.08 mm/rev, t=0.3 mm is 11300 cycles (Figure 3); for specimens machined under the regime V=180 m/min, S=0.08 mm/rev, t=0.3 mm is 15000 cycles (Figure 4); for specimens machined under the regime V=120 m/min; S=0.12 mm/rev; t=0.3 mm is 20500 cycles (Figure 2).

Table 3
The value of the stress and the number of cycles to failure for specimens machined in the cutting mode: V=80 m/min; S=0.08 mm/rev; t=0.3 mm

σ, GPa	N, cycles
0.380294	22200
0.300064	159500
0.250121	211700
0.550974	16500
0.499553	28000
0.449203	51800
0.350847	118800
0.396450	17600
0.320081	193800

Table 4
The value of the stress and the number of cycles to failure for specimens machined in the cutting mode: V=180 m/min; S=0.08 mm/rev; t=0.3 mm

σ, GPa	N, cycles
0.381662	508500
0.507624	33200
0.600757	3100
0,338939	147000
0.300028	218600
0.259888	422700
0.239731	385100
0.239376	361900
0.399994	91550

At a stress of 400 MPa, the number of cycles to failure for specimens machined under the regime V=80 m/min, S=0.08 mm/rev, t=0.3 mm is 40600 cycles (Figure 3); for specimens machined under the regime V=180 m/min, S=0.08 mm/rev, t=0.3 mm is 59700 cycles (Figure 4); for specimens machined under the regime V=120 m/min, S=0.12 mm/rev, t=0.3 mm is 95000 cycles (Figure 2).

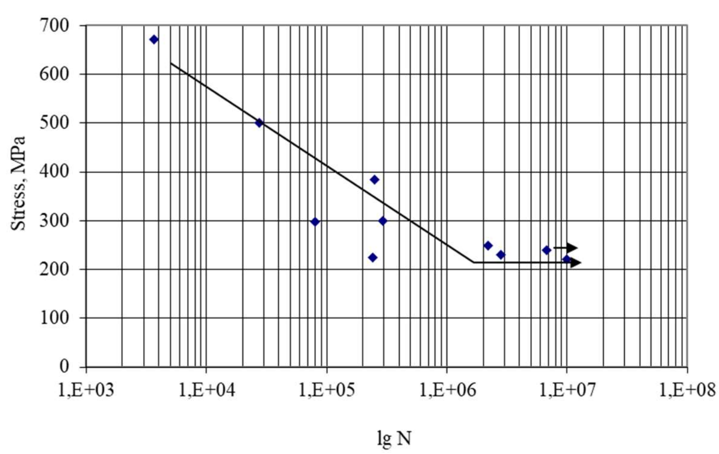

Figure. 2. Fatigue curve for specimens machined by cutting mode V= 120 m/min; S = 0.12mm/rev; t = 0.3mm

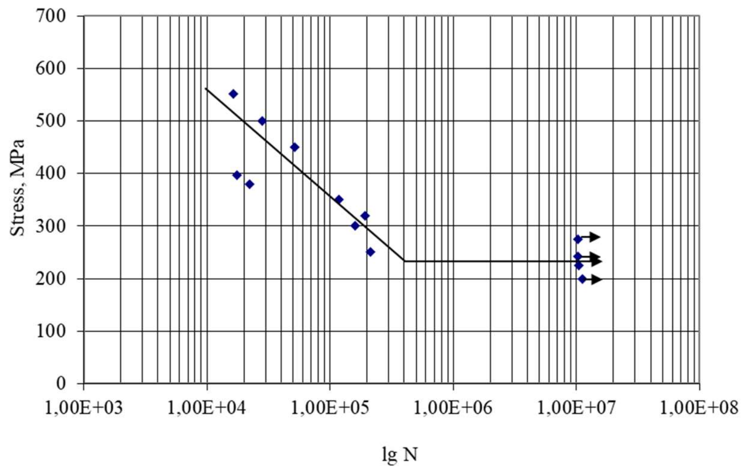

Figure. 3. Fatigue curve for specimens machined by cutting mode V= 80 m/min; S = 0.08 mm/rev; t = 0.3mm

At a stress of 300 MPa, the number of cycles to failure for specimens machined under the regime V=80 m/min, S=0.08 mm/rev, t=0.3 mm is 150000 cycles (Figure 3); for specimens machined under the regime V=180 m/min, S=0.08 mm/rev, t=0.3 mm is 290000 cycles (Figure 4); for specimens machined under the regime V=120 m/min, S=0.12 mm/rev, t=0.3 mm is 430000 cycles (Figure 2).

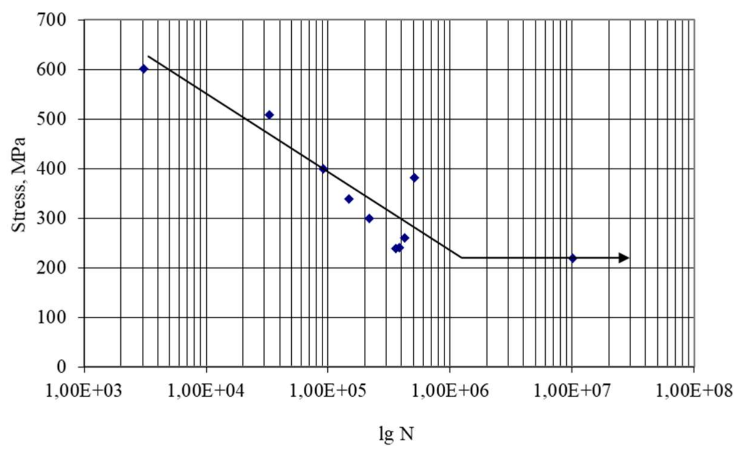

Figure. 4. Fatigue curve for specimens machined by cutting mode V= 180 m/min; S = 0.08 mm/rev; t = 0.3 mm

Thus, the maximum difference in the number of cycles to failure at a stress of 300 MPa for specimens machined under V=80 m/min; S=0.08 mm/rev; t=0.3 mm and specimens machined under V=120 m/min; S=0,12 mm/rev; t=0.3 mm was 2.9 times.

Therefore, it is possible to make a conclusion about the significant influence of turning modes on the cyclic durability of parts which justifies the necessity to find a mathematical relationship between the cyclic durability of parts and turning mode, which helps to predict the value of relevant operational characteristic at the stage of technological preparation of production.

3. Discussion

In order to predict the fatigue life of specimens machined with different cutting modes multiple regression was used. This approach makes it possible to quantitatively assess the relationships between the initial parameters and variables (factors) [13] and to obtain an adequate mathematical model of the studied process.

Based on the results of experimental studies (Tables 2-4) and its correlation by the method of multiple regression data analysis, a mathematical model of the cyclic durability of steel 40X related to the modes of turning processing and stress amplitude was found:

$$N(S, V, \sigma) = e^k, \quad (1)$$

where $k = 14.437 + 0.0048V + 13.006S - 13.19\sigma + 0.002VS - 0.002V\sigma - 5.941S\sigma + +0.0000004V^2 + 2.929S^2 + 3.013\sigma^2$.

Given equation (1) is true according to Fisher's F-test at a confidence probability of 0.95: V=80-180 m/min, S=0.08-0.12 mm/rev, σ=225-670 MPa. The integral influence of turning modes and stress amplitude on the cyclic durability of 40X steel specimens is shown in Figure 5 and Figure 6.

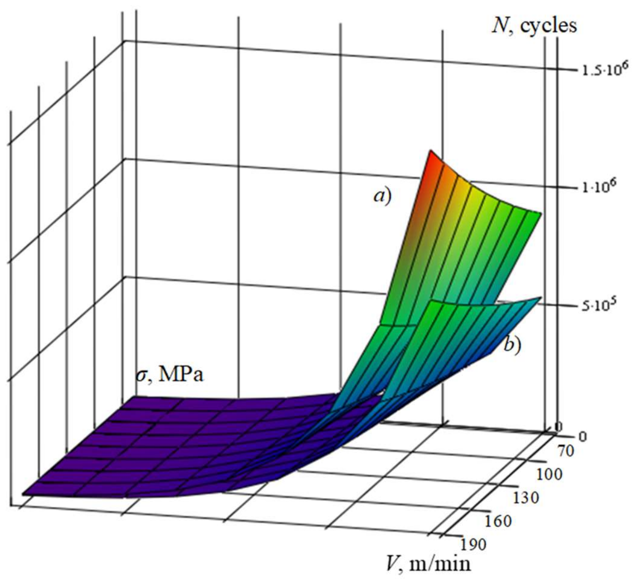

Figure 5. Relationship between cyclic durability, stress amplitude and cutting modes under feed rate – S=0.12 mm/rev (a) and – S=0.08 mm/rev (b)

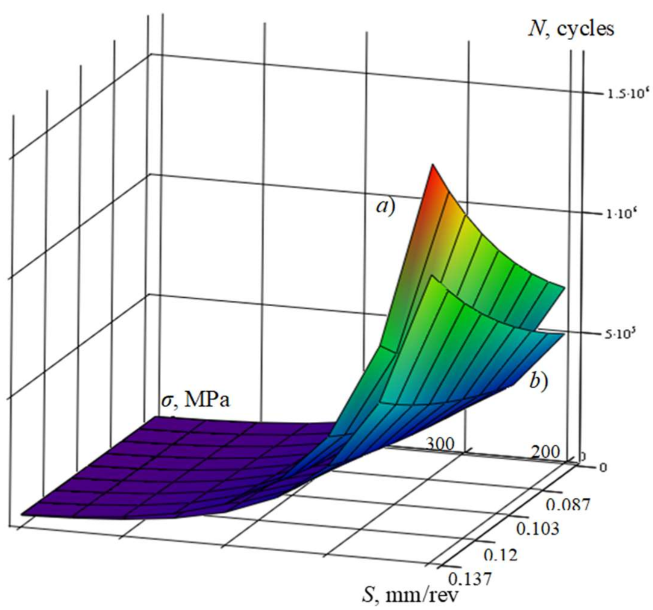

Figure 6. Relationship between cyclic durability, stress amplitude and turning modes under cutting speed – V=150 m/min (a) and – V=80 m/min (b)

Thus, according to the results of the experimental studies, it was found that the cyclic durability during turning of specimens made of 40X steel with a cutting depth of 0.3 mm for the feed range from 0.08 to 0.12 mm/rev, and cutting speeds from 80 to 180 m /min increases as both feed and cutting speed increase. At the same time, the influence of the feed rate is more important.

4. Conclusion

It was found that fine turning increase quality parameters of the surface layer in comparison with grinding. It leads to increased durability of machined parts subjected to cyclic loading. The mathematical model for fatigue life prediction was obtained which allows to determine the number of cycles for failure in correlation with finish-cutting modes. It was also found that the durability of 40X steel specimens increases with increasing both feed rate and cutting speed.

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