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Influence of surface roughness on fatigue life of machine elements – developments in experimental investigations and simulation

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In this paper fundamental information on the influence of surface roughness on fatigue life/limit stresses of machine elements made of different construction materials using different machining/manufacturing processes are presented. The rules for the assessment of surface finish influence represented by the set of microscopic notches on the real machined surfaces, which allow the determination of the stress concentration factor and the correction of a fatigue life limit, are provided. The results of fatigue tests are compared with computed data and predictions using FEM based simulations. The effect of surface discontinuities resulting from surface roughness are related to machine elements made of steels, aluminium alloys, aerospace alloys – titanium and nickel based superalloys and composite reinforced by graphite fibres.

KEYWORDS: machine elements, surface roughness, fatigue life, stress concentration, surface notches

Introduction

The paper is a continuation of the general study on the impact of surface topography on its functional properties, published in *Mechanik* 8-9/2015 [1] and other publications [2-4]. It collected and analyzed the results of research relevant for engineering practice on the impact of surface roughness/topography on strength/fatigue life. In fatigue strength tests, which have a long history dating back to the second half of the nineteenth century, attention is drawn to the large number of factors affecting the durability of elements subjected to variable loads, including: shape and dimensions of the element, state of its real surface, operating temperature and type of working environment [5-7]. In the first case, the notch coefficient is used, and in the second – the surface condition coefficient (β_p), which relates the fatigue strength of a sample with generated roughness to the fatigue strength of a smooth sample after careful polishing [6]. In world literature [7], a surface roughness reduction factor γ is defined with the same meaning as the coefficients in fig. 1a.

Fig. 1 presents the impact of surface roughness assessed by the R_z parameter value on the surface condition coefficient of construction steel samples with different tensile strength, subjected to bending (β_{p1}) and torsion (β_{p2}). It can be concluded that a surface with a roughness R_z below approximately $2 \mu\text{m}$ has no effect on the fatigue strength of the element, while rough machined surfaces ($R_z = 30\div 40 \mu\text{m}$) work in a manner similar to a cut, sharp notch. For this reason, there is a need to accurately assess the surface profile in relation to the micro-notches present on it (grooves of the surface profile) and to include them in the predicting of fatigue/strength durability. Notches occurring on a rough surface increase the concentration of stress and deformation in the place which is the most sensitive to fatigue, i.e. near the surface [5]. The most important parameters of surface roughness are considered to be amplitude (R_a , R_q) as well as height (R_p and R_z) and horizontal ones (R_{sm}) [1-3, 8]. Since the distribution of the amplitude density function (ADF) is usually not Gaussian ($R_{sk} \neq 0$, $R_{ku} \neq 3$), it is recommended [2, 9] to consider the combined effect of the parameters R_t and R_{ku} (kurtosis/profile slope). In this approach, the stress concentration depends not only on the distribution of the profile grooves, but also on the distribution of material at the height of the surface profile.

Figure 2 illustrates the influence of surface roughness on the Wöhler curve (S-N function), and fig. 3 – the effect of the R_a parameter on LCF (low cycle fatigue), i.e. number of cycles to fracture. In this case, the function describing the relationship $N_f = f(R_a)$ has the form $N_f = 2559 \cdot R_a^{-0.1166}$. It can be concluded that the optimal surface roughness of the parts subjected to variable loads is in the range $R_a = 0.2\div 0.6 \mu\text{m}$.

Fig. 1. Impact of surface roughness on the notch action coefficient for bending β_{p1} and torsion β_{p2} (a) [6], 1 - grinding, 2 - finish turning, 3 - rough turning, 4 - sample with a sharp notch; illustrative effect of roughness impact on steel fatigue strength (b) [7]

Fig. 2. Illustrative effect of surface roughness impact on fatigue characteristics of S-N high-strength steels [8]

Fig. 3. Impact of surface roughness on fatigue life of alloy steel ($Y = 420$ MPa) [10]

**Fig. 4. Impact of surface roughness on:
1 – fatigue life, 2 – crack initiation life [11]**

For rough surfaces, the classic fatigue life (N_f) should be separated from the durability, i.e. time to the initiation of fatigue crack, as shown in fig. 4. The lines in this graph were obtained on the basis of bending tests ($\sigma_b = 800$ MPa, maximum load $F_{\max} = 6500$ N) of non-alloy steel S55C JIS with a hardness of $180 \div 230$ HB [11]. Notches were prepared on samples with roughness values of $Ra = 0.03$ and 0.30 and 1.27 μm . The moment of crack initiation was detected by measuring the resistance of a thin silver (Ag) film deposited on the sample by ion-sputtering.

Distribution of measurement points in fig. 4 clearly indicates that the surface roughness has a significant impact on the development of fatigue cracks (the difference in the predicting fatigue life clearly increases for the rougher surfaces) – this aspect should be taken into account in the engineering assessment of fatigue life.

Analytical and numerical methods for assessing the impact of surface notches on fatigue life

The influence of macroscopic geometric discontinuities on the strength of machine parts is usually expressed by means of a stress concentration coefficient (K_t), determined by the relationship given by Pedersen [12]:

$$K_t = 1 + 2 \sqrt{\frac{t}{\rho}} \quad (1)$$

where: t – notch height, ρ – notch rounding radius.

Fig. 5. Explanation of the nature of the stress concentration coefficient for various roughness profiles (a) and stress distribution within single and multiple notches (b) [12]

Formula (1) was derived for a single surface notch in a plate (fig. 5b) subjected to uniform tensile, and the notch height t and the notch bottom rounding radius ρ were assumed as variable factors. The formula (1) was adapted to the surface profile by Neuber [12], assuming that the average notch height on a rough surface t can be replaced by the characteristic surface roughness parameter Rz :

$$K_t = 1 + n \sqrt{\lambda \frac{Rz}{\rho}} \quad (2)$$

where: n – stress state coefficient, Rz – maximum height of the surface roughness profile on the elementary length, λ – coefficient between distance and height of micro-irregularities in the analyzed surface profile (in fig. 5: $\lambda = b/t$), ρ – average radius of the notch bottom.

Usually, the coefficient $\lambda = 1$, which is explained by the difficulties of unambiguous interpretation, while the coefficient n is taken as 1 for shear and 2 for tensile.

An alternative relationship to formula (2) was proposed by Arola [12, 13]:

$$K_{t,2} = 1 + n \frac{Ra \cdot Rt}{\rho_v \cdot Rz} \quad (3a)$$

where: Ra – the average roughness of the surface, Rt – maximum roughness height on the measuring length, Rz – maximum roughness height on the elementary section, ρ_v – mean rounding radius of the profile groove.

To increase the accuracy of the prediction, instead of 2D roughness parameters for the profile, it is recommended [14] to enter analogous 3D parameters for the surface topography:

$$K_{t,3} = 1 + n \frac{Sa \cdot St}{\rho_v \cdot Sz} \quad \text{or} \quad K_{t,3} = 1 + n \frac{Sa(Sp_{\max} + Sv_{\max})}{\rho_v \cdot Sz} \quad (3b)$$

where: $Sp_{\max}$ – height of the highest surface peak, $Sv_{\max}$ – depth of the lowest surface valley.

For the experimentally determined stress concentration factor K_t the equivalent fatigue stress concentration factor K_f is determined [12]:

- in general form:

$$K_f = \frac{\sigma_{D(\text{smooth})}}{\sigma_{D(\text{rough})}} \quad (4a)$$

- in a form related to an equivalent surface notch:

$$K_f = 1 + q(K_t - 1) \quad (4b)$$

where: $\sigma_{D(\text{smooth})}$ – allowable stress for a smooth sample (with no notch), $\sigma_{D(\text{rough})}$ – allowable stress for a rough sample (with notch), q – notch sensitivity factor.

In turn, the coefficient q is defined depending on the equivalent radius of the pit (instead of the radius of a single notch ρ):

$$q = \frac{1}{1 + \gamma / \bar{\rho}} \quad (5)$$

where: γ – material constant depending on the ultimate tensile strength (UTS):

$$\gamma = 0,025 \left(\frac{2070 \text{ MPa}}{R_m} \right)^{1,8} [\text{mm}], \quad UTS \geq 550 \text{ MPa} \quad (6)$$

Value of the stress concentration coefficient can be determined analytically assuming circular or elliptic micro-notches repeating on the surface or using the finite element method (FEM) in relation to the filtered surface profile – as in fig. 6.

A fragment of the valley of the roughness profile obtained from 3D measurements of the surface with the applied finite element mesh is shown in fig. 7a. The smallest mesh size was about $0.1 \mu\text{m}$. The groove profile was obtained by interpolation with a Bézier curve, and the mesh elements were shaped as triangular axisymmetric elements. The points on the groove outline represent the results of the WLI (white light interferometer) measurements carried out on the interferometer. For all grooves on which crack initiation was observed, the strain amplitude ε_a was determined with the correction given by Neuber according to the formula (1) and Hoffmann-Seeger (H-S) according to the formula:

$$K_f = \frac{K_t}{1 + \sqrt{c\chi}} \quad (7)$$

where: c – material constant, χ – stress gradient.

The simulation results, presented in fig. 7b, indicate that roughness can even reduce the fatigue life by up to 10 times [14]. It is confirmed that the Neuber formula (1) better predicts high-cycle fatigue (HCF).

Fig. 6. Principle of numerical calculations of the stress concentration coefficient [13]

Fig. 7. FEM mesh within a notch (a) and comparison of the determined fatigue life (b) [14]

Determining the impact of surface micro-notches on fatigue life

Methodology for determining the effect of surface roughness on fatigue strength/life, based on the empirical method of assessing the impact of micro-notches, was verified for AISI 4130 CR alloy steel [10, 12], ($\alpha+\beta$) titanium alloy Ti-6Al-4V [15], aluminum alloy 7010 – T7451 [18], A357 aluminum alloy produced by the additive method (SLM) [17], nickel-based super alloy alloy 720Li [16] and laminate reinforced with graphite fibers [13].

Figure 8 shows a flat sample made of Ti-6Al-4V titanium alloy after milling ($v_c = 20 \div 110$ m/min, $f_z = 0.02 \div 0.05$ mm/tooth, $a_e = 0.5 \div 2.0$ mm) and a representative roughness profile, recorded on the surface of the neck (SF) (fig. 8a), with a micro-irregularities (notch) radius (fig. 8b).

Fig. 8. View of the sample for fatigue testing (a) and the characteristic surface roughness profile (SF) (b) [15]

Fatigue tests were carried out for the stress ratio $R = 0.1$ and the maximum stress value $\sigma_{\max} = 1000$ MPa, which is slightly higher than the yield strength ($Y = 894 \div 903$ MPa) of the titanium alloy. The measured values of the radius of valleys of micro-irregularities for various milling conditions ($\rho = 1.50 \div 7.10$ μm) were used to calculate the coefficients $K_{t,2}$ and $K_{t,3}$ (i.e. for profile and surface topography respectively) according to formulas (3a) and (3b). Three mathematical models determining the influence of K_t factor and milling parameters on fatigue life N_f were determined:

$$N_{f,2} = 6695,7 \cdot K_{t,2}^{-0,531} \quad (8a)$$

$$N_{f,3} = 11071,7 \cdot K_{t,3}^{-1,056} \quad (8b)$$

$$N_f = 624,02 \cdot v_c^{-0,0469} f_z^{-0,681} \cdot a_e^{0,0152} \quad (8c)$$

It was found that the number of cycles to material failure did not exceed 103 [15].

Figure 9 presents a view of the topography of the turned surface of the nickel-based Alloy 720Li, which is used on the elements of aircraft turbine rotors operating under high fatigue loads below 10^5 cycles [15]. The tests were carried out for samples with surface roughness $Sa = 1.6$ μm and 3.2 μm , subjected to trapezoidal (LCF) and sinusoidal (HCF) loads. Samples were cut from the discs in the radial direction, by EDM.

S-N charts obtained for low cycle life (fig. 9b) show slight differences due to deterioration resulting from surface roughness for large maximum stress values, rather due to the dispersion of results. They are larger when the number of cycles increases to 10^5 (fatigue life is about 10% lower for a sample with a higher surface roughness). A noticeable border between the different effects of surface roughness (runs 2 and 3 in fig. 9b) occurs for a stress of about 750 MPa. In turn, for high cycle life – over 10^6 cycles – the effect of surface roughness clearly disappears.

Based on fractional fracture studies, it was found that multiple fatigue cracks appear within the valleys of micro-irregularities, and therefore the assessed effect of surface roughness is topological ($K_t > 1.0$) [16]. It is suggested to include other spatial parameters, such as S_v , and hybrid parameters – S_{dq} , S_{sc} and S_{dr} . Their definitions are given in Adamczak's book [19].

Figure 10a shows an example of the surface profile obtained for a sample of AISI 4130 CR steel ($R_m = 752$ MPa, $R_e = 655$ MPa) after abrasive water jet machining with abrasive water jet, roughness $Ra = 2$ μm (symbol A in fig. 10a). In addition, the effect of increasing surface roughness to $Ra = 4$ μm (symbol B in fig. 10a) and $Ra = 6$ μm (symbol C) was investigated. The mean measured values of the bottom radius of the pit were

10.8 μm , 9.2 μm and 9.0 μm , respectively. The resulting S-N graph is shown in fig. 10b. It should be noted that the border between LCF and HCF occurs approximately for the stress amplitude $\sigma_a = 315 \text{ MPa}$ ($N_f = 10^4$ cycles). It was found that sample C with the surface with the highest roughness ($Ra = 6 \mu\text{m}$) showed the highest strength in the low cycle range – for $N \leq 10^4$ cycles. In turn, reducing the roughness to $Ra = 2 \mu\text{m}$ results in greater life in the high cycle range (over 10^6 cycles). It is worth noting that the change in surface roughness does not significantly affect the value of the notch sensitivity factor ($q = 0.057 \div 0.067$). Based on fractographic studies, it has been shown that in the low-cycle range, fatigue cracking is caused by geometric discontinuities within the profile valley, and in the high-cycle range, ductile fracture dominates (profile geometric discontinuities are of secondary nature here).

Fig. 9. Topographies of the turned sample surface for fatigue tests (a) and S-N chart for low-cycle fatigue (b) [16] (1: $Sa = 0.8 \mu\text{m}$; 2: $Sa = 1.6 \mu\text{m}$; 3: $Sa = 3,2 \mu\text{m}$)

Fig. 10. Surface profile and determined micro-notch radius ($Ra = 6 \mu\text{m}$) (a) and S-N graph for low-cycle fatigue of AISI 4130 CR (b) [12]

In the case of identical processing of the Gr/Bmi (graphite/bismaleimide resin) laminate reinforced with IM-7 carbon fibers, significantly greater radii of valleys of irregularities were obtained (e.g. $\rho = 18 \mu\text{m}$ for roughness parameter $Ra = 2 \mu\text{m}$ and $\rho = 65 \mu\text{m}$ for roughness parameter $Ra = 10 \mu\text{m}$), which means that the corresponding values of the K_t coefficient for double-sided bending are equal to 0.75 and 0.90 [13]. Thus, the increase in surface roughness reduces the laminate rigidity under variable load conditions.

Figure 11b compares the results of FEM simulation (according to the methodology presented in fig. 6) with experimental data for samples made of aluminum alloy 7010-T7451 (Al-Cu-Mg) after finishing milling (end milling) and roughing (ball-end milling). The surface roughness Ra varied in the range from $0.25 \mu\text{m}$ to $11 \mu\text{m}$, which translates into the corresponding values of the stress concentration coefficient determined from the formula 3a): $K_t = 1.022$ and $K_t = 1.154$ (fig. 11b). Figure 11a shows the result of the simulation of fatigue life as a function of the coefficient K_t for the maximum von Mises stress of 320 MPa . To validate the simulation results, fatigue tests were carried out for a load factor of $R = 0.1$ and a frequency of 10 Hz [18]. Figure 11b shows a clear boundary between the areas belonging to LCF and HCF, corresponding to the number of cycles of about $3 \cdot 10^5$. The corresponding S-N curves show that the effect of surface roughness is more visible for $N_f > 3 \cdot 10^5$ cycles.

Figure 12 shows a comparison of fatigue strength of samples from aluminum alloy A357 produced by the selective laser sintering (SLM) in the initial state ($Ra \approx 7 \mu\text{m}$, $Rz \approx 60 \mu\text{m}$) and after additional machining ($Ra \approx 0.2 \mu\text{m}$) and samples in the form of pressure castings. Figure 12 shows that precision machining increases fatigue life, especially in the case of lower stress values, which is explained by the occurrence of fatigue crack propagation in the sintered materials at higher stresses. A fatigue life comparable to that of cast samples is obtained. However, it is important to emphasize the large dispersion of results resulting from surface and sub-surface defects as well as high residual stresses induced after cutting. An important observation from the fatigue strength tests of the Ti-6Al-4V titanium alloy sintered by the STM method, which was then subjected to finishing turning and milling and polishing, was the lack of correlation with the roughness parameter Sa [20]. In turn, fatigue strength was sensitive to changes in skewness Ssk – surfaces with high skewness $Ssk > 0$ work better under variable loads. AM samples had approximately half the fatigue strength than cast samples.

Fig. 11. Dependence of fatigue life on the factor K_t (a) and comparison of FEM simulation results with experimental data (b) [18]

Fig. 12. Impact of machining on the fatigue strength of A357 aluminum alloy produced by the SLM method [17]

Summary

Review of the literature clearly shows that surface roughness is an important factor influencing the nucleation of fatigue cracks. Therefore, reducing the strength/fatigue life in proportion to the γ factor is an approximate solution, because the surface roughness may differ for the same machining conditions, and the measurement of the surface roughness itself may be affected by a large error. An important question arises whether the same value of γ coefficient is ensured for the notch surface, because the roughness effect is superimposed on the notch effect. In practical terms, the sensitivity of fatigue strength to the surface roughness increases when the material strength increases, e.g. for hardened steels and precipitation hardened aluminum alloys [7, 8]. For this reason, it is recommended to strengthen the impact of the structural notch (index: notch) by the interaction of surface micro-notches (index: sr), i.e. correction according to the relationship:

$$K_t = (K_t)_{\text{notch}} \cdot (K_t)_{\text{sr}} \quad (9)$$

Special surface strengthening (deformation, phase transformation and alloying) processes are not included in the study, although they are often used in practice [21]. Information on strengthening machine parts by surface strain-hardening by burnishing and its impact on fatigue strength is presented in Przybylski's book [22].

Fig. 13. Impact of surface layer modification (WW) on the formation of fatigue cracks (FC) [8]

Figure 13 shows some important directions of the impact of technological changes in the surface layer (SL), taking into account surface roughness, material strain-hardening and the presence of compressive residual stress – i.e. factors that determine the nucleation and propagation of fatigue cracks. It should be noted, however, that their impact is definitely different when taking into account nucleation and propagation of fatigue cracks.

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