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INFLUENCE OF SURFACE TEXTURES PRODUCED BY FINISHING OPERATIONS ON THEIR FUNCTIONAL PROPERTIES

This literature survey highlights the possible influences of surface roughness parameters on functional properties of surfaces produced by different finishing operations. The prediction of such functional properties as fatigue, sealing capacity, adhesion, friction, wear and corrosion resistance based on five groups of spatial (S) roughness parameters is overviewed. In contrast, traditional approach based on 2D roughness parameters is provided. Some real 3D surface topographies produced with desired functional properties by finishing cutting and abrasive operations are characterized. This survey confirms the vital role of machined surfaces in the functionality of machine components.

1. INTRODUCTION

The prediction of the functional properties of machined parts belongs to the fundamental challenges of manufacturing engineering. In general, three groups of functional properties (mechanical, tribological and corrosion) are distinguished as shown in Fig. 1. In practice, functional properties are related to 2D and 3D surface roughness, waviness and surface texture. It should be noted that engineering knowledge required to the prediction of functional properties is fragmentary apart from the advanced surface metrology techniques [1],[2]. Typically, the design of machine components is based on the dimensional and shape tolerances and partly on the surface roughness parameters.

According to Whitehouse [3] it is not possible now to predict functional performance accurately based on measured surface parameters but to identify various functional regimes based on functional maps. At present design and manufacturing engineers are equipped with many engineering tools such as surface characterization and visualization using 2D/3D surface roughness parameters specified in ISO 25178 and ISO 16610 standards, VR software and FEM simulations. In this paper, some important functional properties including fatigue strength and life, sealing capacity, sliding friction, abrasive wear resistance, adhesion and bonding and corrosion resistance are characterized in terms of 2D and 3D surface roughness parameters including both 12 S-parameters specified in ISO 25178-2 (2012) standard [4],[5]and three functional indexes Sbi, Ski and Svi specified in EUR 15178 EN [4].

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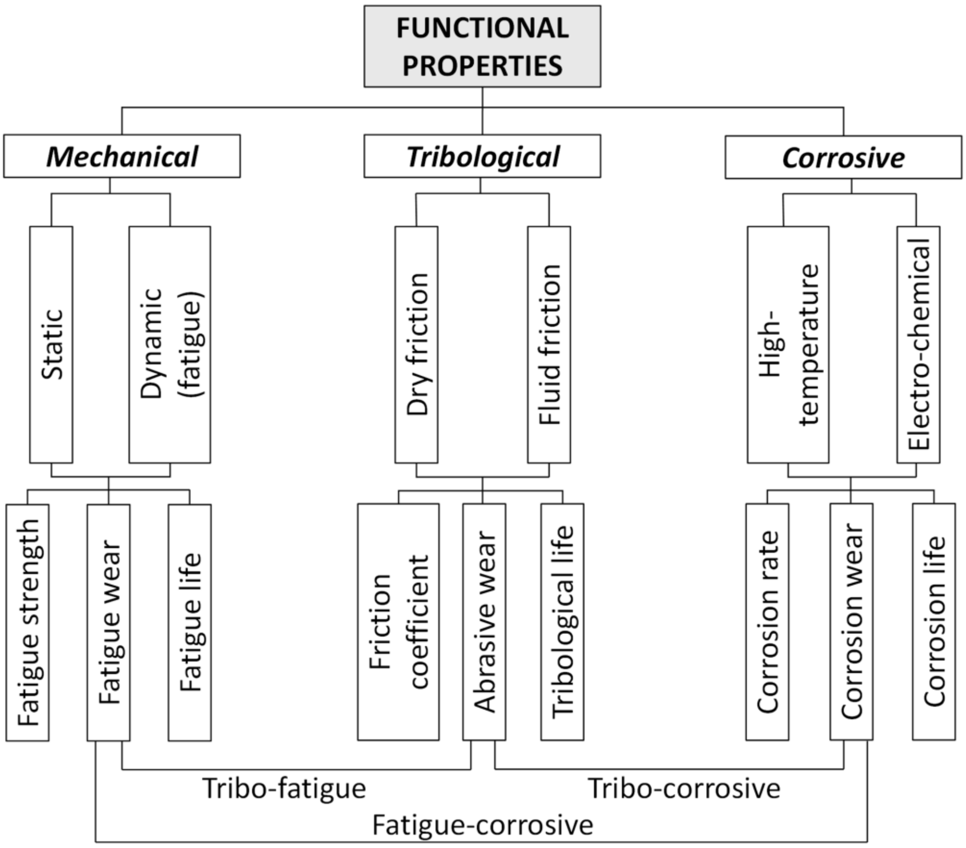

Fig. 1. Three groups of functional properties after [6]

Table 1. Influence of S-parameters on functional performance (author's proposal based on Refs. [3],[4],[5],[6],[7],[8]

Functional performance	Group of area field parameters				
	Height	Amplitude	Spatial	Hybrid	Functional
Bearing capacity	●●●	●●●	●●	●●	●●●
Sealing capacity	●●●	●●●	●●	●●●	●●●
Friction intensity	●●●	●●●	●●●	●●●	●●●
Joint stiffness	●●●	●●●	●●	●●	●●●
Wear resistance	●●●	●●●	●●	●●●	●●●
Bonding/adhesion	●●●	●●●	●	●●	●●●
Fatigue life	●●●	●●	○	●	●●●
Corrosion resistance	●●●	●	○	●●●	●●●
S-parameters	Sa, Sq, Sz	Ssk, Sku	Sds, Str, Sal,Std	Sdq, Ssc, Sdr	Sbi, Sci, Svi

Influence evidence: (●●●)-much, (●●)-some, (●)-little/circumstantial, (○)-no

The importance of 3D parameters which characterize surface topography over 2D surface finish parameters is that the surface functionality depends strongly on machined lays which, in turn, influence the directionality of the surface texture. The survey provides the possible relationships between various functional performance categories and five finish and topography classes.

2. FATIGUE STRENGTH AND LIFE

The influence of surface roughness (surface integrity of a greater significance), is one of the greatest and oldest concern for design components subjected to cyclical loads [6],[7]. In general, low surface roughness causes better fatigue performance but for values of the Ra parameter between 2.5–5 μm residual stresses along with strain-hardening effect and material microstructure became a better indicator in relation of fatigue life. However, in the absence of residual stresses, the surface roughness Ra>0.1 μm characteristic for polished or micro-finished surfaces strongly influences fatigue performance [7]. When the working temperature exceeds 400°C the influence of both residual stresses and surface roughness is distinctly reduced.

The testing of fatigue performance in terms of the surface topography demands employing stress-free specimens because the predicted fatigue strength scatters can differ about 20% for surfaces with a comparable Ra value. The influence of the Ra and Rt roughness parameters on the fatigue strength of AISI 4140 (40Cr6) steel specimens was investigated in Ref. [7]. It can be reasoned that the ground surface exhibits lower fatigue strength than finish milled surface (690 MPa versus 775 MPA) due to unsuitable surface lays resulting in deeper micro-grooves. The effect of polishing in relation to finish grinding due to the smoothing effect (Rt=3-5 μm versus Rt=7-14 μm) is more visible.

It is reported [7] that the influence of the total roughness height Rt should be considered along with kurtosis Rku (Sku in Table 1) because not only micro-grooves but also material distribution at the profile height is decisive for the stress concentration limiting the fatigue. Because machined surfaces are, in general, non-Gaussian (Rsk#0 and Rku#3), both the Ra(Rt) parameter and kurtosis should be taken into account in controlling fatigue performance [5],[7].

According to Table 1 also 3D surface spatial parameters such as the texture direction Std, the autocorrelation length Sal, the functional parameters such as the core fluid retention index Sci and the valley fluid retention index Svi, and hybrid parameters such as the arithmetic mean summit curvature Ssc should be included in correlating surface characteristics with fatigue performance of dynamically loaded parts. Initial topography of contacting bodies also influences the intensity of surface degradation caused by abrasive-fatigue wear (fretting), which occurs at micro-contacts of roller bearing rings and balls [6].

3. SEALING CAPACITY

This functional property concerns often the counter face for rotary shaft lip seals produced by plunge grinding and hard turning operations (axial, plunge and tangential ones) [14]. The required roughness parameters are the maximum roughness height (SL) Rz between 1 and 5 μm or equivalently the roughness average Ra between 0.2 and 0.8 μm and the maximum roughness height (EL) Rt<0.63 μm. Because these parameters are not sufficient to characterize the shaft surfaces for sealing applications, some additional bearing parameters such as the upper material ratio Mr1 between 50 and 70% at the cut of 0.25 Rz and two ratios Spk/St (0.40 after turning and 0.55 after plunge grinding) and Sk/St (0.40 after turning and 0.48 after plunge grinding) are proposed [14],[15],[16]. Moreover, the skew parameter Rsk (Ssk) has been shown to be a useful measure for seals and peak curvature Ssc to define elastic contact which characterizes lip seal performance [6].

4. SLIDING FRICTION

Tribological properties of tribo-pairs are assessed quantitatively using the friction coefficient, wear margin and tribological life (tribological margin in the whole) [6]. Friction is a very important engineering problem because about 30% of world energy consumption is used to overcome excessive friction for instance in such tribo-pairs as bearings, gears, cylinder-piston rings, etc.

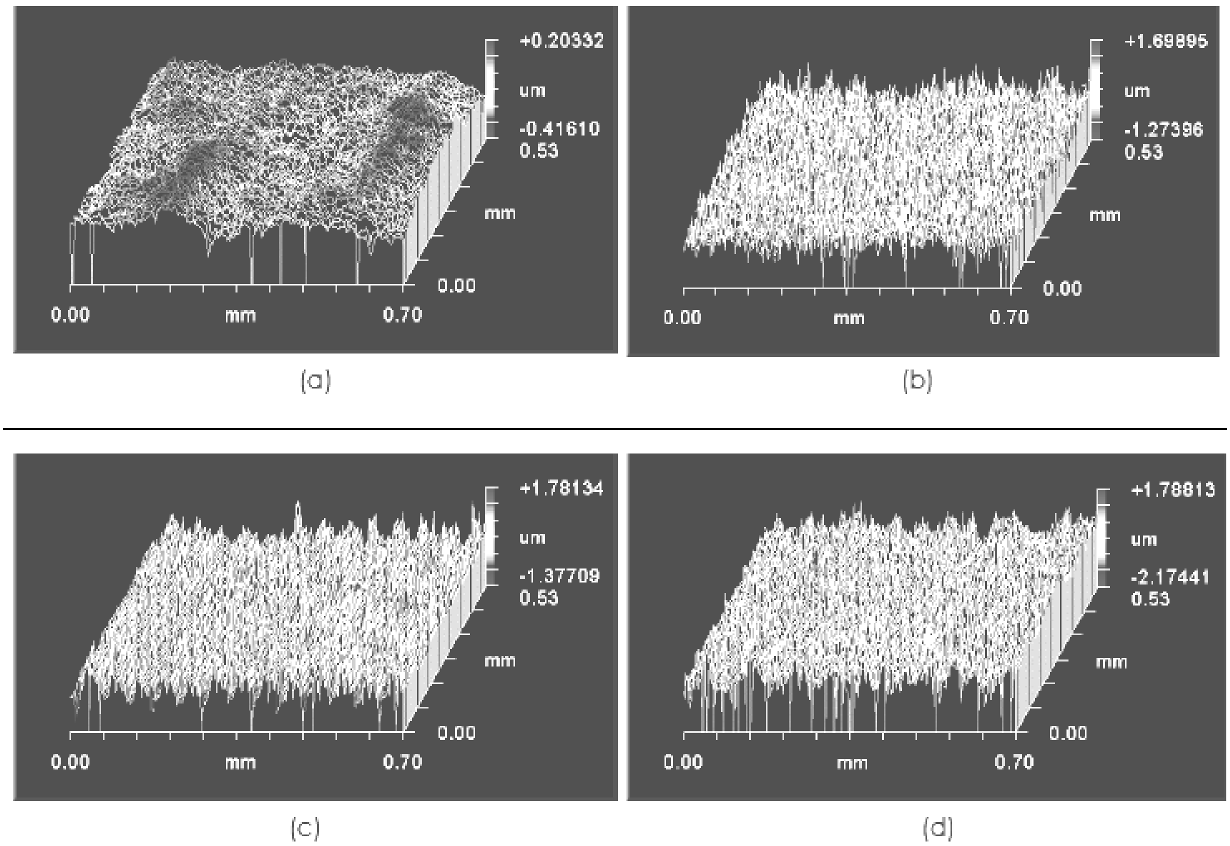

Fig. 2. Surface topographies produced by isotropic finishing (a), honing (b), hard turning (c) and grinding (d) after [9]

Four topographies of machined surfaces produced by grinding, honing, hard turning and isotropic finishing made of an AISI 52100 bearing steel (Fig. 2) were characterized and compared in terms of representative 3D roughness parameters presented in Fig. 3a. Friction tests were performed using a ball-on-flat tribometer and the values of the friction coefficient are presented in Fig. 3b.

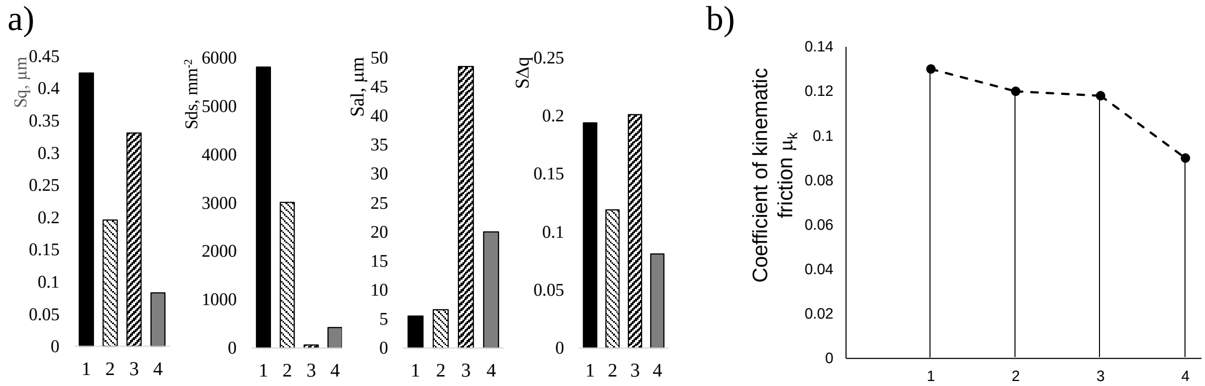

Fig. 3. Values of 3D roughness parameters (a) and corresponding values of friction coefficient (b) for various surfaces produced on hardened AISI 52100 bearing steel (data selected after [9]); 1-hard turning, 2-grinding, 3-honing, 4-mass (isotropic) finishing

It should be noted in Fig. 3a that the ground surface contains the highest density of summits (Sds ≈ 5800 mm^{-2}) but the isotropic finished surface is depicted by the lowest mean slope of SΔq ≈ 0.08.

As shown in Fig. 3b the maximum and minimum values of kinetic friction coefficients (0.14 versus 0.1) were determined for ground and isotropic finished surfaces respectively. Surfaces produced by honing and hard turning have comparable tribological properties (μ≈0.12).

For the isotropic finished surface the Sq parameter is about 75% lower and the number of summits is about 85% less than for the ground surface. For these reasons, the coefficient of friction for the ground surface is about 27% higher than for a very smooth surface produced by mass finishing. The values of the autocorrelation length Sal (Fig. 3a) suggest that surface textures produced by hard turning and isotropic finishing contain components with longer wavelengths (Sal =48.5 and 20 respectively).

It was documented that the minimum friction achieved by isotropic finishing corresponds well with relevant values of torque and working temperature of a roller bearing, These values are lower about 20% and 40% respectively in comparison to ground surfaces.

In case of an anisotropic ground surface the influence of lays is also important and, as a result, the friction coefficient increases by 44.5% when the friction tests is running parallel to lays (typically across the lays).

Isotropic finished surfaces with a very low mean surface slope SΔq =0.081 (see Fig. 2a) express the lower tendency of surface irregularities to plastic deformation and increased contact stiffness.

It was documented in Ref. [10] that a positive skewness causes that the friction coefficient decreases but for a negative skewness (Rsk<0) friction becomes more intensive than for the Gaussian distribution (Rsk=0, Rsk=3). The reverse influence of kurtosis was observed for non-Gaussian distribution, when Rku>3.

5. ABRASIVE WEAR RESISTANCE

Abrasive (tribological) wear of contacted surfaces depends distinctly on their structures under dry or mixed friction conditions [6]. The reduction of wear intensity of various tribo-pairs is very important at the design and technological stages.

Fig. 4 presents the development of manufacturing of cylinder liners including traditional one-pass honing (a) producing net of crossing grooves inclined at 45°, plateau honing (b) producing oil pockets in the form of deeper grooves, helical honing (c) producing elongated grooves at 140° which ensure about 40% reduction of the wear in the reversal zone in comparison to plateau structure, laser texturing (d) which further reduces wear and friction losses and minimize the risk of seizure, and laser honing (e) producing deterministic structure of oil pockets which ensure 2-3 times smaller oil consumption and longer durability of the piston-piston rings system.

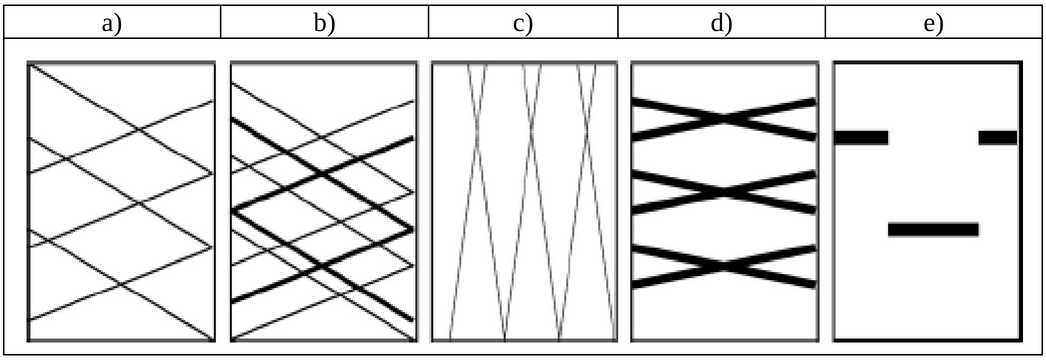

Fig. 4. Possible modifications of surface topographies of cylinder liners in order to reduce engine oil consumption and running-in wear after [1]: a) one-pass honing, b) plateau honing, c) helical honing, d) laser honing (texturing), e) regular structure of oil pockets

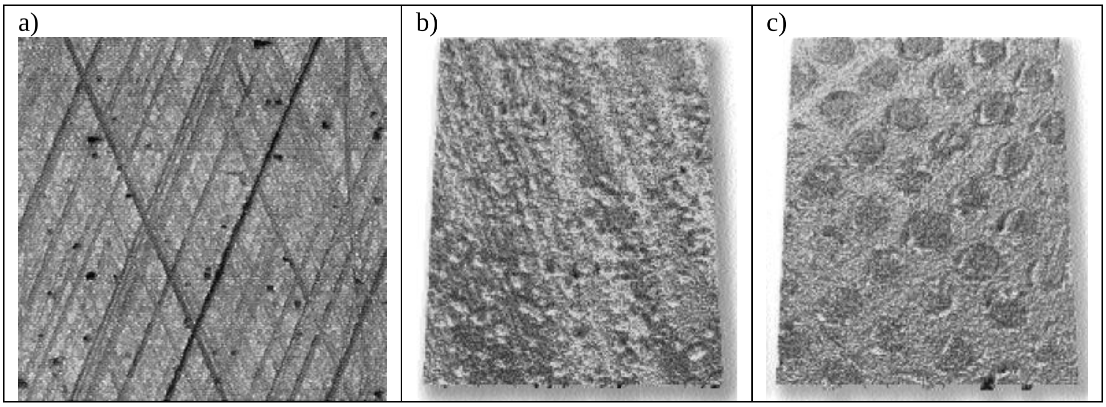

Fig. 5. Surfaces of clutch plates with various topographies after [11,[12],[13]: a) crossing lays, b) micro-finished, c) textured with regular pits

It should be added that the plateau surface of a cylinder liner is typically characterized according to ISO 13565-2 standard by five functional parameters –Rpk, Rk, Rvk, Mr1, Mr2 but ISO 13565-3 standard recommends also an Rq family (Rpq, Rpq, Rmq) [1].

Laser texturing as an effective way for reduction of abrasive wear is currently extended to such functional elements as piston rings, bearing raceways, brake and clutch plates (Fig. 5c). It should be noted that the main challenge for such tribological systems as brake and clutch plates is to intensify friction and increase the friction coefficient [6].

It is reported [11] that friction coefficients as high as 1.6 were measured for the sliding interaction of specially designed textures. In addition, the reduction of the parasitic friction in operating machinery due to optimized surface texturing can be as much as 5% [12]. In case of surface topographies their tribological properties were assessed based on their dependences on skewness Ssk and kurtosis Sku. In summary, the appropriate data in Table 1 depicts that wear depends on all groups of surface parameters including lays and leads [8].

6. ADHESION AND BONDING

In case of adhesion and bonding the developed surface area ratio Sdr expressed in % is the most important than the Sa or Sz parameters (for an ideal flat surface Sdr=0). In practice two surfaces with practically the same value of Sa parameters can have about 200% higher value of Sdr parameter [13].

It is evident that the machined surface with a larger developed area ensures more strong joint with another surface and the deposited coating will be more stable. On the other hand, the area of developed surface depends on the height and amplitude surface parameters including Sq, Ssk, Sku and Ssc parameters (see Table 1).

7. CORROSION RESISTANCE

In general, higher surface roughness weakens corrosion resistance due to the fact that the real contact area increases [6]. As a result, the corrosion wear is decisively influenced by height roughness parameters (predominantly Sz parameter) and hybrid parameters including the arithmetic mean summit curvature Ssc (Table 1).

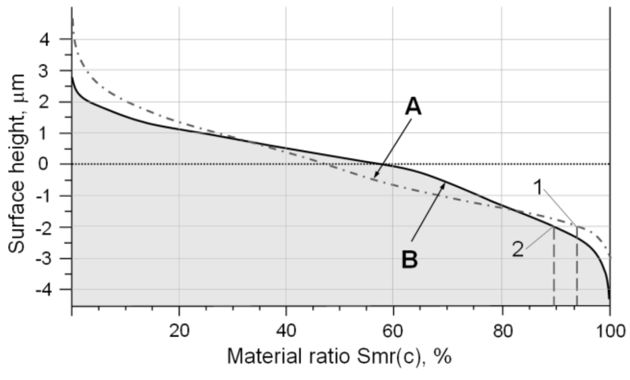

Fig. 6. Comparison of surface bearing curves for surfaces with lower (A) and higher (B) tendency to corrosion. Coordinate points: 1- (93.9%, -2 µm); 2- (89.3%, -2 µm)

It was observed that the surface textures which are more exposed to corrosion have distinctly deeper valleys and, in contrast, surfaces more resistant to corrosion are more anisotropic [6]. Corrosion resistance can also be related to the shape of bearing area curve (BAC) and especially to the valley fluid retention index Svi (Table 1). In Fig. 6 values of the material ratio Smr(c) for bearing area curves A and B were determined at the cut c= 2 μm below the nominal surface (0). As shown in Fig. 6 surfaces with a progressive - degressive surface bearing curve (SBAC no. B) and deeper valleys are less resistant to corrosion than those with nearly linear bearing characteristic (SBAC no. A). In particular, surface represented by SBAC (B) have a greater percentage of valleys deeper than 2 μm.

8. CONCLUSIONS

The possible correlations between surface roughness/surface texture and fundamental functional properties- fatigue, sealing capacity, adhesion, friction, wear and corrosion resistance are overviewed.

It was documented that 12 surface roughness parameters and three functional indexes play a vital role in designing and producing functional surfaces.

In particular, the obviously used approach based on only one or a group of height roughness parameters- Ra or Ra, Rq, Rz, Rt is highly insufficient. For instance, prediction of fatigue life required measurements of both amplitude and hybrid parameters (Ssk, Sku, Sdq).

Friction intensity and abrasive wear resistance depend on all five groups of S-roughness parameters and, as a result, their prediction is very complex.

Three functional indexes (Sbi, Sci, Svi) influence, similarly as S-height parameters, all selected functional properties.

R&D centers should be deeply engaged in the problems concerning the functional performance of machined parts with demanded functional properties.

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