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Fatigue strength of chromium coated elements and possibility of its improvement with slide diamond burnishing

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ABSTRACT

Surface layer condition and fatigue strength of chromium coated elements were tested. Special shape samples cut out of chromium coated shafts were symmetrically deflected on electrodynamic vibrator at sample frequency oscillations in the 1000 Hz order. They were 42CrMo4 and 41Cr4 steel samples with a 25 and 50 µm chromium coat finished by slide diamond burnishing and polishing. Surface topology parametres, surface microhardness and residual stresses in the surface layer were checked and fatigue strength was tested. Before the coating was applied, the roller surfaces of the samples were ground and band polished. It was found that chromium electroplating causes detrimental, tensile stresses in the surface layer and worsens the fatigue strength limit. Slide burnishing of chromium coatings produces advantageous, compressive stress in the surface layer and the oscillatory bending fatigue strength of elements with burnished coatings can be improved up to 40%, which completely reduces the detrimental chromium plating effects. It can also be stated that slide burnishing of coatings does not create bigger technical problems and gives better results than band polishing.

1. Introduction

Numerous components of industrial machines and facilities are exposed to abrasion and corrosion. In some cases, to ensure adequate life-time and better reliability at low production costs, these components are made of steel and chromium coated. Some of them are movable (e.g. pump and feeder parts) and work under varying load conditions, their durability depending on their fatigue strength. Unfortunately, the chromium coating causes substantial worsening of fatigue properties [1–3].

It is generally known that applying burnishing at the final stage of the machine part treatment makes it possible to improve considerably their fatigue strength. During the burnishing, the surface layer of the treated element is subjected to cold plastic deformation: this confers adequate properties (surface roughness is reduced, compressive stresses are created in the surface layer and it becomes harder). Such condition of the surface layer improves many usable properties, particularly fatigue strength [4–6]. This method is relatively inexpensive compared to other post-treatments such as peening, easy to implement and does not require any complicated devices. Many industrial applications of burnishing consist in so called anti-fatigue burnishing used for improving fatigue strength. Unfortunately, hard and thin chromium coatings put on a relatively soft base make conventional burnishing impossible as the (great) force while burnishing results in coat damage. Conventional methods can therefore be used only for coats of great thickness [2,3] which are rather rare in practice.

Machine parts are most often covered with chromium coats whose thicknesses ranges from a few up to several dozen micrometres. The only method which can be used for burnishing regular shape elements (shafts, surfaces and the like) and coated with chromium of such small thickness is slide burnishing. During this treatment, the ball tip of the

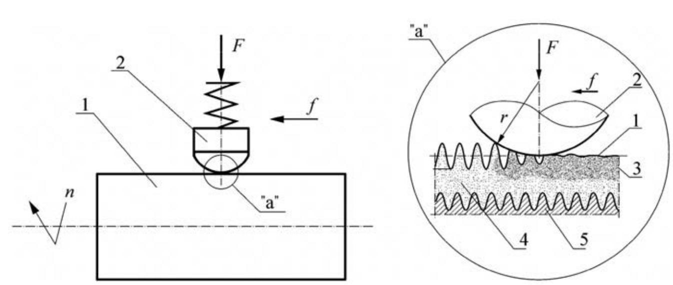

Fig. 1. Scheme of slide diamond burnishing: 1–workpiece, 2–burnishing tool, 3–zone of plastic deformation, 4–chromium coating, 5–steel base, *F*–burnishing force, *f*–feed, *n*–workpiece rotation, *r*–radius of tool tip.

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Table 1
Tested materials and slide burnishing parametres of coatings

Variant	Materials (EN 10083-1) and coatings	Burnishing parametres values		
		Loading force F [N]	Tool tip radius r [mm]	Feed f [mm p r]
I	42CrMo4 (32 HRC)+Cr 25 µm	50	4	0.05
II	41Cr4 (230 HB)+Cr 50 µm	110	3	0.083

Table 2
Results of roughness, stress level and microhardness measurements

Variant	Series	Tested materials (EN 10083-1) and coatings (P–polished, SDB–slide diamond burnished)	Parametres values			
			Ra [µm]	Range of Ra [µm] values	Maximum stress σ_{max} [MPa]	Surface VHN_{1N} [MPa]
I	A	42CrMo4 (32 HRC)+P	0.14	0.08–0.18	770	–
	B	42CrMo4 (32 HRC)+ Cr 25 µm	0.32	0.25–0.42	–	375
	C	42CrMo4 (32 HRC)+ Cr 25 µm+SDB	0.09	0.04–0.16	−1100	375
	D	42CrMo4 (32 HRC)+ Cr 25 µm+P	0.14	0.08–0.20	1200	380
II	E	41Cr4 (230 HB)+P	0.24	0.18–0.28	418	–
	F	41Cr4 (230 HB)+ Cr 50 µm	0.55	0.50–0.63	600	350
	G	41Cr4 (230 HB)+ Cr 50 µm+SDB	0.14	0.12–0.16	−1130	410
	H	41Cr4 (230 HB)+ Cr 50 µm+P	0.21	0.20–0.24	360	400

burnishing tool presses down and slides over the treated surface (Fig. 1). To make the treatment possible without excessive heat release, such tool has to be made of a material of low slide friction coefficient on metals. Diamond is such a material. It shows very high hardness, too, which makes it possible to treat even the hardest metals and their alloys. For economical and technical reasons, diamond tools for slide burnishing (burnishers) are made of small dimensions. This is their disadvantage because high burnishing feeds are not possible. At the same time, it is possible to perform treatments at low loading forces. Small dimensions of the tool result in a relatively small contact of the surface with the treated element—when the burnishing tool radius is of the order of a few millimetres and the contact surface equals a few hundredths of a square millimetre. Only a small loading force is needed in this condition to generate plastic deformation on such small zones. During slide burnishing, the force of a few but not more than 20 daN is usually applied [7,8].

The features mentioned above explain why slide burnishing is suitable for burnishing chromium coatings as the only method of static burnishing.

2. Aim and methodology of the tests

The aim of the carried-out tests was to define the possibilities of improving the fatigue strength by burnishing chromium coatings.

The burnishing of hard coatings on soft bases is a challenging technical problem. The loading force applied to the tool (burnishing force) need not be very high—both cracking and exfoliation of the coating from the base have to be avoided. However, the force cannot be too small to keep on the treatment.

The force as well as other operating parametres of burnishing were selected experimentally during the tests so as to obtain the best (the lowest) roughness of the burnished chromium coating and the depth of zone plastic deformation not deeper than the chrome coating thickness. The burnishing parametres and the other experimental data are given in Table 1. For comparison purposes also polished samples (band polished) without any coatings and samples in which chromium coatings were also band polished and tested.

Basic research involved measuring surface topology parametres, measuring surface hardening and stresses in the surface layer as well as testing oscillatory bending fatigue strength. The tested samples were rollers of 36 mm in diametre and 110 mm in length. They were 42CrMo4 steel rollers, quenched and tempered up to 32 HRC, with a 25 µm coat of technical chromium and 41Cr4 steel rollers of 230 HB hardness with a 50 µm chromium coat. Before the coat was put on, the roller surfaces of the samples were ground and band polished with the silicon carbide abrasive of 360 mesh size (grain size 39–42 µm). *Ra* values after polishing are given in Table 2. Chromium plating was carried out in a universal bath having a temperature of 50–55 °C, a 40–45 A/dm^2 cathode current density and a 15% current output. The workpieces were not dehydrogenated after treatment. The burnishing of the samples was carried out using a universal lathe with PCD tools [9] and a special fixture which made the elastic pressure of the tool down to the treated surface possible. The polishing of chromium coats was carried out under the same conditions as those mentioned above.

In the tests, the characteristics of the surface layer of the samples were compared using the standard techniques: surface roughness measurement *Ra* with Surtronic 3 profile measurement gauge at a 0.25 mm cut-off value. To compare other surface topology parametres that may effect fatigue strength extra tests were carried out making use of a TalyScan 150 measuring device fitted with the Taly Map 3D surface analysing software. The tracer method together with the use of an inductive sensor was applied. The measurements were made on a 2×2 mm sampling area; the spacing was 10 µm. Topology of the examined surfaces was characterized with norm EN standard parametres [10]. Also microhardness measurements were taken with a Brivisor KL2 microhardness tester fitted with the HME measuring electronics by means of the static indenter drive-in Vickers' method, the load was 1 N (so as not to pierce the chromium coat) and the intender's action time was 15 s [11]. The microhardness of the surface layer was measured on the chromium surface. Also, stress pattern measurement in surface layer was carried out using the

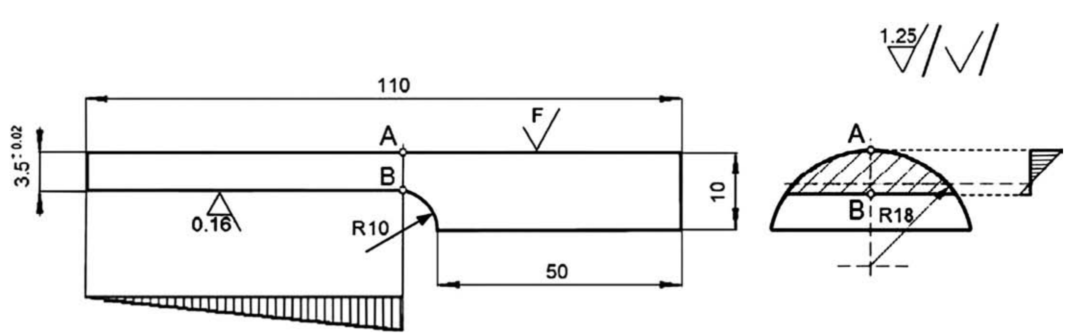

Fig. 2. Fatigue test sample geometry and theoretical stress distribution: F–surface roughness *Ra* after final technological operation.

Weisman–Phillips method where consecutive material layers were removed by electrochemical etching. All the tests were repeated three times.

Oscillatory bending fatigue strength was investigated. The fatigue strengths were determined by the stair-case method [12–14] at the base number of 2×10^6 load cycles. To speed up the tests they were carried out with an electrodynamic vibrator at a sample frequency oscillation of 1000 Hz order (resonance frequency), running the test to the first fatigue crack and its propagation to about 0.15 mm depth (first crack appears as a drop in free vibration frequency whereas the test stand control system must automatically maintain the resonance). The methodology of the tests is described in [14,15]. Every fatigue test was run with a minimum of 16 samples. All the tests were carried out three times.

To estimate the efficiency of burnishing treatments the fatigue tests were carried out using samples [8,9] illustrated in Fig. 2. These are samples cut out of shafts whose surfaces were easy to treat by various comparison methods of finishing treatment used in these

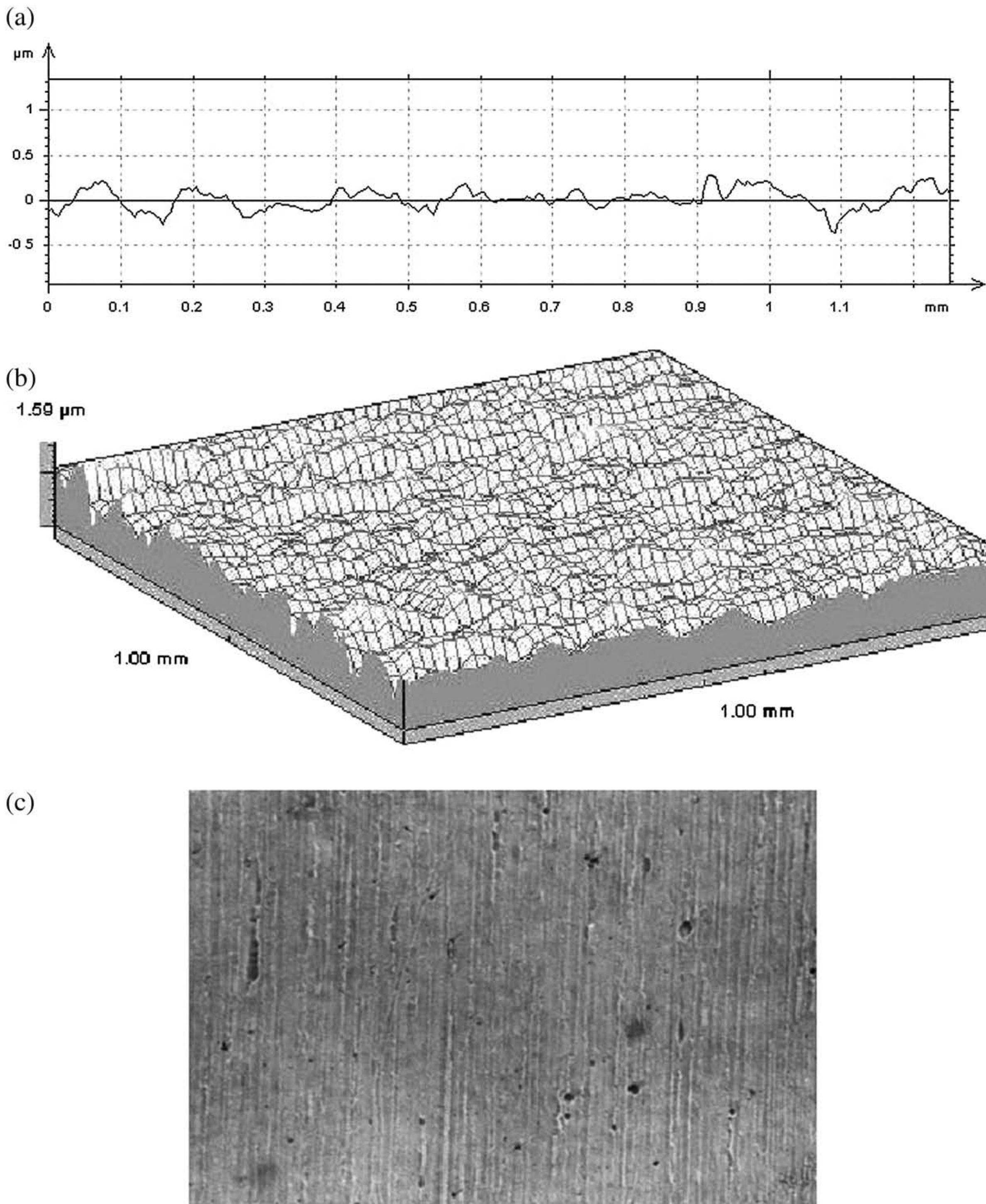

Fig. 3. Polished coating: a) profilogram, b) 3D scan, c) view (mag. ~110×).

tests. The samples have the profile of a cantilever beam whose thicker end was clamped in a fixture and the thinner end was symmetrically deflected. The loading of the sample was controlled by constantly measuring the deflection amplitude of the free sample end.

For a given sample, dimensions of the amplitude value are selected in such a way as to obtain the proper (assumed) stress value and it can be calculated because we know the value of the stress of the material's geometric relation to the cantilever beam. The selected sample profile permits accurate localization of a fatigue crack. It can be concluded from the relation between the stresses of the materials, that the crack always occurs in the cylindrical surface, in the vicinity of point A (Fig. 2), where the stresses are more than 30% greater than at point B [14,16]. That makes it possible to reliably assess the efficiency of various methods of treatment of that surface.

3. Results

The results of the measurement of the parametres of the surface layer are presented in Table 2. They make it possible to find out that in the case of coats thinner than 50 µm slide burnishing did not

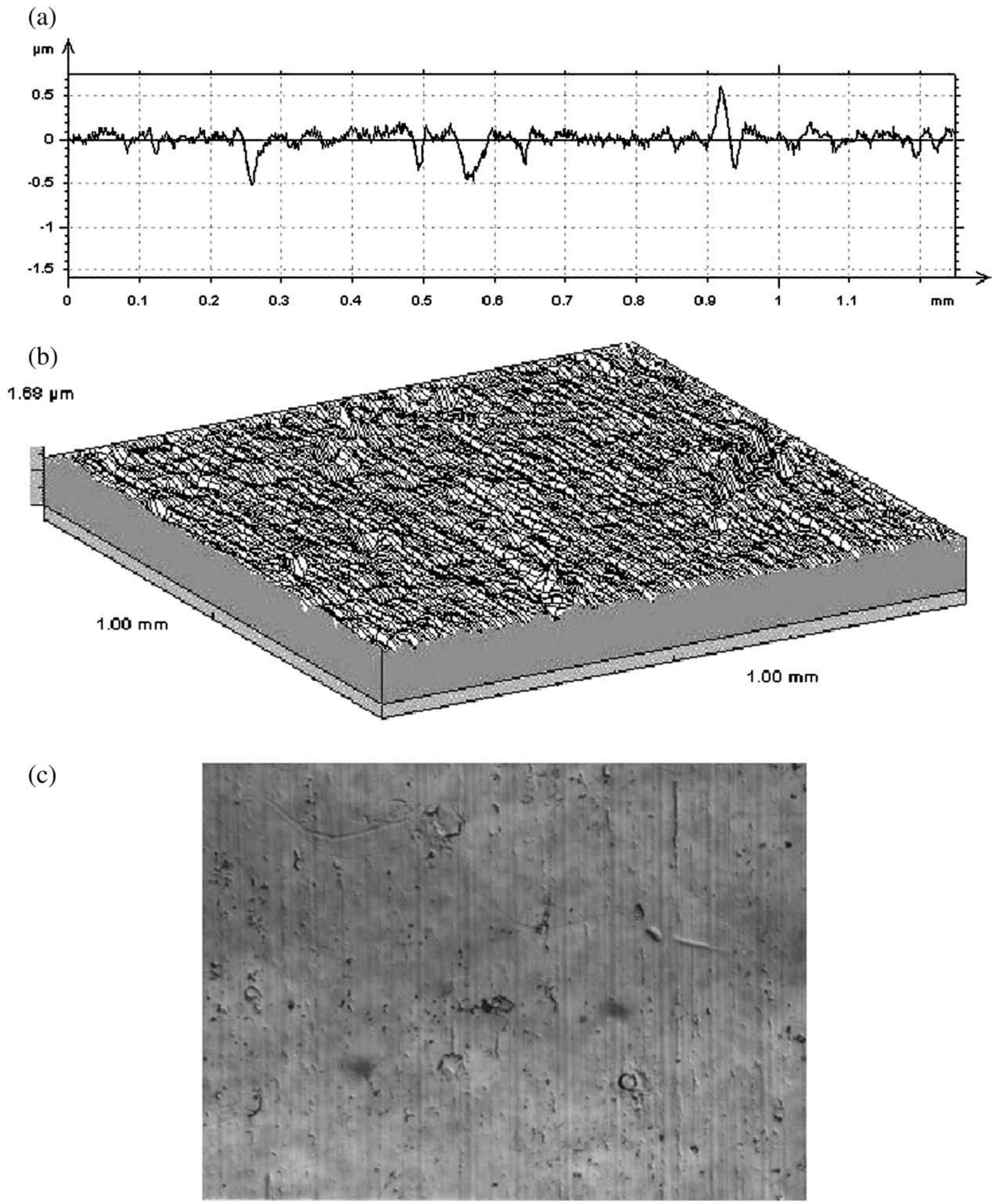

Fig. 4. Slide burnished coating: a) profilogram, b) 3D scan, c) view (mag. ~110×).

Table 3
Measurements results of surface texture parametres of samples with chromium coatings treated according to variant I

Parametre		After slide burnishing (sample C)	After polishing (sample D)
name	symbol	Parametres calculated by mean of all the sampling lengths.	
		A microroughness filtering is used, with a cutoff of 2,5 μm.	
		Roughness parametres, Gaussian filter 0.25 mm. The series contains 251 profiles.	
Arithmetic mean deviation of the roughness profile	*Ra*	0,0733 μm ± 0,0127	0,0613 μm ± 0,0123
Root-mean-square (RMS) deviation of the roughness profile	*Rq*	0,103 μm ± 0,022 μm	0,079 μm ± 0,0178 μm
Maximum peak height of the roughness profile	*Rp*	0,224 μm ± 0,0389 μm	0,171 μm ± 0,0566 μm
Maximum valley depth of the roughness profile	*Rv*	0,356 μm ± 0,108 μm	0,163 μm ± 0,0339 μm
Total height of roughness profile	*Rt*	1 μm ± 0,351 μm	0,499 μm ± 0,193 μm
Skewness of the roughness profile	*Rsk*	−2,09 ± 1,74	0,109 ± 0,867
Kurtosis of the roughness profile	*Rku*	18 ± 14,7	5,39 ± 4,58
Maximum height of roughness profile	*Rz*	0,58 μm ± 0,136 μm	0,334 μm ± 0,0831
Roughness profile section height difference	*RHTp*	0,126 μm ± 0,0166 μm (20%–80%)	0,124 μm ± 0,0208 μm (20%–80%)
Mean width of the roughness profile elements	*RSm*	0,0156 mm ± 0,00327 mm	0,0687 mm ± 0,0129 mm
Root-mean-square slope of the roughness profile	*RDq*	2,82° ± 0,105°	0,449° ± 0,0791°
Root-mean-square wavelength of the roughness profile	*RLq*	0,0132 mm ± 0,0025 mm	0,0631 mm ± 0,00634 mm
Developed length of the roughness profile	*RLo*	0,226% ± 0,00985%	0,504% ± 0,00171%
Ten point height of the roughness profile	*Rz(JIS)*	0,386 μm ± 0,0707 μm	0,169 μm ± 0,0254 μm
Mean of the third maximum height of the roughness profile	*R3z*	0,43 μm ± 0,083 μm	0,162 μm ± 0,0229 μm
Peak count on the roughness profile	*RPc*	0,0159 pks/mm ± 0,125 pks/mm (±0,5 μm)	0 pks/mm ± 0 pks/mm (±0,5 μm)
Mean height of the roughness profile elements	*Rc*	0,17 μm ± 0,0334 μm	0,188 μm ± 0,0473 μm
Fractal dimension of the roughness profile	*Rfd*	1,49 ± 0,0533	1,37 ± 0,0573
High spot count on the roughness profile	*RHSC*	0,49 peaks ± 0,614 peaks (1 μm under the highest peak)	0,124 peaks ± 1,06 peaks (1 μm under the highest peak)
Arithmetic mean slope on the roughness profile	*RDa*	2,12° ± 0,083°	0,354° ± 0,0542°
Arithmetic mean wavelength on the roughness profile	*RLa*	0,0124 mm ± 0,00207 mm	0,0607 mm ± 0,0071 mm
Maximum peak-to-valley height	*Rmax*	0,972 μm ± 0,355 μm	0,474 μm ± 0,191 μm
Maximum height of the roughness profile	*Rtm*	0,58 μm ± 0,136 μm	0,334 μm ± 0,0831 μm
Maximum height of the roughness profile	*Ry*	0,972 μm ± 0,355 μm	0,474 μm ± 0,191 μm
Suedish height on the roughness profile	*RH*	0,331 μm ± 0,0699 μm	0,262 μm ± 0,0586 μm
Mean spacing of local pits on the roughness profile	*RS*	0,0386 mm ± 0,0341 mm	0,0579 mm ± 0,0155 mm
Fluid retention volume on the roughness profile	*RVo*	$1{,}63 * e^{-0.05}$ mm^3/mm^2 $\pm 3{,}41 * e^{-0.05}$	0,000108 mm^3/mm^2 ± 0,000122 mm^3/mm^2
Material ratio on the roughness profile	*Rmr*	− (1 μm under the highest peak)	− (1 μm under the highest peak)
Profile section height on the roughness profile	*Rdc*	0,126 μm ± 0,0166 μm (20%–80%)	0,124 μm ± 0,0208 μm (20%–80%)

considerably change the surface microhardness of chromium coatings. It happened that way because the parametres of the burnishing were selected in such a way as to obtain the lowest surface roughness—the lowest possible pressure of the tool was applied which was enough for crushing (levelling the tips of the surface irregularities). The small thickness of the coats may have been responsible for the fact that the investigation (by Vickers method) did not show any changes in their hardness.

After finishing the 50 μm coatings there was (Table 2) an increase in surface microhardness after both polishing and burnishing. In the two cases it was similar and rather small (14–17%) and if it somehow affected fatigue strength, we may presume it occurred in a similar way.

In the profile plots shown in Figs. 3 and 4 and 3D surface scans, differences between polished and burnished samples can be seen. The height of surface irregularities is similar in the two cases. However, in the surface subjected to slide burnishing there were isolated deeper scratches and pits. They impair fatigue strength as they may become the beginning of fatigue induced cracks. Fig. 3b shows a surface structure with sharp roughness peaks, which is typical of abrasive

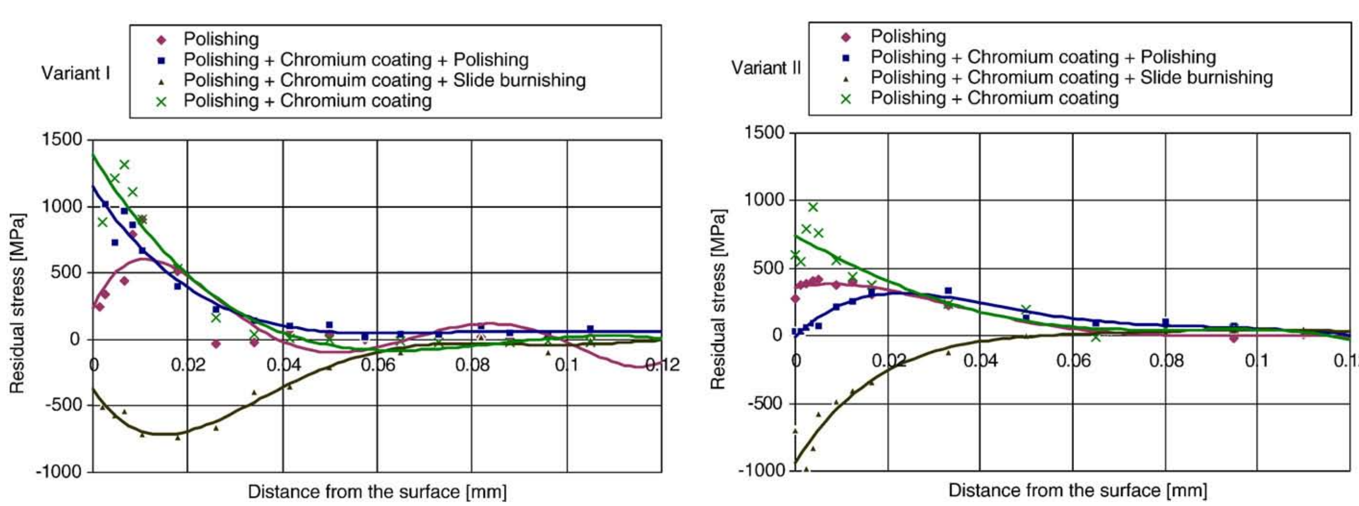

Fig. 5. Longitudinal residual stress distribution in surface layer.

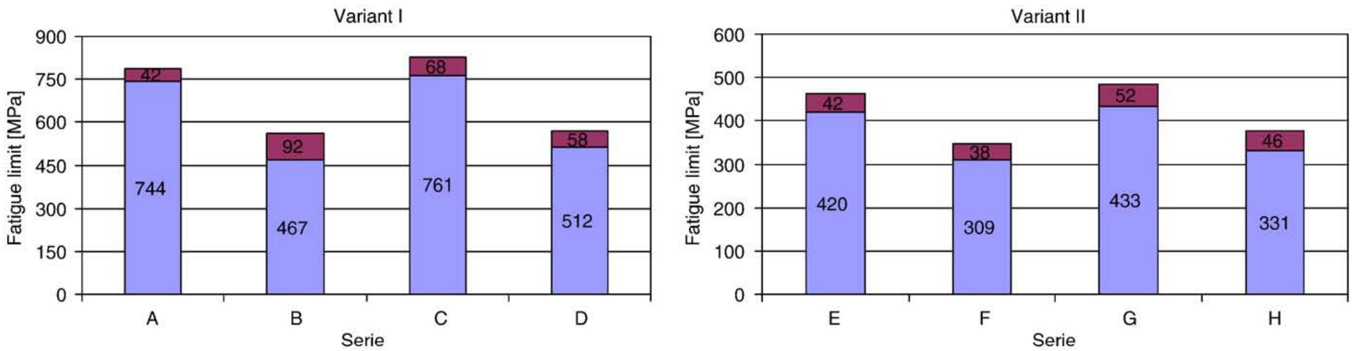

Fig. 6. Fatigue strength limit after various finishing methods, minimum levels were written and confidence intervals calculated at 5% significance level (denotations according to Table 2).

finishing. However, after burnishing, surface irregularities are not as sharp as after polishing (Fig. 4b).

In the photo of surface (Fig. 4c) it can be seen that the surface structure after burnishing is more regular (parallel placed after-finishing traces) than after polishing (Fig. 3c). The spacing of the traces depends on the applied tool feed. However, after polishing, it depends on the graininess of the abrasive band. More regular and less random structure of surface irregularities after burnishing is also evidenced by the value of *Rku* parametre which is far higher than after polishing (Table 3).

After slide burnishing, the average surface roughness (*Ra*) of the coating was 3.5 to 6 times smaller than that of the surface which was not treated (Table 2) and only slightly greater than that of the polished coat. Also the differences between the rest of the surface topology indices of the two after-finished coats are fairly small (Table 3).

Considering the results of the surface texture investigation it can be said that polished surfaces are a little better than burnished ones, but the differences are not too significant.

However the greatest difference was found in the distribution of stresses in the surface layer (Fig. 5) at which the example stress pattern is illustrated in samples treated according to both variants of finishing treatment. It is known that chromium plating creates tensile stress in the surface layer (usually marked as +), which worsens the fatigue strength. It was confirmed by the fatigue tests (Fig. 6) which show that chromium plating can reduce the fatigue strength by as much as 37% (variant I) compared with the material without any coating.

After burnishing, compressive stresses (marked as −) of very high level (even up to about 1100 MPa) are generated in the surface layer. The depth of the maximum stress level (Fig. 5) is not very important (<0,02 mm), but it is enough to change the character of the fatigue load cycle from oscillatory to asymmetrical with the centre of amplitude at the side of negative stresses, which permits, as it is known, the loaded element to withstand greater loads.

It can be found from the carried out tests that using the slide burnishing on chromium coatings improves the oscillatory bending fatigue strength by 40% (in relation to untreated coatings). In this way the detrimental effects of chromium plating disappear and the chromium plated substrates have the same fatigue properties as the base material.

Polishing coatings also improves the fatigue strength but only by about 8%. It is nevertheless much less effective than slide burnishing. Moreover, polishing machines, because of their abrasive machining, are much less environmentally friendly.

Surface topology differences (Table 3; Figs. 3 and 4) among indices after polishing and slide burnishing are not big enough to account for such considerable fatigue strength changes as those found out by the research. It seems that in the case of similar technology, hydrogenation and the characteristics of chromium coated elements, the decisive factor is the state of stresses in the surface layer which is changed by slide diamond burnishing.

4. Concluding remarks

Coating the steel elements of machine parts with chromium causes a considerable worsening of their fatigue properties due to:

- increase in surface roughness after chromium electroplating,
- hydrogenation of steel base,
- un favourable interaction of physical and mechanical properties of bonded materials,
- creation of tensile stresses in the surface layer.

In the carried out experiments, sample batches with significantly different stress patterns in their surface layer were compared. Different stress patterns were obtained using different finishing treatment methods whose parametres were selected in such a way that the samples did not significantly differ, particularly in hardness and average surface roughness. In these circumstances very distinct relationships between the final stress pattern in the surface layer of the samples and their oscillatory bending fatigue strength was found—the pieces with compressive stresses had a distinctly higher fatigue strength than those with tensile stresses. Thus, this seems to have confirmed the known fact that the fatigue properties of chromium plated samples depend crucially on the stresses in their surface layer.

Contrary to the conventional treatment methods (especially polishing), slide burnishing of chromium coatings results not only in an improvement of the surface quality (roughness reduction) but also brings about yet another positive effect, i.e. the occurrence of compressive stresses in the surface layer, which makes it still more effective.

It may improve the oscillatory bending fatigue strength of elements with burnished coatings up to 40%, which can completely remove the harmful chromium plating effects. It can be said that slide burnishing of coatings gives better results than band polishing and is undoubtedly more friendly to the environment.

The treatment of chromium coatings by slide burnishing does not cause any significant technological problems; even coatings as thin as 5 μm can be burnished. What is more, only this method enables treating such coatings with forces weak enough not to damage the coating, and, at the same time, sufficiently strong to bring about plastic deformation and consequently result in further advantages.

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