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*aluminium, milling, burnishing,
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CHARACTERISTICS OF SURFACE TOPOGRAPHY AFTER ROLLING BURNISHING OF EM AW-ALCU4MGSI(A) ALUMINIUM ALLOY

This paper characterizes surface topographies produced by medium milling of EM AW-AlCu4MgSi(A) aluminium alloy in hardened state T451 using a ball-end cutter of 8 mm diameter and subsequent finish by roller burnishing using a Si_3N_4 nitride ceramic ball of 8mm diameter. It was revealed that ball burnishing operations performed on curvilinear milled surfaces allow obtaining the machined surfaces of high quality and exceptional smoothness with different textures and, as a result, ensuring demanded functional properties such as fatigue strength, bearing properties and contact strength [1]. It was experimentally verified that precision ball burnishing performed with a low stepover of 0.04mm produced a very smooth with the Sa roughness of about 0.02μm characteristic for polishing.

1. INTRODUCTION

Lightweight alloys such as aluminium, magnesium and titanium alloys belong to a growing group of construction materials with wider applications in many industry sectors (aircraft, automotive, precision, mechanical engineering) [2]. The main technological advantage of aluminium alloys is that they have a good machinability in comparison to steels which promotes the application of HSM technique.

Currently, the advanced industry introduces more and more hybrid and sequential machining technologies which are more efficient, sustainable and generate lower production costs. Among sequential processes the combination of removal and non-removal machining operations, i.e. subsequent turning or milling and burnishing operations, is a very competitive alternative for typical finishing cutting and abrasive operations. It is very important that these sequential processes can be realized on CNC lathes or multi-axis CNC machining centres with commercial cutting and burnishing tools [3],[4]. Roller and sliding

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burnishing belong to non-removal machining operations which influences distinctly the surface integrity including surface topography, strain-hardening index and the distribution and profile of the residual stresses. Burnishing is an eco-friendly technological process in comparison to finishing abrasive processes such as precision grinding because no chips, sparks and dust are produced and the use of coolants and lubricants is reduced to the essential minimum. It can be effective for both hard and soft ferrous and non-ferrous materials, including plastics. Burnishing tools can be stored in the tool magazine of a CNC machine tool and both medium and finish operations can be performed at one working stand which contributes to the reduction of the machining cost and time [4]. In this paper the measuring results concerning the ball burnishing of concave surfaces with a EM AW-AlCu4MgSi(A) aluminium alloy of 110HB hardness are presented. A set of 3D surface roughness parameters was used to characterize the superficial effects of precision burnishing operations and their influence on the parts functionality.

2. EXPERIMENTAL DETAILS

2.1. CHARACTERIZATION OF MACHINED MATERIAL AND EXPERIMENTAL METHODOLOGY

In this study the workpiece material used was a EN AW-AlCu4MgSi(A) aluminium alloy in the hardened state T451 of the quality guaranteed by the metallurgical certificate 3.1. This alloy features high tensile strength and high fatigue resistance. In addition, it has a good corrosion resistance but a low weldability. The main applications cover aircraft industry, manufacturing industry, weapon (armaments) and automotive industry. In addition, it is used in mold industry due to the necessity of final polishing. Tables 1 and 2 specify its chemical composition and the mechanical properties.

Table 1. Chemical composition of EN AW-AlCu4MgSi(A) alloy

Ti	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti+Zr	other
0.06	0.64	0.04	4.2	0.95	0.76	0.04	0.17	0.06	0.02

Table 2. Mechanical properties of EN AW-AlCu4MgSi(A) alloy

Ultimate tensile strength Rm [MPa]	Yield stress $Rp_{0.2}$ [MPa]	Elongation A5 [%]	Hardness [HB]	Density [g/cm^3]
445	292	17	110	2.80

The concave specimens with the curvature radius of 250mm and the dimensions of a 80mm in width and a 120mm in length were partitioned into 6 equally sized segments of 20mm×80mm as shown in Fig. 1a. All segments were distinguished by a 5mm groove made by slot milling. As indicated in Fig. 1b the segments were shaped with the same curvature of 250mm. Initially, the segments were milled using a monolithic ball-end cutter (VHM) of a 8mm diameter with the cutting speed of v_c = 350m/min, the feed per tooth of f_z = 0.04mm, the pitch (stepover) of f_{wf} =0.53mm and the axial depth of cut (the back engagement) a_p = 0.5mm. Milling operation (Fig. 1b) was performed with the constant stepover and the tilt angle (ψ) of 7.5° in the direction perpendicular to the Y axis.

a) b)

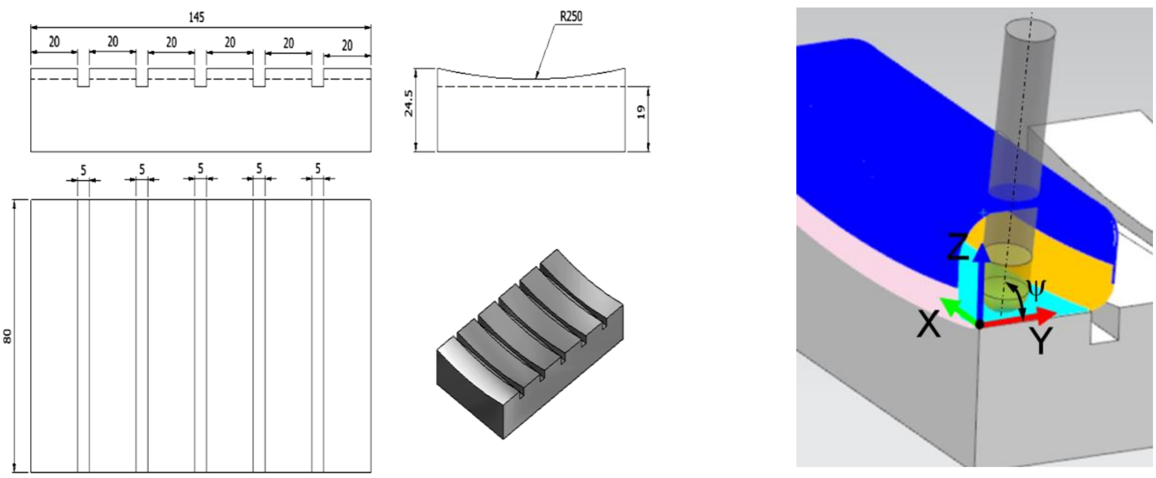


Fig. 1. Specimen with 6 concave segments (a) and ball-end milling in the direction perpendicular to the Y axis (b)

a) b)

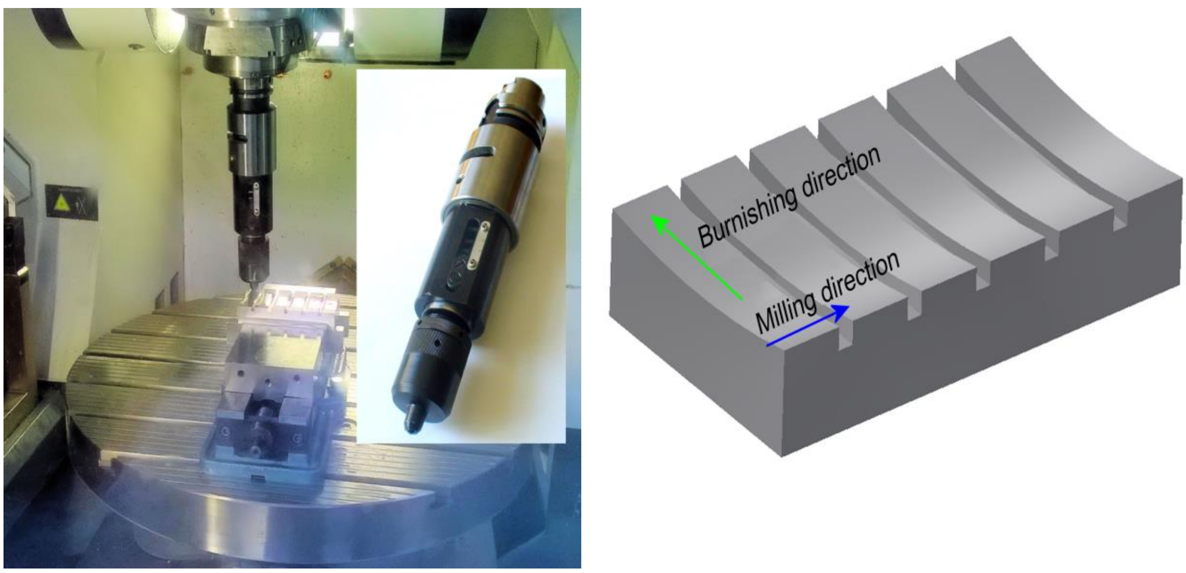


Fig. 2. View of the working space and burnishing tool (a), specimen with marked directions of tool movements (b)

Both milling and burnishing operations were carried out, each in one pass on a 5-axis machining centre model DMC 75V Linear as shown in Fig. 2a. Burnishing was performed using a spring-loaded burnishing tool equipped with a Si_3N_4 ceramic polished ball of a 8mm diameter. Before burnishing the burnishing tool was displaced at 0.3mm in relation to the specimen surface by appropriate spring deflection. The working feed of the table was the same at f_t = 6000mm/min for all burnishing trials B1-B4. The values of the elastic load were equal to F_n= 25N and 100N, whereas the feed rates in the direction perpendicular to milling lays (Fig. 2b) were equal to f_{wn}=0.04mm and 0.08mm. Similar process kinematics was applied in Ref. [5]. The appropriate coding of machining operations is specified in Table 3. During burnishing the ball was lubricated by machine oil. All CNC programs used are edited using a NX CAM programming system.

Table 3. Codes of machining operations and machining conditions

Symbol	Operation	Stepover f_{wn}, mm	Normal force F_n, N
M	Ball–end milling	-	-
B1	Burnishing	0.08	100
B2	Burnishing	0.08	25
B3	Burnishing	0.04	100
B4	Burnishing	0.04	25

2.2. MEASUREMENTS OF 3D SURFACE ROUGHNESS

Surface profiles/ topographies produced by milling and burnishing operations were recorded and 3D roughness parameters were estimated by means of a TOPO-01P profilometer with a diamond stylus radius of 2μm. The 3D visualization of machined surfaces was performed using a Digital Surf, Mountains® Map package.

Nowadays, 3D roughness parameters are normalized by ISO 25178 and EUR 1517EN because surface topography generated by precision machining is critical for surface functionality and component performance. ISO 25178 [6] is the first international standard taking into account the specification and measurement of 3D surface texture.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The effects of the ball burnishing of initially turned pre-cooled surfaces based on characterization of their geometrical features are shown in Figs. 3-8.

Figure 3 presents the measured values of the Sa and Sz parameters and their reduction due to burnishing action for different stepovers and normal loads. It was decided that the value of Sa= 2.6μm obtained after milling seems to be an optimum for further burnishing.

In general, for sequential (M+B1, M+B4) operations the index Sa_m/Sa_b increases from 25 to about 140 when the stepover decreases. This indicates that burnishing diminishes the Sa and Sz parameter but its reduction below 0.02μm was obtained for variant M+B4 with a minimum stepover of 0.04mm. In this case the minimum value of Sa=0.019μm was obtained.

The milled and burnished surface profiles obtained for different machining conditions are presented in Fig. 4. As shown in Fig. 4a all sharp peaks within milled profile are completely deformed by the ball and a very smooth profile is generated. This effect related to different burnishing conditions is zoomed in Fig. 4b. It can be noted that burnishing with the lower stepover of 0.04mm causes that the surface profiles consists of a large number of local micro-peaks and a visible smoothing takes place. In the case study, the profile slope Sdq is reduced from 0.05 (about 0.50) for milled surfaces down to 0.005 and 0.004 (about 0.040) for burnishing operations # B1 and B4 respectively.

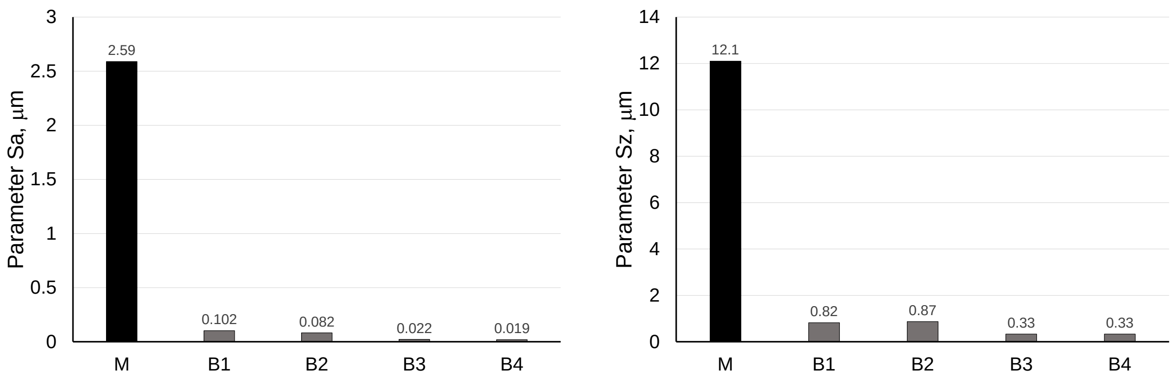


Fig. 3. Comparison of Sa and Sz roughness parameters for milling (M) and burnishing (B) operations

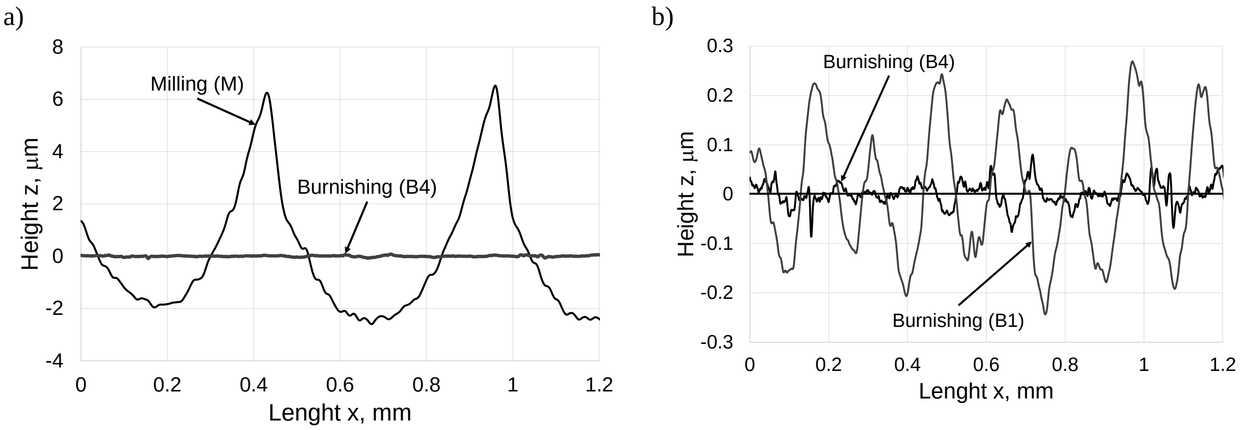
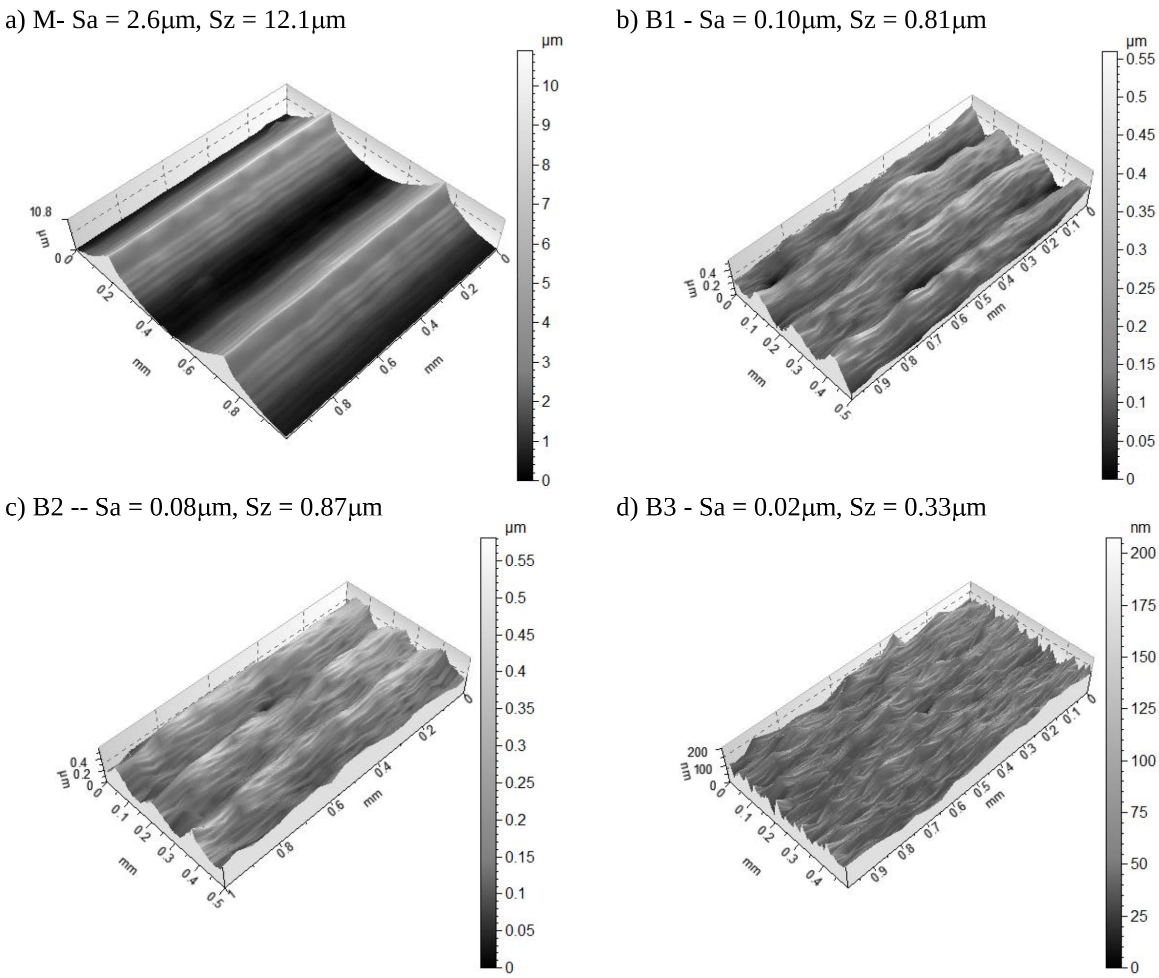


Fig. 4. Examples of surface profiles produced in sequential machining operations: a) M+B4, b) M+B1and M+B4

The relevant 3D visualizations are presented in Fig. 5. It is evident that the reduction of the stepover from 0.08 (Fig. 5 b and c) to 0.04 (Fig. 5 d and e) results in the deterioration of a deterministic texture with visible lays similar to milling. In addition, the surfaces burnished with the stepover of 0.08mm have distinct waviness along the trace of ball-end milling cutter. The initial surface topography is practically entirely modified and only small fragments of longitudinal lays remain. It should also be noticed that the increase of the normal load leads to the deterioration of surface quality due to deep troughs and visible flashes of highly plasticized material. In general, the Sa parameter is reduced by 20% when the normal load increases from 25N to 100N (case #B1 versus case #B2).

Bearing area curves (BAC denoted by symbol M) determined for milling and sequential machining operations are presented in Fig. 6a. First, ball-end milling produces degressive BACs which implies that a subsequent ball burnishing is needed to increase the material ratio of milled surfaces.

It can be noted that the decrease of stepover results in improving the material ratio (cases # B1 and B2 versus cases #B3 and B4). By burnishing the material ratio curves become more progressive. This fact can be explained in terms of the areal material ratio (Smr), in this case the ratio Smr(20) is defined at the cut of 20% as shown in Fig. 6b. The interpretation of the areal material ratio (Smr) is that its higher value indicates better bearing and wear properties.



e) B4 - Sa = 0.02μm, Sz = 0.33μm

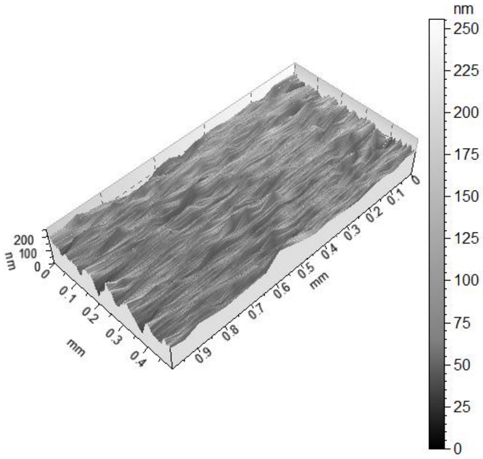
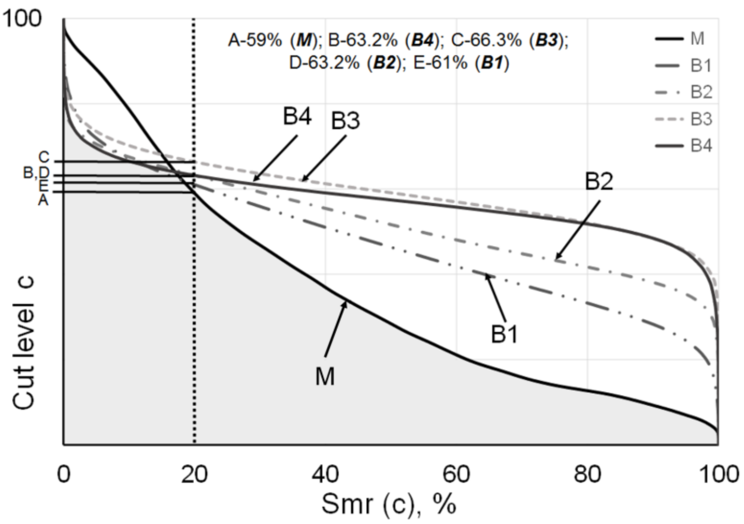


Fig. 5. Surface textures produced in milling (M) (a), burnishing for f_{wn}=0.08mm and F_n=25, 100N(B1, B2) (b,c) burnishing for f_{wn}=0.04mm and F_n=25, 100N(B1, B2) (c,d) operations

In this aspect, the maximum value of Smr(20)=66.3% determined for burnished surfaces (B4) confirms again their better bearing properties in comparison to milled surfaces for which Smr(20)=59%. The inverse areal material ratio (Sdc(mr)) defines the height which gives the specified material ratio Smr. Hence, the material ratio Smr(20)=59% for the burnished surface (variants B1 and B2) was determined at the height of 0.28 and 0.22μm and 0.05μm (variants B3 and B4), but for highly peaked milled surface the Smr(20)=59% was obtained at the height of 8μm. The values of the peak extreme height Sxp decreases due to burnishing from initial 2.74μm down to 0.16-0.20μm and 0.05μm for the stepover of 0.08mm and 0.04mm respectively.

a) **M**-Sdc=7.96μm, Sxp=2.74μm, **B1**-Sdc=0.28μm, Sxp=0.21μm, **B2**-Sdc=0.22μm, Sxp=0.16μm, **B3**-Sdc=0.059μm, Sxp=0.053μm, **B4**-Sdc=0.048μm, Sxp=0.053μm



b) **M**-Ssk=0.79, Sku=2.49; **B1**-Ssk=-0.177, Sku=2.47, **B2**-Ssk=0.0795, Sku=2.33, **B3**-Ssk=-0.0855, Sku=3.24, **B4**-Ssk=-0.269, Sku=5.06

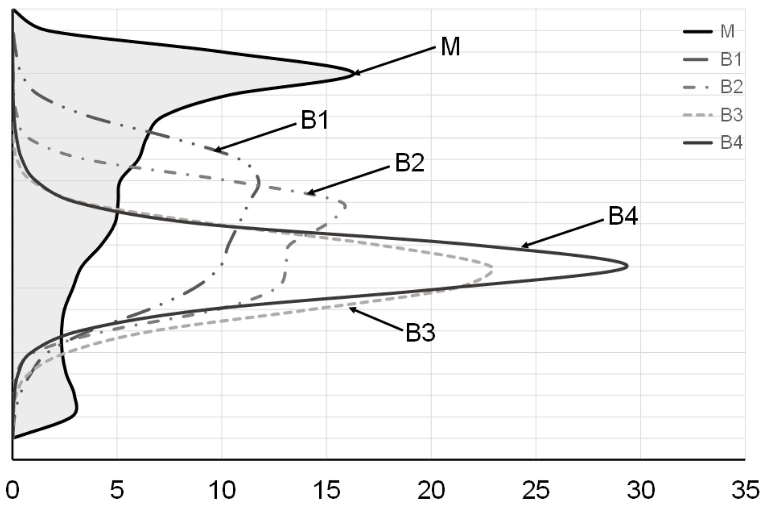


Fig. 6. 3D BAC shapes (a) and ADF distributions (b) for milling (M) and burnishing (B1,2,3,4) surfaces

It can be reasoned based on the modifications of amplitude distribution function (ADF) curves shown in Fig. 6b that ball-end milling and subsequent ball burnishing operations produced surfaces with visibly different shapes of ADF curves. The transformation of ADF curve from asymmetric one obtained for milling (M) to symmetric one obtained for ball burnishing B4 take places. This observation was previously noted in Ref. [7]. In particular, the decrease of the stepover from 0.08mm to 0.04mm results in an ideal symmetric distribution of ADF curves with higher values of kurtosis Sku like bell curves characteristic for normal Gaussian distributions (cases # B3 and B4 in Fig. 6b). For instance, the value of Sku increases to about 5 after burnishing coded by the symbol B4. It is well known that such surfaces are classified as “plateau” with exceptional good bearing properties [8].

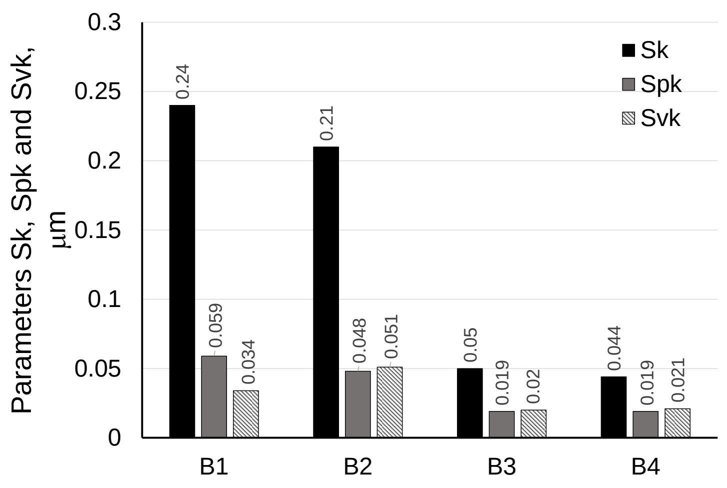


Fig. 7. Distribution of Sk, Spk and Svk parameters for burnished surfaces

The distributions of three bearing parameters Sk, Spk and Svk implies that the bearing properties of burnished surfaces differ distinctly depending on the process conditions applied, as shown in Fig. 7. It can be noted, based also on Fig. 6a, that milled surfaces are characterised by the linear-degressive bearing curves and exceptionally high values of Spk=5.26μm. It is reduced about ten times after burnishing (down to 0.06-0.05μm) with the stepover of f_{wn}=0.08mm independent of the normal load exerted (F_n=25 and 100N)- see appropriate bars for B1 and B2 burnishing operations in Fig. 7.

In particular, the reduced peak height Spk is further reduced down to 0.02μm when decreasing the stepover down to 0.04mm (cases # B3 and B4). It should also be noted that for all burnishing operations B1-B4 the reduced peak heights are the same as the reduced valley heights. Nevertheless, the extremely small values of Spk for burnishing cases # B3 and B4 suggest that the smoothing effect by burnishing results in good tribological properties and minimum running-in effects [9].

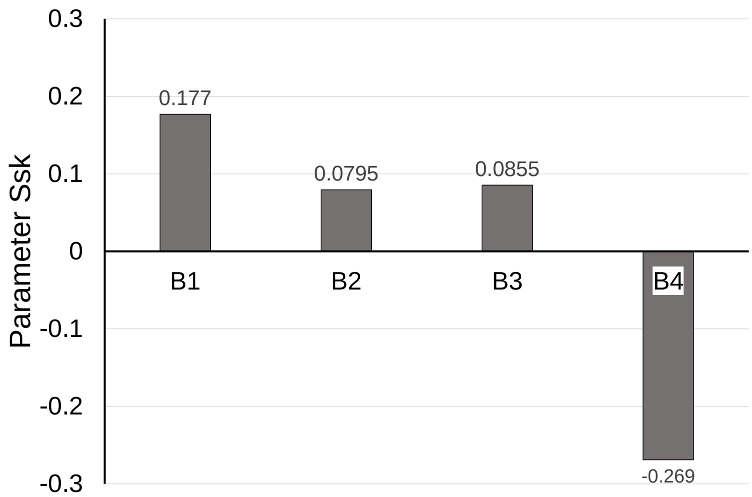


Fig. 8. Values of skewness Ssk for burnished surfaces

Fig. 8 presents the values of skewness Ssk obtained for four characteristic burnished surfaces keeping the burnishing conditions (B1-B4) specified in Table 3. It can be noted in Fig. 8 that for one set of burnishing conditions, i.e. the lower normal force of F_n=25N and the lower stepover of f_{wn}=0.04mm, coded by index B4, the negative Ssk=-0.27 was determined. On the other hand, for all other combinations of burnishing conditions, the positive values of Ssk ranging from 0.08 to 0.18 were obtained. The latter fact indicates that for such burnishing conditions the surfaces with better contact stiffness are produced.

4. CONCLUSIONS

1. An aluminium alloy machined is distinctly deformed during ball burnishing. As a result, the milled surfaces are smoothed and optical quality sculptured surfaces are produced.

2. The ratio of the Sa parameters for milled and burnished surfaces ranges from 25 to above 100 depending on the stepover used. In this study the stepover was kept at 0.08mm and 0.04mm. The smoothing effect does not depend on the normal load used.
3. The surfaces burnished with the stepover of 0.08mm have distinct waviness along the trace of ball-end milling cutter. The reduction of the stepover down to 0.04mm results in an thorough modification of the surface texture within which only small fragments of longitudinal lays are remained. Moreover, the increase of the normal load leads to the deterioration of surface quality due to deep troughs and visible flashes of highly plasticized material.
4. Burnishing with the lower stepover and normal load leads to producing surfaces of optical quality with the Sdq slope of about 0.004. In addition, such smooth surfaces have improved bearing properties and wear resistance because negative skewness of Ssk=-0.27 and a very low reduced peak height of Spk= 0.02μm. This superficial effect is comparable to polishing.
5. It can be reasoned based on the multi-parameter characterization of surface textures of that sequential processes including ball-end milling and ball burnishing they seem to be highly efficient in improving surface quality of sculptured aluminium parts.

   In contrast, as reported in Ref. [10], burnishing of turned aluminium surfaces needs more tool passes in order to obtain the Ra parameter about 0.3μm.

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