Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 40
ISSUE 2
June
2010

An investigation of machining efficiency of internal roller burnishing

A. Stoić [a,*], I. Lacković [b], J.Kopač [c], I. Samardžić [a], D. Kozak [a]
[a] Faculty of Mechanical Engineering, University of Osijek,
Trg I.B. Mažuranić 2, 35000 Slavonski Brod, Croatia
[b] University of Applied Sciences of Slavonski Brod,
M. Budaka 1, 35000 Slavonski Brod, Croatia
[c] Faculty of Mechanical Engineering, University of Ljubljana,
Aškerčeva 6, 1000 Ljubljana, Slovenia
* Corresponding author: E-mail address: antun.stoic@vusb.hr

Received 11.02.2010; published in revised form 01.06.2010

Manufacturing and processing

ABSTRACT

Purpose: of this paper is investigation of fine machining efficiency of 34CrMo4 steel with roller burnishing tools. Application of roller burnishing process as a clean and environmentally friendly machining process which can replace other pollution processes is of great interests. It is important to evaluate the influence of material properties (primary hardness) for smoothing efficiency and achieving of lower roughness and higher work piece hardness.
Design/methodology/approach: Experimental tests of cutting outputs have been done on specimens prepared for final machining process to estimate the rate of roughness decrease, and diameter increase. Roughness measured data before and after roller burnishing process have been compared.
Findings: It was found that surface roughness is significantly lower after roller burnishing. Roughness ratio (before/after process) and decrease factor was 4 what doesn't satisfy expected results. Some roughness results after burnishing exceed upper limits.
Research limitations/implications: Results and findings presented in this paper are qualitative and might be slightly different in other machining condition (e.g. higher hardness materials and higher roughness of row material).
Practical implications: Smoothing process can be performed on standard machine tools without additional reconfiguration tasks. Process is very rapid. Process is very versatile for any workshop and can be conducted without coolant what is additional advantages for the environment and pollution free machining.
Originality/value: Originality of the paper is in analysis of results and smoothing efficiency with Wilcoxon test.
Keywords: Machining; Roller burnishing; Surface roughness; Smoothing

Reference to this paper should be given in the following way:
A. Stoić, I. Lacković, J. Kopač, I. Samardžić, D. Kozak, An investigation of machining efficiency of internal roller burnishing, Journal of Achievements in Materials and Manufacturing Engineering 40/2 (2010) 188-194.

1. Introduction

Fine machining process of cylindrical surfaces exposed to the high exploitation loadings has to ensure acceptable surface quality and it's as longer functionality. In the last decades, selection of the process to satisfy these demands is additionally determined with short cycles and low-pollution priorities. These production demands means that machining processes with low waste and low energy consumption are required while long cycles of fine machining have to be avoided.

In today's cost-efficient manufacturing aimed to achieve acceptable accuracy and surface finish of the machine parts, roller burnishing can help to eliminate additional operations and cost savings, while at the same time improving the quality of product.

Surface geometry machined with traditional processes consists of scallops causing additional finishing operation. Surface roughness bellow 0.1 mm [1] is required for minimizing friction losses and high fatigue strength. To increase production efficiency and these requirements, it is necessary to look either for new tool designs gathering better machining outputs or either for more cheaply actions toward optimization of the machining parameters [2].

When the scalloped surface is exposed to loadings, high local pressures on surface peaks can be expected and rapid wear as well.

Contact of tool and work piece in traditional machining processes producing scalloped surface with plastic deformation is mainly performed with sliding tool over machined surface what requires a lot of lubrication and a lot of friction energy. Additionally to lubricants that circulate through the cooling system and over machine tool, some quantity of lubricants remain on chips after the process is finished and is also potential waste material and a risk for pollution.

Most of the investigations towards improvement of fine machining processes are concerned with the process outputs: surface roughness and surface hardness. It was pointed out by many investigators that an improvement in wear resistance can be very easy achieved by burnishing, but very few actual studies analyzed environmental implications and versatility.

Roller burnishing is a fine machining process that is used to improve certain physical and mechanical properties, such as surface roughness, corrosion resistance, friction coefficient, wear, and fatigue resistance. The principle of the burnishing process, shown in Fig. 1, is based on the rolling movement of a tool (a ball or a roller) over the work piece's surface. With application of roller burnishing process, plastic deformation of machining surface and allocation of material starts from peaks to valleys. Roller burnishing is a material micro-displacement process which (Fig. 1) in comparison with other finishing processes, like grinding process, also lowers the surface roughness height but the burnishing process can be achieved by applying a highly polished and hard roll on to a metallic surface under pressure. Microscopic "peaks" on the machined surface are during roller burnishing process caused to cold flow into the "valleys," creating a plateau-like profile in which sharpness is reduced or eliminated in the contact plane.

As the yield strength of the work piece's material is exceeded, plastic flow of the original asperities takes place. This leads to a smoother surface. Simultanliously with plastic deformation, compressive stresses are induced in the surface layer. The increase in the burnishing force will increase the plastic deformation, as well as the penetration of the ball or roller into machining surface. This will lead to an increase in the internal compressive residual stress, which causes a considerable increase in the surface hardness. The increase of surface hardness and strength mainly serves to improve wear resistance and fatigue resistance under dynamic loadings.

Burnishing of hardened steel is applied as a subsequent operation after hard machining. Hard machining process is applied in order to ensure the dimensional accuracy. Hardened and highly polished steel rollers are brought into pressure contact with a softer work piece.

Burnishing process results with no chips, no sliding wear (rolling of tool is present) and no wasted coolants.

Burnishing is a method to smooth-out the rough surface, therefore the diameter also changes as a result. The inner diameter expands and the outer diameter compresses. In order to finish within the dimensional tolerance, it is necessary to calculate the pre-machining dimension considering this diameter change. Since the variation of the diameter depends on the material, the hardness, and the burnishing value, conducting tests with several samples and determining the best beginning dimension is recommended.

Dimension of the cylindrical surface is changed for hundreds of the millimeter, and even 10 times smaller roughness can be achieved. Roughness of the pre-machined surface has to be within the range $Ra = 0.8$ to 3.2 μm.

The burnishing is good process to improve the surface roughness for metals where grinding is not possible due to wheel loading effect in material like aluminum etc.[3].

The surface of the material is during the process smoothed out and become hardened because of the plastic deformation process happening on the surface. The machined surface left with a residual compressive stresses distribution [3].

Oppositely to burnishing, sharp peaks on the contact surface left on ground surface.

Work piece surface integrity is in burnishing process ensured due to the compression effect of this surface and its associated cold working.

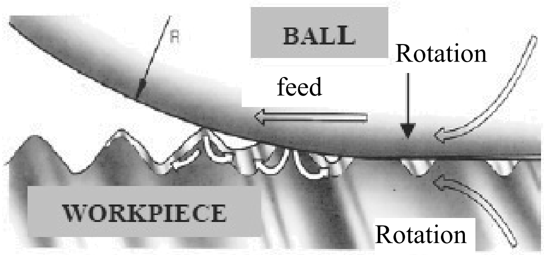

Fig. 1. Scheme of roller burnishing process [4]

Burnishing processes are being used in different types of industries like Automobile, Aircraft, Military, Railways, Textile, Machine Tool, Motors and Pump Industry, Hydraulic and Pneumatic Equipment, Home Appliances etc., and other areas where close tolerance and superior surface finish is required.

Lopez de Lacalle et. al. [5] research the ball burnishing process aimed to improve the final quality of Inconel 718 surfaces. Efficiency of improvements of surface has been evaluated with changing the roughness and residual stresses of the previously end milled surfaces, achieving the finishing requirements for engine components. The main conclusions are that using a large radial width of cut in the previous end milling operation, together with a small radial width of cut during burnishing can produce acceptable final roughness.

Roller burnishing produce accurately sized (tolerances within 0.0075 mm or better, depending on material type and other variables) and finished surface (typically *Ra* is between 0.05 to 0,50 µm) with increased surface hardness (increase of hardness is in the range of 10 HRC) that resists wear.

Safwan & Al-Qawabah [6] investigated burnishing of copper alloy (with Zinc-aluminum containing 4 % aluminum) found that there is an enhancement on the hardness and the maximum is 18 %. In the same study, the best surfaces result was 0.05 micrometer that obtained at 0.04 mm/rev burnishing feed rate. The micro hardness was increased with increasing the burnishing feed rate up to specific point then it become to decrease. In study [7], the best result of surface roughness was obtained at 0.06 mm/rev burnishing feed rate. The surface roughness is increased with increasing the feed rate up to certain point (0.06 mm/rev) then it begins to decrease. Higher reduction in surface roughness happened at very low burnishing feed rate.

Other process advantages include: reduced cycle time (parts are processed in seconds), cleaner production (it is cleaner than honing or other abrasive finishing methods) and versatility (it can run on any rotating spindle).

Because the metal must be capable of cold flowing under roll pressure, workpiece hardness normally should not exceed 40 HRC [8].

El-Tawel & El Axir [9] were used Taguchi technique to identify the effect of burnishing parameters, i.e., burnishing speed, burnishing feed, burnishing force and number of passes, on surface roughness, surface micro-hardness, improvement ratio of surface roughness, and improvement ratio of surface micro-hardness. The analysis of results shows that the dominant influence on cutting outputs have had burnishing force with a contribution of 39.87% for surface roughness and 42.85% for surface micro-hardness followed by burnishing feed, burnishing speed and then by number of passes.

Al-Qawabeha et. Al. [10] refers that hardness increases with increasing of the applied force. Hardness improvements are found to be within 12 and 65 % what depends on applied burnishing force value [10].

One of the most important advantage of this cold process is lowering or even avoid of crack initiation and the crack speed propagation during the use. The influence of roller burnishing within this objective has been analysed by Gardin et. al. [11] on both crack initiation and propagation. The aim of the work performed is to study roller burnished notched shafts . Roller burnishing permits the fatigue strength of structures to be increased. Crack propagation speed is lowered by the introduction of compressive residual stresses. Crack propagation in round bars has been widely investigated, experimentally and numerically.

In [6] it was observed that the increase of burnishing force, the surface roughness decreased, the subsequent increase of burnishing force (more than 159.5 N) gets worst surfaces.

El-Axir [7] refers in his study the relationship between residual stress and both burnishing speed and force. For predicting the surface microhardness and roughness of St-37 caused by roller burnishing under lubricated conditions, authors used mathematical models. From a pre-machined roughness of about *Ra* = 4.5 µm, the specimen could be finished to a roughness of 0.5 µm. It is shown that the spindle speed, burnishing force, burnishing feed and number of passes have the most significant effect on both surface microhardness and surface roughness and there are many interactions between these parameters.

Hua refers at the effect of finishing process on the subsurface residual stress profile related to innovative geometry [13]. The advantages of machining hard components with application of tangential turn-milling process, with higher removal rate are investigated by [14] with the normally available range of speed and feeds. The investigations have been mainly focused on surface roughness and timing process, while influence of cutting depth, feed rate and cutting speed considered by Savas & Ozay [14].

2. Description of the problem

Roller burnishing tool are very versatile and can be used on most of the machine tools already installed in the shop, like turret lathes, engine lathes, drill machines or other NC machines. In most cases, roller burnishing operation can be integrated with the automatic cycle or indexing sequence, eliminating secondary operations.

Burnishing occurs as an additional phase in machining processes. In turning, burnishing occurs if the cutting tool is not sharp, if a large negative rake angle is used, if a very small depth of cut is used, or if the work piece material is gummy. As a cutting tool wears, it becomes blunter and the burnishing effect becomes more pronounced. In grinding, since the abrasive grains are randomly oriented and some are not sharp, there is always some amount of burnishing. This is one reason the grinding is less efficient and generates more heat than turning [15].

Burnishing tools operate at standard speeds and feeds found in the most conventional shop machines. Burnishing process is a very low consumption power process due to the small amount of torque generated for machining. Work-piece fixturing problems are therefore considerably simplified when machine set-ups to be employed in surface finishing with this type tool.

Burnishing also generates heat during due to rubbing between roller/ball and work pieces. The heat generated at the deformation zone and friction zones over heats the tool and the work pieces [12]. Any standard grade, lightweight, low-viscosity lubricating oil, or any mineral, sulfur or soluble oil compatible with the metal or alloy to be burnished, is suitable for most metals. Coolant filtration is very important to keep metal particles or grit from being rolled into the part surface [8].

Before performing of burnishing, surface must be pre-machined on lathe, milling or on drilling machine. Surface profile is shown in Fig.3. Surface roughness of pre-machined surface should be in the range *Ra* = 0.8 do 3.2 µm.

The most appropriate pre-machining formula to be used to obtain the most appropriate surface for the process of roller burnishing is as given as follows [16]:

Feed rate per revolution (mm/rev.) = 0.5 x cutter radius (mm).

Burnished surface roughness is increased with increase of the pre-machined surface roughness. The surface roughness can be also increased with increasing the burnishing force. The burnished surfaces could start to deteriorate, if the work piece surface is over hardened due to extreme plastic deformation caused by very high burnishing force.

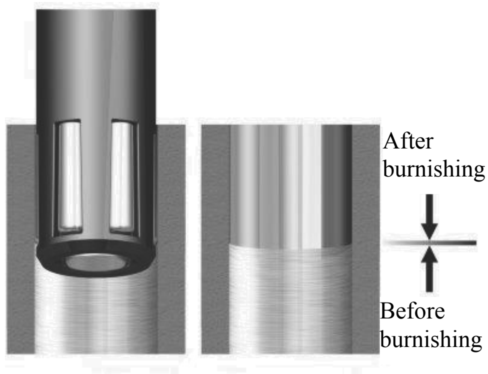

Fig. 2. Surface before and after roller burnishing [16]

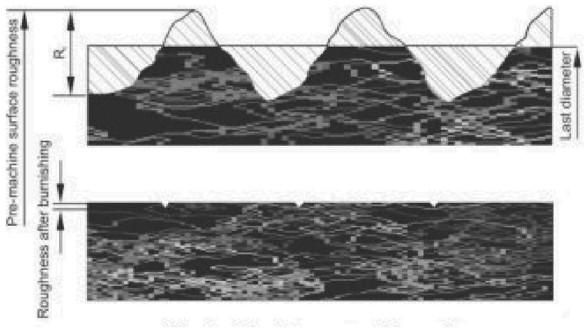

Fig. 3. Surface profiles after pre-machining and after roller burnishing [16]

When a metal is continuously moving over a surface, and a plastic deformation takes place work hardening effect starts. The surface hardness is based on the pre-machined surface hardness of the materials to be burnished. The surface hardness is directly proportional to applied force. i. e. an increase in force increases the surface hardness [17]. This is due to the increase of depth of roller penetration. The surface hardness increases with increase in the depth of penetration. The increases of the number of tool passes and/or burnishing force also leads to an increase in the surface hardness [18]. S. Thamizhmanii et al [17] refers that surface roughness is improved by high spindle speeds, feed rate and depth of penetration on non-ferrous metals like aluminium, copper and brass materials.

3. Design of experiment

For estimating the significant factors of influence for the process, a screening experiment was planned. The output parameter taken into consideration was the mean surface roughness *Ra* and deviation from nominal size of diameter. Roller burnishing tests were in our experiment performed on connecting rod produced of heat treatable high strength steel 34CrMo4 previously forged and with reduced residual stresses with shot peening. Burnishing was performed on radial drilling machine with 280 rev/min and with feed 0.5 mm/rev. Mechanical properties and chemical composition of material are given in tables 1& 2.

The sketch of test sample is shown in fig. 4. Inner cylindrical surface (ϕ 195 H6) was burnished. Roughness was measured on six samples and results are given in Table 4. Deviation was measured on five samples and results are given in Table 6.

Table 1.
Mechanical properties of steel 34CrMo4

Hardness	Strength Rm, MPa	$Rp_{0.2}$,MPa
HV700	950	750

Table 2.
Chemical composition of steel 34CrMo4

C	Si	Mn	P	S	Cr	Mo
0.30 - 0.37	max. 0.40	0.60 - 0.90	max. 0.035	max. 0.030	0.90 - 1.20	0.15 - 0.30

Values in Table 4 are arithmetical means of three measurements performed on each test sample. Fig. 5 shows roughness profile on test sample nr. 4.

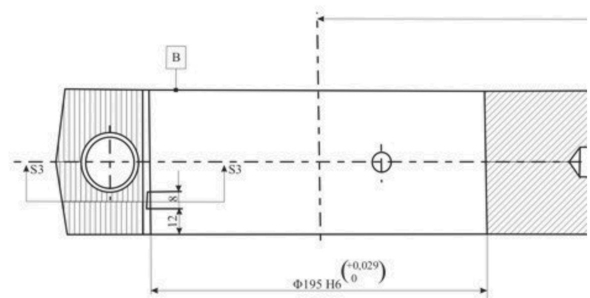

Fig. 4. Test sample

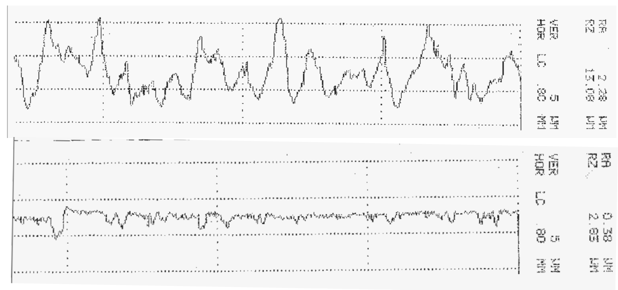

Fig. 5. Surface profile (before and after burnishing)

Roughness was in our experiments measured with device type SURTRONIC with head feeding into range 1.5-60 mm. Accuracy of head feeding was 0.2 μm/60 mm, referent profile length l_e=0.8 mm and observed length l_m=4mm (DIN 4762). Used filter had 75% filtering. It measured values of *Ra*, *Rt* and *Rz* (DIN 4762, DIN 4768 and ISO 4287/1).

Deviation from nominal size of diameter was measured with micrometer.

3.1. The results of roughness measurements

One of observed parameter was pre-machined hardness. Experiment has to estimate its influence on the surface roughness measurement results. It is evident that roughness of the harder surface after pre-machining is significantly better than that of the soft surface. Some prior test indicate the importance of rate of cutting depth and its instability on pre-machined surface roughness.

After the surface has been burnished, surface roughness data have been evaluated applying Wilcoxon test. It is often used to test the difference between scores of data collected before and after an experimental manipulation, in which case the central point under the null hypothesis would be expected to be zero.

During the test we collect 2n observations of surface roughness *Ra* and *Rz*, two observations of each of the n pieces (n=6). Let i denote the particular subject that is being referred to and the first observation measured on subject i be denoted by *Ra*i and second observation be Ra_Bi.

If we induce assumptions Ti = Ra_Bi – *Ra*i for i = 1,2 ... , 6. The differences Ti are assumed to be independent.

Each Ti comes from a continuous population (they must be identical) and is symmetric about a common median θ.

The null hypothesis tested is H0: θ = 0. The Wilcoxon signed rank statistic T+ is computed by ordering the absolute values T1|, ..., |Tn|, the rank of each ordered |Ti| is given a rank of Ri. Denote where I(.) is an indicator function. The Wilcoxon signed ranked statistic T+ is defined as

Scores exactly equal to the central point are excluded and the absolute values of the deviations from the central point of the remaining scores is ranked such that the smallest deviation has a rank of 1. Tied scores are assigned a mean rank. The sums for the ranks of scores with positive and negative deviations from the central point are then calculated separately. A value S is defined as the smaller of these two rank sums. S is then compared to a Table of all possible distributions of ranks to calculate p, the statistical probability of attaining S from a population of scores that is symmetrically distributed around the central point.

Results of measurements are given in Table 3.

In both parameter (*Ra* & *Rz*) measuring results T+=0 and T=21. That means Tmin = 0 for Ra and Rz

For hypotesis

H0 - there is no difference between measurements before and after burnishing

Table 3.
Mean values of roughness data

	before burnishing	after burnishing
mean value of Ra, μm	2.52	0.88
mean value of Rz, μm	13.17	5.66

Critical value for α=0.05 and n=6, (T = 0). Since Tmin ≤0 hypotesiss Ho has been rejected and one can conclude that burnishing process has significant influence on surface roughness.

Table 4.
Roughness measuring results

Sample nr.	1		2		3		4		5		6	
Roughness, μm	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz
before burnishing	2.72	13.50	2.89	13.31	2.22	12.70	2.28	13.08	2.43	13.39	2.57	13.05
after burnishing	0.96	7.64	1.14	6.33	1.10	6.41	0.38	2.83	0.48	3.68	1.2	7.05

Table 5.
Wilcoxon test results

Measur. Nr.	Roughness results, μm			Ranking of absolute data differences │Ti│	Ranks with diff. forsigns
	Before burn.	After burnishing	Difference		
Ra1, μm	2.72	0.96	-1.76	4	-4
Ra2, μm	2.89	1.14	-1.75	3	-3
Ra3, μm	2.22	1.1	-1.12	1	-1
Ra4, μm	2.28	0.38	-1.9	5	-5
Ra5, μm	2.43	0.48	-1.95	6	-6
Ra6, μm	2.57	1.2	-1.37	2	-2
Rz1, μm	13.5	7.64	-5.86	1	-1
Rz2, μm	13.31	6.33	-6.98	4	-4
Rz3, μm	12.7	6.41	-6.29	3	-3
Rz4, μm	13.08	2.83	-10.25	6	-6
Rz5, μm	13.39	3.68	-9.71	5	-5
Rz6, μm	13.05	7.05	-6	2	-2

Table 6.
Results of measurements for deviation from nominal size (ϕ 195 H6)

Sample nr.	1			2			3			4			5		
Position measurement	a1	b1	c1	a1	b1	c1	a1	b1	c1	a1	b1	c1	a1	b1	c1
before burnishing	0.01	0.015	0.015	0.01	0.02	0.02	0.005	0.005	0.005	0.01	0.015	0.015	0.01	0.02	0.025
after burnishing	0.02	0.03	0.035	0.02	0.03	0.035	0.015	0.015	0.015	0.015	0.025	0.02	0.02	0.03	0.03

Table 7.
Wilcoxon test results

Measur. Nr.	Measuramant results, mm			Ranking of absolute data differences │Ti│	Ranks with diff. forsigns
	Before burn.	After burnishing	Difference		
a11, mm	0.01	0.02	-0.01	3.5	-3.5
a12, mm	0.01	0.02	-0.01	3.5	-3.5
a13, mm	0.005	0.015	-0.01	3.5	-3.5
a14, mm	0.01	0.015	-0.005	1	-1.0
a15, mm	0.01	0.02	-0.01	3.5	-3.5
b11, mm	0.015	0.03	-0.015	5	-5.0
b12, mm	0.02	0.03	-0.01	2.5	-2.5
b13, mm	0.005	0.015	-0.01	2.5	-2.5
b14, mm	0.015	0.025	-0.01	2.5	-2.5
b15, mm	0.02	0.03	-0.01	2.5	-2.5
c11, mm	0.015	0.035	-0.02	5	-5.0
c12, mm	0.02	0.035	-0.015	4	-4.0
c13, mm	0.005	0.015	-0.01	3	-3.0
c14, mm	0.015	0.02	-0.005	1.5	-1.5
c15, mm	0.025	0.03	-0.005	1.5	-1.5

3.2. The results of measurements for deviation from nominal size

Because of the measurement uncertainty or deviation from the shape, circularity, in our experiment, we compared the measure from three measuring sites on cylindrical surface. On the measurement data, we applied Wilcoxon test to show whether the burnishing process affects the nominal size of diameter. Wilcoxon test are described in the previous measurement. Results of measurements are given in Table 6.

For hypotesis: H0 - there is no difference between measurements before and after burnishing .

The Wilcoxon's Test on all three position measurement show the same value of T+ = 0 and T- = 15. That means Tmin = 0 In this case the test statistic is T = 0 and the critical value is 0 for a one-tailed p-value of 0.05 (from Table of Critical Values for Wilcoxon signed ranks test).

The test statistic must be less than this to be significant at this level, so in this case the null hypothesis must be rejected and we can conclude that burnishing process has significant influence on nominal size of diameter. At 6 measurement results have exceeded tolerance field

4. Conclusions

This paper presents the results of the research of fine machining conditions with roller burnishing of 34CroMo4 steel. The experimental results show that all the smoothing outputs can be detected in all observed regimes. Roller burnishing process of cylindrical surface can be performed on standard performance machine tools. Surface quality improvement is evident and can be visually detect when comparison of two parts before and after burnishing is conducted. Roughness measuring data for those couples are significantly different. Wilcoxon test confirm the difference on the couples of workpieces (not burnished and burnished part). Burnishing process is more efficient in comparison with grinding, specially if feeding value is observed.

The following conclusions can be drawn from measurements:

- The possibility of burnishing steel components with high hardness, was proven.
- The surface roughness of pre-machined material is determined by the contact geometry of cutting tools and work piece, and showed the most important influence on the burnishing roughness.

- The ball-burnishing tool employed offers a series advantages to the process: pure rolling contact, low coolant consumption, use of the same machine as previous.
- Under the different roller burnishing parameters, the obtained surface roughness is dependant also on work piece hardness and pre-machining conditions.
- Cold deformation of peaks to valleys on surface results with higher surface hardness. Depending on material ductility, peaks of the soften materials are more deformed.
- The surface hardness also increased as the spindle speed, feed rate and depth of penetration was increased.
- Burnishing process has significant influence on nominal size of diameter (pre-machined diameter).
- In the case of burnishing surface with very narrow tolerance range, pre-machined diameter hole must be stetted carefully because burnishing process can increase dimension and exceed tolerance field.

Experimental results and numerical modeling of roller burnishing process offers a great potential in improving the efficiency and quality of machined parts.

Acknowledgements

Authors would like to thank to Ministry of Science, education and Sport of the Republic of Croatia for supporting of Project 152-0000000-3309.

References

[1] P. Ravindra Babu, T. Siva Prasad, A.V.S. Raju, A. Jawahar Babu, Effect of internal roller burnishing on surface roughness and surface hardness of mild steel, Journal of Scientific & Industrial Research 68 (2009) 29-31.

[2] S. Dolinšek, J. Kopač, Mechanisms and types of tool Wear; particularities in advanced cutting materials, Journal of Achievements in Materials and Manufacturing Engineering 19 (2006) 11-18.

[3] S. Thamizhmanii, B. Saparudin, S. Hasan, A study of multi-roller burnishing on non-ferrous metals, Journal of Achievements in Materials and Manufacturing Engineering, 22/2 (2007) 95-98.

[4] Tools for roller burnishing, deep rolling, forming, Prospectus, Ecoroll A.G. Werkzeugtechnik, 2000.

[5] L.N. López de Lacalle, A. Lamikiz, J.A. Sánchez, J.L. Arana, The effect of ball burnishing on heat-treated steel and Inconel 718 milled surfaces, The International Journal of Advanced Manufacturing Technology 32/9-10 (2007) 958-968.

[6] M.A. Safwan, U. Al-Qawabah, Invistigation of Roller Burnishing on Zamac5 Alloyed by Copper, Journal of Applied Sciences Research 5/10 (2009) 1796-1801.

[7] M.H. El-Axir, An investigation into roller burnishing, International Journal of Machine Tools and Manufacture 40/11 (2000) 1603-1617.

[8] F. Ogburn, Burnishing For Improved Part Quality And Lower Costs, Production Machining, Cogs dill Tool Products, Inc., 2004.

[9] T.A. El-Taweel, M.H. El-Axir, Analysis and optimization of the ball burnishing process through the Taguchi technique, The International Journal of Advanced Manufacturing Technology 41/3-4 (2009) 301-310.

[10] U. Al-Qawabeha, A.E. Al-Rawajfeh, E. Al-Shamaileh, Influence of roller burnishing on surface properties and corrosion resistance in steel, Anti-Corrosion Methods and Materials 56/5 (2009) 261-265.

[11] C. Gardin, S. Courtin, D. Bertheau, G. Bézine, H. Ben Hadj-Hamouda, The influence of roller burnishing on the fatigue crack propagation in notched round bars—Experimental observations under three-point bending, Fatigue & Fracture of Engineering Materials & Structures 30/4 (2007) 342-350.

[12] E.M. Rubio, A.M. Camacho, J.M. Sánchez-Sola, M. Marcos, Chip arrangement in the dry cutting of aluminum alloys, Journal of Achievements in Materials and Manufacturing Engineering 16 (2006) 164-170.

[13] J. Hua, D. Umbrello, R. Shivpuri, Investigation of cutting conditions and cutting edge preparations for enhanced compressive subsurface residual stress in the hard turning of bearing steel, Journal of Materials Processing Technology 171 (2006) 180-187.

[14] V. Savas, C. Ozay, Analysis of the surface roughness of tangential turn-milling for machining with end milling cutter, Journal of Materials Processing Technology 186/1-3 (2007) 279-283.

[15] S. Kalpakjian, S.R. Schmid, Manufacturing Processes for Engineering Materials. Pearson Education, ISBN 8178089904, OCLC 66275970, 2003, 152.

[16] Roller Burnishing Technology, Yamasa, http://www.yamasa.com.tr, last access 01/09.

[17] S. Thamizhmnaii, B. Bin Omar, S. Saparudin, S. Hasan, Surface roughness investigation and hardness by burnishing on titanium alloy, Journal of Achievements in Materials and Manufacturing Engineering 28/2 (2008) 139-142.

[18] M. Nemat, A.C. Lyons, An investigation of the surface topography of ball burnished mild steel and aluminium, International Journal of Advanced Manufacturing Technology 16 (2001) 469-473.