Magnetic abrasive finishing of rotational symmetrical bodies: actual experimental results

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Abstract

Article focuses on authors actual experimental research results regarding magnetic abrasive finishing (MAF) of rotational symmetrical bodies in order to develop unconventional automatised production of X-ray optics. Except for opening technological principles description article consists of description of factors having influence on final workpiece quality, screening experiment methodology, experiment execution, evaluation (ANOVA, Pareto) and in particular interpretation of the results. Analytical results of screening experiment are then confirmed by verification experiment. For variability definition and reproducibility declaration is then proceeded and evaluated replication of one of screening experiments treatment.

Keywords: Magnetic Abrasive Finishing; screening experiment; Plackett-Burman model

1. Introduction

X-ray devices conceived with X-ray optics offers far wider functionalities than those without such optics. These are for example more economical usage of total radiant flux of X-ray source, adjustment of spectral composition of radiation and others. For the new generation of smaller and energy saving X-ray devices for nondestructive X-ray metrology or microscopy is such optic simply a must have. Reverse side of contemporary implementation are high production costs and difficult availability of these optics.

Production of these can be accomplished in two ways, whereas has to be kept on mind, that one of basal characteristic of X-ray optics is a cavity-like form. First possible way of production is direct polishing of final product – this one consists of technologically more challenging inner surface polishing. Second way is a replication technology, which can be splitted into two production phases – first of all negative optical surface (so-called mandrel) is produced, consequently particular layers of final optics are subsequently deposited through galvanoplastic deposition on mandrels surface. Mandrel production is achieved by technologically easier outer surface polishing. Production through galvanoplastic deposition enables special layers deposition (these influence final optics functionality) and especially (compared to conventional production) attainment of thin-walled, thus less voluminous and lighter product. Main added value lies in possibility of multiple use of mandrel. [1] Influence of production technology on price, and also research motivation, is obvious.

Final optics properties are close-knitted with final surface quality of the mandrel, for mandrels negative surface is in the course of galvanoplastic deposition perfectly transferred in the surface of the optic. Such transfer means not only surface roughness, but also all surface defects such as microcracks. Magnetic abrasive finishing was chosen just with regard to such property, because in comparsion with for example honing, MAF acquires up to six order lesser pressure on workpiece (approx.7 Pa), thereby surface defects occurence is being minimized. [2]

2. Technological principles

Magnetic abrasive finishing is based on electromechanical reaction of polishing suspension in magnetic field. In working gap is between workpiece and magnetic poles of coils created magnetic field and then the ferromagnetic polishing suspension is inserted in. Owing to magnetic field is then created nonuniform multi-point polishing tool, which embodies diminutive pressure on the surface of the workpiece – such tool is called the Flexible Magnetic Abrasive Brush (FMAB). Polishing is acquired through relative motion of FMAB against the workpiece. Firmness and density of this tool can be driven by coil amperage. [3]

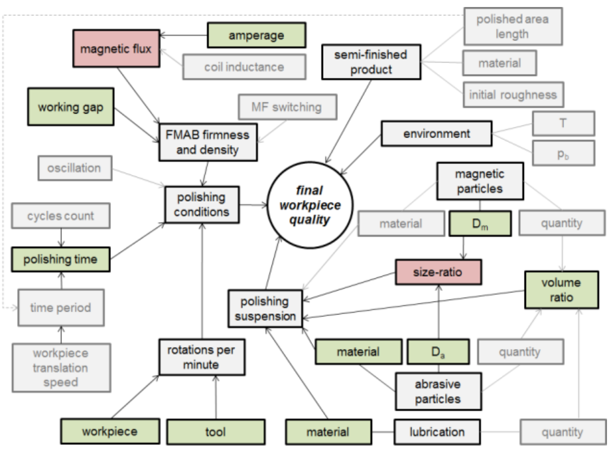

Fig. 1. *Polishing process parameters diagram.*

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Polishing process parameters diagram (Fig. 1) depicts parameters, which have influence on final workpiece quality. Parameters are divided into logical groups, relative dependencies and their volume are distinguished with colors. Green labeled factors are independent (final chosen experimental factors), red factors are dependent and grey ones are stationary or (due to construction reasons) unrealizable. Diagram shows not only complexity of polishing conditions, but also complexity of polishing suspension due to wide extent of properties (material combination, sizes of particle fractions, chemical or mechanical attachment etc.).

3. Experimental design

Experimental methodology goes out of two level linear Plackett-Burman screening experiment design. Purpose of such experiment is separation of factors having major influence on the response. Experimental design consists of twelve treatments without replication with a priori presumed neglectable interactions effect. Particular independent factors are (for evaluation purposes) labeled with their substituents in following order: amperage (A), working gap between tool and workpiece (B), polishing time (C), tool (D) and workpiece (E) rotations per minute, type of abrasive particles (F), magnetic and abrasive particles volume ratio (G), lubricant (H) and fraction size of magnetic (I) and abrasive (J) particles.

Table 1. *Plackett-Burman experimental design. [4]*

	factor									
treatment	A	B	C	D	E	F	G	H	I	J
1	1	1	1	1	1	1	1	1	1	1
2	-1	1	-1	1	1	1	-1	-1	-1	1
3	-1	-1	1	-1	1	1	1	-1	-1	-1
4	1	-1	-1	1	-1	1	1	1	-1	-1
5	-1	1	-1	-1	1	-1	1	1	1	-1
6	-1	-1	1	-1	-1	1	-1	1	1	1
7	-1	-1	-1	1	-1	-1	1	-1	1	1
8	1	-1	-1	-1	1	-1	-1	1	-1	1
9	1	1	-1	-1	-1	1	-1	-1	1	-1
10	1	1	1	-1	-1	-1	1	-1	-1	1
11	-1	1	1	1	-1	-1	-1	1	-1	-1
12	1	-1	1	1	1	-1	-1	-1	1	-1

These factors are in particular levels considered in following values:

Table 2. *Particular level value assignment.*

factor		A [A]	B [mm]	C [min]	D [rpm]	E [rpm]
level	1	1	2	5	250	250
	-1	2	3	10	500	500

factor		F	G	H	I	J	
						F = 1	F = -1
level	1	Al_2O_3	1:1	H_2O	S070	F100	B134
	-1	SiO_2	1:2	C_3H_8	S170	F40	B9

4. Actual experimental results

Statistical evaluation results from second set of average measured roughness values on the workpiece. With regard to initial surface roughness ($\bar{A}$) tolerance higher than $\pm$ 1% (which means big confidence interval) is evaluation of resulting surface roughness ($\bar{Y}$) replaced by evaluation of relative surface roughness values (ΔRa). Measurements were done with calibrated tangent roughness checker Taylor Hobson Surtronic 25 in resolution of 0,01μm with accuracy of ± 2%.

Table 3. *Average measured roughness values (Ra).*

treatment	1	2	3	4	5	6
$\bar{A}$ [μm]	1,513	1,507	1,553	1,527	1,58	1,513
$\bar{Y}$ [μm]	1,56	0,953	0,933	1,247	0,94	1,627
ΔRa [nm]	-46,7	553,3	620	280	640	-113

treatment	7	8	9	10	11	12
$\bar{A}$ [μm]	1,553	1,507	1,54	1,62	1,62	1,547
$\bar{Y}$ [μm]	1,26	1,22	0,947	1,133	1,253	1,207
ΔRa [nm]	293,3	286,7	593,3	486,7	366,7	340

Analysis of variance (null hypotesis H_0: $p < 0,05$ affirmation) discovered three statistical significant factors – lubricant, size of abrasive particles and polishing time (Fig. 2 - marked red).

ANOVA; Var.:Y; R-sqr=,99932; Adj:,99253 (screening_2,4-4_DRa)
10 Factor Screening Design; MS Residual=448,1526
DV: Y

Factor	SS	df	MS	F	p
(1)A	14700,0	1	14700,0	32,8013	0,110047
(2)B	65514,8	1	65514,8	146,1885	0,052533
(3)C	82225,7	1	82225,7	183,4769	0,046914
(4)D	44003,8	1	44003,8	98,1894	0,064029
(5)E	19737,0	1	19737,0	44,0408	0,095213
(6)F	23114,9	1	23114,9	51,5782	0,088077
(7)G	5070,4	1	5070,4	11,3139	0,183969
(8)H	180892,2	1	180892,2	403,6397	0,031661
(9)I	65515,0	1	65515,0	146,1890	0,052533
(10)J	158699,9	1	158699,9	354,1203	0,033798
Error	448,2	1	448,2		
Total SS	659921,7	11			

Fig. 2. *Analysis of variance (ANOVA).*

Resulting effects order of particular factors can be identified both from analysis of variance results (Fisher test – the higher F value, the bigger expected factor effect) and standardized Pareto chart. Resulting effects order of particular factors matches.

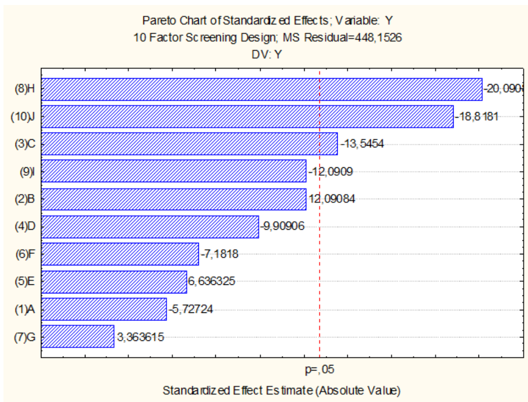

Fig. 3. *Standardized Pareto chart.*

Pareto chart (Fig. 3) depicts null hypotesis outline by red dashed line and also enables identification of optimal level setting of particular factors, which should allow accomplishment of best possible results in given setting. Obtained results can also be derived from other statistical tools (normal distribution chart, vector graphs and others), but their detailed citation would be redundant.

Table 4. *Optimal level setting.*

factor	A	B	C	D	E	F	G	H	I	J
optimal level	-1	1	-1	-1	1	-1	1	-1	-1	-1

Mentioned optimal level combination was validated by verification treatment, which enabled obtaining of hitherto best resulting average surface roughness of $\bar{Y} = 0{,}88\mu m$ Ra and highest average stock removal of $\Delta Ra = 666{,}7nm$.

Variability definition and reproducibility declaration (compliance with particular factor setting) was checked by replication of one screening experiment treatment (random chosen no. 7). Compliance with respective settings should provide equal results in all treatments (no. 7a-7d).

Table 5. *Reproduced treatment results.*

treatment	7	7a	7b	7c	7d
Ā [μm]	1,553	1,653	1,607	1,56	1,573
Ȳ [μm]	0,94	1,06	1,02	0,96	0,967
ΔRa [nm]	613,333	593,333	586,667	600	606,667

Evaluated are (again) relative average roughness values ΔRa, which embodies resulting values 600nm ± 2,2%.

4. Conclusion

Affirmation of null hypotesis H_0: $p < 0{,}05$ of analysis of variance discovered three statistical significant factors – lubricant, size of abrasive particles and polishing time. These three should be in focus of following experiments. Experimental resolution can be considered as sufficient.

Resulting optimal level combination of particular factors was validated by verification treatment, which enabled obtaining of hitherto best resulting average surface roughness of $\bar{Y} = 0{,}88\mu m$ Ra and highest average stock removal of $\Delta Ra = 666{,}7nm$. Verification of analytical conclusion of screening experiment was successfully accomplished.

At last was evaluated reproducibility – experimental treatments returned resulting average roughness values 600nm ± 2,2%. Such result fluctuation can be marked as minor and the method can be stated as reproducible on used polishing machine.

Was demonstrated, that MAF technology can be used in such matter. Following experiment will focus on surfaces with boldly lower initial surface roughness. Assuming positive results can be said, that such technology can not only obtain superfine surface roughness of rotational symmetrical bodies, but through proper factor alternation cover whole production process.

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Nomenclature and Abbreviations

$\bar{A}$	average initial surface roughness (μm)
Al_2O_3	aluminium oxide (corundum)
B9	ballotine fraction (size 0,3-0,4mm)
B134	ballotine fraction (size 0,1-0,2mm)
$C_3H_8O_3$	glycerol
D_a	abrasive particle size
D_m	magnetic particle size
F40	corundum fraction (size 0,3-0,6mm)
F100	corundum fraction (size 0,09-0,2mm)
H_2O	water
MF	magnetic field
p_b	barometric pressure (hPa)
S070	steel shot fraction (size 0,15-0,45mm)
S170	steel shot fraction (size 0,4-0,85mm)
SiO_2	silicon dioxide (ballotine)
T	temperature (°C)
$\bar{Y}$	average resulting surface roughness (μm)
ΔRa	average stock removal (nm)

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