Robust development of a CNC turning process

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Abstract. The article presents an optimization study developed on a CNC HSM center for the external turning of spheroidal graphite iron precision mechanics parts. For isolating as much as possible the thermal error effects on the machining accuracy study, there were developed studies for statistically controlling the machining process and for mastering the measuring process, also. For assessing the process there were measured the dimensional critical quality characteristics. As analytical tools, were designed experiments applying the Taguchi Method, and the results are analyzed with ANOM method.

1 Introduction

The cutting processes are a base technology, despite of the new trends in manufacturing, as it is the additive manufacturing concept. Even if the cutting technologies are generally considered matured (especially within the industrial field), there is enough room for optimizations taking account of the developments trends: cutting machines with increased dynamics, optimized or new cutting tools materials and geometries, new materials to be machined, etc.

In this context, the current study presents an optimization research for improving the turning process in a real industrial environment case.

The paper is organized in the following manner. An overview of the parameter design based on the Taguchi method is given first. Then, the parameter design with the characteristics is introduced. The experimental detail of using the parameter design to determine and analyze the optimal cutting parameters in turning operations is described next. Finally, the paper concludes with a summary of this study.

2 Robust engineering by Taguchi Method

2.1 The concept of Robust Engineering / Taguchi Method

The Robust Engineering approach, as an innovative concept applied through the Taguchi Method, can be used for the optimization of the industrial processes starting with the earliest product and process development lifecycle phases.

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Generally, within the organizational management, product development is considered a major tactic for profitability. It consists of the following two aspects [1]:

- (1) Product quality: what consumers desire (functions or appearance);
- (2) Engineering quality: what consumers do not want (functional variability, running cost, pollution).

The manufacturing process must take in considerations the aspects regarding the product development, and, for achieving these goals, it can be designed in an optimal manner using the Robust Engineering.

Quality engineering is robust design based on the following three procedures:

- (1) Orthogonal array,
- (2) SN ratio, and
- (3) Loss function.

These three procedures are not robust design per se because they are used to evaluate technical means, products or processes. To design robustness, it is required to understand the meaning of robust design before considering technical or management means [1]. Those who consider practical means are engineers and production people.

Robust design (including product and process design) generally means designing a product that can function properly under various conditions of use or a process that is non-sensitive at the noise (see the Fig. 1 and Fig. 2) [2]. The noise factors being external controllable or not controllable factors.

The objective of the parameter design is to optimize the settings of the process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values.

In addition, it is expected that the optimal process parameter values obtained from the parameter design are insensitive to the variation of environmental conditions and other noise factors. Therefore, the parameter design is the key step in the Taguchi method to achieving high quality without increasing cost.

Fig. 1. The generic Parameter Diagram for the non-robust processes.

Fig. 2. The generic Parameter Diagram for the robust processes.

2.2 State-of-the-art of using Robust Engineering on CNC turning process optimization

Dedicated state – of – the art literature present extensive approaches regarding the methods used for optimization of the cutting process. Therefore, the [3] reference present researches regarding the next techniques for the optimization of industrial processes:

- (1) Lagrange’s method;
- (2) Geometric programming;
- (3) Goal programming;
- (4) Dynamic programming;
- (5) Fuzzy logic;
- (6) Genetic algorithm;
- (7) Scatter search;
- (8) Taguchi method;
- (9) Response surface methodology.

The Robust Engineering is becoming more and more used for the optimization of the manufacturing by cutting processes, too. One of the most used cutting process within the worldwide manufacturing industry is the turning process, a relatively simple operation but that continues to need applied research especially because of the cutting high performance dynamics, workpiece materials and cutting tools. Therefore, within the Table 1 it is presented a brief state of the art containing some studies on the same argument, treated within this paper.

Table 1. State of the art of several researches regarding the use of Taguchi Method on optimization of turning operation.

Reference	Optimizati on method	Optimization criteria	Optimization parameters	Part’s material	Factorial lattice	Data analysis
[4]	Hybrid: Taguchi Method& Differential evolution algorithm	Unit cost	Cutting parameters:cut ting speed, cutting feed, cutting depth	Metal	L ₁₆ 5 ⁴	SNR(STB)& ANOVA
[5]	Hybrid: Taguchi Method &Grey relational analysis	Surface quality: R _a andR _t roughness and circularity	Cutting parameters: cutting speed, cutting feed, cutting depth & cutting fluid	high carbon high chromium alloy tool steel	L ₉ 3 ⁴	SNR(STB)& ANOVA
[6]	Taguchi Method	Ra roughness, cutting force, cutting tool wear	Cutting parameters: cutting speed, cutting feed	nitrogen alloyed duplex stainless steel DSS ASTM A 995 grade 5A and grade 4A	L ₉ 2 ³	SN (STB)& ANOVA

[7]	Taguchi Method	Surface roughness R_a	Cutting parameters: cutting speed, cutting feed, cutting depth & cutting tool material	High-alloy white cast iron (Ni-Hard) at two different hardness levels (50 HRC and 62 HRC)	$L_{18} 4^3$ (2 levels for cutting tool material)	SNR(STB) & ANOVA
[8]	Taguchi Method & RSM	Surface roughness R_a and R_z	Cutting parameters: cutting speed, cutting feed, cutting depth	AISI 304 austenitic stainless	$L_{27} 3^3$	SNR (STB) & ANOVA and RSM with regression analysis
[9]	Taguchi Method	Surface roughness R_a and R_z and flank wear (VB)	Cutting parameters: cutting speed, feed rate and depth of cut	Hardened AISI 4140 (51 HRC)	$L_9 3^3$	SNR & ANOVA
[10]	Taguchi dynamic approach coupled with a proposed ideal function model	Dimensional precision and accuracy and the surface roughness R_a	Coolant, cutting speed, feed, depth of cut, coating type, chip-breaker geometry, nose radius and shape of the insert	A range of steels	$L_{18} 2^1 \times 3^7$	SNR & ANOVA
[11]	Taguchi Method	Surface roughness (R_a)	Insert radius, feed rate, and depth of cut	AISI 1030 steel bars	$L_9 3^3$	SNR & ANOVA
[12]	Taguchi Method	Surface roughness (R_a), tool wear, power consumption and chip reduction co-efficient	Cutting speed, feed rate and depth of cut	Hard metal	$L_9 3^3$	SNR & ANOVA, multiple regression analysis

2.3 The design of the experiment

2.3.1 The process to be optimized

The process to be optimized is a turning process of a cast iron part (a forged shaft used in a mechanical mechanism), on a high performance CNC turning machine. Because the part is a precision part, it is very important to master the dimensional accuracy at different levels. For that scope, it was studied the influence of the two main cutting parameters on the external diameter accuracy, at different temperature measurement levels. It is very well known that the cutting process it is developed with heat generation and propagation as a gradient within

the part’s material, also. That temperature gradient changes the dimensional accuracy within the time. For underlining and researching this phenomenon, the external diameters were measured at 2 temperatures. The first diameter measurement was developed at the moment of machining, when the part is discharged automatically from the chuck (at 33,5°C), and the second diameter measurement was measured at after several hours, after the coldness of the part, within the metrological laboratory environment (at 21,4 °C). The part’s superficial temperature was measured with an infrared pyrometer.

The material machined is a continuously cast spheroidal graphite iron EN (-1563)-GJS-500-7 (GGG50). This kind of spheroidal graphite offers higher wear resistance, strength & heat-treatment response compared to other materials while still possessing good machinability and excellent surface finishes. Noise and vibration damping are good in this grade. For further detailed data regarding the material, within the Table 2 and the Table 3 there are presented another properties.

Table 2. Chemistry(Typical Ranges) (Subordinate to Mechanical Properties) [13].

Element	Car bon	Silic on	Manga nese	Sulphur	Phosph orous	Magnes ium	Others / Alloyin g	Iron
Typical values	3.25 – 3.70	2.40 – 3.00	0.10 – 0.30	0.005 – 0.020	0.015 – 0.08	0.04 – 0.07	Residual	Balance

Table 3. Mechanical Properties (Anticipated Values) [13].

EN-GJS 500-7:1997 (GGG40)	Tensile strength UTS N/mm2	0.2% Proof Stress N/mm2	Elongation %
25mm – 50mm	500	320	7
55mm – 100mm	450	300	7
105mm – 200mm	420	290	5
205mm – 600mm +	420	290	5
Another characteristics:			
- Brinell Hardness 170 ... 230			
- Microstructure - Contains Type I & II nodular (spheroidal) graphite in accordance with ASTM A247. The rim contains approximately 200/250 nodules/ mm2, and is predominately ferritic with the core containing 90/150 nodules/mm2. The core matrix is mixed ferritic/pearlitic (10–50% pearlite). Chill carbides will be less than 5%, well dispersed.			
- Heat Treat Response - EN-GJS-500-7 can be hardened by conventional methods but EN-GJS 600-3 is recommended.			
- Density - 7.3 g/cc

Fig. 3. The cutting insert used (DNMG 110404 MF 1105) for the turning process and the cutting data recommended ranges [14].

The turning process is developed with a DNMG 11 04 04-MF 1105 cutting insert, with corner radius (R_E) of 0.3969 mm and made of a carbide that is grade 1105, coated by PVD with Aluminum oxide (Fig. 3). According with the same Fig. 3, the feed is recommended to be in the range 0.05 ... 0.2 mm / rot and the cutting speed is recommended to be adopted in the rage 80 ... 70 m /min.

The cutting tool wear was not took in consideration because the entire experiment was developed within the prescript range and the level of machining constituted by the 25 test parts does not influence on the wear.

Fig. 4.The machine tool used for the experimentation [15].

Nakamura Super NTX is a CNC machine tool with twin spindle and twin turret. The used configuration can hold 24 tools on stock, the main spindle (for milling) turret can arrive at up to 8000 rot / min and the indexing range is on 230 degree (± 115 degrees). The left and right spindles (for turning) can arrive up to 4500 rot/min. The turrets can arrive at 3600 rot / min for each of the 12 individual rotation tools stations from the total of 24 tools [15]. The forged workpiece initial diameter was 12 ± 0.4 mm and the final turned nominal diameter is 10.9 ± 0.1 mm. Therefore, the radial cutting depth is 0.55 mm.

2.3.2 The process parameters and DoE

Very accurate prescriptions for the cutting data it was not available for that particular application. Therefore, starting from the cutting tool producer’s prescriptions (Fig. 3) there were considered 5 levels for the cutting speed parameter and 5 levels for the cutting feed parameter. The machine tool is a Nakamura high performance turning and milling HSM CNC (Fig.4).

As experimental matrix, it was selected an $L_{25}2^5$ fractioned factorial lattice. That means that the 2 experimental factors are variated at five levels each one, and the entire fractionated factorial design has 25 trials (Table4).

Table 4. The DoE - $L_{25}2^5$ fractioned factorial lattice and the correspondent parameter setup.

Run order	Level of cutting speed	v_c	RPM	Level of cutting feed	f
		[m/min]	[rot/min]		[mm/rot]
1	1	70,0	1857,7	5	0,2000

2	2	72,5	1924,1	4	0,1625
3	5	80,0	2123,1	2	0,0875
4	4	77,5	2056,8	4	0,1625
5	1	70,0	1857,7	4	0,1625
6	5	80,0	2123,1	3	0,1250
7	5	80,0	2123,1	4	0,1625
8	2	72,5	1924,1	2	0,0875
9	1	70,0	1857,7	1	0,0500
10	4	77,5	2056,8	5	0,2000
11	2	72,5	1924,1	5	0,2000
12	5	80,0	2123,1	1	0,0500
13	3	75,0	1990,4	1	0,0500
14	4	77,5	2056,8	2	0,0875
15	5	80,0	2123,1	5	0,2000
16	3	75,0	1990,4	4	0,1625
17	1	70,0	1857,7	3	0,1250
18	3	75,0	1990,4	2	0,0875
19	1	70,0	1857,7	2	0,0875
20	2	72,5	1924,1	3	0,1250
21	3	75,0	1990,4	3	0,1250
22	3	75,0	1990,4	5	0,2000
23	2	72,5	1924,1	1	0,0500
24	4	77,5	2056,8	3	0,1250
25	4	77,5	2056,8	1	0,0500

Fig. 5. The measurement of the external shift diameter (workshop and laboratory environment).

2.3.3 The metrological validation of the gage used for measuring

The measurement system used is a QuantuMike Mitutoyo micrometer (Fig. 5), IP 65 Coolant Proof wired directly at a PC station with MeasurLink version 7.4.10 full configuration [16].

An important moment for the measuring process is the measurement instrument and process metrological validation, done by applying the GRR methodology (Fig. 6). The overall GRR index has the value of 2.7% and the number of the distinct categories is 8, fact that validate the measuring process (the repeatability, reproducibility and the resolution are appropriate for that particular case).

Fig. 6. Gage Repeatability and Reproducibility study results.

3 Results, data analysis and conclusions

3.1 Experimental results, the data analysis and conclusions

The 25 machined parts were measured at 2 different material temperatures and the final results are presented graphically analyzed by ANOM (see Fig. 7, Fig. 8 and Fig. 9).

The Fig.7 presents the analysis of means (ANOM) of the influence on the test piece external diameter measured immediately after being machined (at a material temperature of 33,5°C). Therefore, there are presented the influence on the specified characteristic of the “A” factor (cutting speed) and the “B” factor (cutting feed). For each factor, by ANOM, there are computed the means of the values for each one of the 5 experimental levels of the researched parameters. With dotted line it is represented the mean of means.

The Fig. 8 represents an ANOM graphic obtained by the same approach as the one from Fig. 7, but it is for the measurements obtained by measuring the test parts in laboratory

environment, after that the parts material arrived at 21,4 °C (after 15 hours of thermal stabilization in an ambient temperature of 20,0 °C).

Fig. 7. ANOM for the measurements of the external shift diameter (workshop environment).

Fig. 8. ANOM for the measurements of the external shift diameter (laboratory environment).

Fig. 9. ANOM for the range of the dilatation / contraction of the external shift diameter (workshop and laboratory environment).

According with Fig. 7 and Fig. 8, the general trend for the external diameter is to decrease once the cutting speed (“A” parameter) is increasing. The phenomenon is considered to be validated by theory knowing that the heat gradient is growing in intensity once the cutting speed increases. The dilatation of the cutting tool system and of the part’s material generate that decrease of part’s external diameter. The same trend is underlined by the measurements developed within the laboratory environment.

According with the same Fig. 7 and Fig. 8, the influence of the raise of the cutting feed (“B” parameter) present an inflexion point at the third level of the experimental parameter. Also, it can be observed by comparing the two graphics that the influence of the two researched parameters on the diameter’s variation range is a little bit higher for the cutting feed case than of the cutting speed case.

Also, it can be observed that the level of influence on the external diameter of the two experimental parameters range is practically the same (approximately 6 μm), by comparing the diameters measured before and after contraction.

The final remarks can be extracted from the Fig. 9 that present the dilatation / contraction range. Therefore, the best cutting process setup would be at the first levels of the two parameters: $v_c = 70 \text{ m / min}$ and $s = 0,05 \text{ mm / rot}$. Because of economic reasons, it can be considered to be better to higher the level of two parameters, reason for which it can be choose their third levels $v_c = 75 \text{ m / min}$ and $f = 0,125 \text{ mm / rot}$. To continue the compromise by gaining more productivity and losing some accuracy, it can be choose the fifth levels $v_c = 80 \text{ m / min}$ and $f = 0,2 \text{ mm / rot}$.

The results were took in consideration for the next batch of pieces and the optimization was, in that manner, confirmed. The surface quality (dimensional and roughness) was measured and the results were according with the customer’s requirements.

3.2 Future development

As future developments, it is interesting to take in consideration the roughness quality characteristic for a simultaneous optimization of the turning process. Also, it may be opportune the change of the tool’s insert grade and taking this parameter in consideration as a distinctive experimental parameter within the factorial lattice, for future optimization developments.

The measurements realized in the present research were made using the infrastructure of the”Mitutoyo Metrology Laboratory” from the ” Institute High Tech Products for Sustainable Development: PRO-DD” of “Transilvania” University of Brasov, laboratory created with the contribution of Mitutoyo Romania S.R.L.

Table 5.Abbreviations.

Abbreviation	Meaning
PVD	Physical Vapor Deposition
DoE	Design of Experiments
HSM	High Speed Machining
CNC	Computer Numerically Controlled
L _a b ^c	Lattice with a runs for b factors variated at c levels
SNR	Signal to Noise Ratio
STB	Smaller The Best (Better)
ANOVA	ANalysis Of VARIation
ANOM	ANalysis Of Means
IP	Instrument Protection
GRR	Gage Repeatability and Reproducibility
Xbar / R	Average and Range

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