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THE INFLUENCE OF CUTTING MILLING PARAMETERS ON SURFACE ROUGHNESS FOR PRETREATED MOLD STEELS

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Abstract: *The main objective of this paper is to experimentally analysis the influence of the 3d milling cutting parameters on the surface roughness for the new pretreated material 1.2714HH used in the execution of the active parts (injection cavities) for the injection molds. The main advantage of the 1.2714 HH steel is the increased hardness (39-45 HRC) by approximately 10 HRC units compared to 1.2312 (29-34 HRC). The experimental analysis has as its starting point the pretreated steel 1.2312, a steel widely used and analyzed in the execution of the active parts of plastic injection molds. Based on the resulting experimental data, at identical milling parameters, the difference in hardness of the 2 materials (10 HRC units) did not drastically influence the surface roughness. The stepover (width of cut) ae[mm] have an important influence on the surface roughness also for the same material, but also for the both types of pretreated steels.*

Key words: *milling cutting parameters, injection molds, surface roughness, pre-treated steel.*

1. INTRODUCTION

Plastic injection process is a very well-developed market with continuous and constant growth worldwide, in almost all industrial areas. From household, electronics to high-end areas (automotive, medical and aeronautical), injection molded parts are increasingly finding their usefulness. According to the European Council of Vinyl Manufacturers (ECVM) there are about 1000 components in a vehicle, weighing from several hundred kilograms to several thousand, and the weight of plastic parts is 150-200 kg and the tendency is to reach at 350 kg [1].

In the future to be able to reduce the weight of cars and reduce consumption (electric or fossil). Especially in the case of electric cars (actual trend), a drastic reduction in weight is required because according to analyzes the average mass of electric cars is 1940 Kg [2].

Starting from these realities and trends, the manufacturers of plastic injection molds are in a continuous competition regarding the reduction of production times for injection mold, as well as a good quality and durability of the executed product.

For an optimal choice of the steel used in the execution of the active zones (the cavity where the plastic material is injected), as well as other active components from the injection molds, the mold manufacturers must take into account a series of steel properties, such as: good machinability, dimensional stability and wear resistance, good thermal conductivity as well as good polishing behavior, but also possibilities for subsequent treatment (etching, nitriding, etc.).

The hardness of the steel is the most important point when choosing the steel for injection cavities (active zones) and components for injection molds and die casting molds. Depending on the plastic material injected (thermoplastic or thermoset), but also on the number of injection cycles (tool life) desired with the respective mold, a series of materials can be chosen as follows:

- Prototype molds - materials with 150-195 HB, aluminum 7075 or steel 1.1730.
- Molds with medium working life: pretreated steels, materials with hardness 280-325 HB:

1.2311-1.2311-1.2312; 1.2738; 1.2083; 1.2316.

- Molds with a long working life: steels that will be quality at high hardness (50-65HRC): 1.2343-1.2344; 1.2379.

To increase the life time of an injection mold, but also to reduce the execution time of a mold, steel manufacturers continue to bring new materials to the market, pretreated steels with high hardness without the need for subsequent heat treatment. By using a hardened steel with a high hardness, the subsequent heat treatment process is removed to increase the hardness and durability of the mold and, last but not least, it reduces the processing time of the components. One of these steels is 55NiCrMoV7 (1.2714 HH). Depending on the steel manufacturer, it can reach a hardness of up to 45 HRC (421 HB or 446 HV equivalent).

According to FALLBÖHMER [3], the largest consumer market of injection molds is the automotive industry, followed by the electronics and household goods industry.

Taking into account both the evolution of machine tools, which have become machining centers, and the development of cutting tools for machining, the high-speed milling (HSM) operation has proven to be a high-productivity manufacturing process for achieving parts with a high level of precision and a high quality of the machined surface [7].

The milling operation has become the most used machining process and which can be used in at least one manufacturing step in manufacturing industries. This is due to the versatility and flexibility of CNC milling machines. These machining centers allow to reduce the manufacturing times of the parts and ensure an optimal cost vs quality ratio (high roughness). The milling operation with an end ball mill is widely used in the processing industry because it allows the execution of complex geometric surfaces, machined surfaces with controllable precision and a high surface condition [8].

2. LITERATURE REVIEW

An analysis of the most important manufacturing costs for an injection mold and die casting mold, it consists of the following mathematical formula:

$$MP = \text{material} + \text{design} + \text{manufacturing}$$

About 60% of the actual execution cost is given by the manufacturing of the functional parts and the mold cavities [3].

Due to some technological limitations of the milling process as well as the equipment used, the surface resulting from the milling process needs a manual polishing to meet the quality requirement imposed for injected parts. According to - RIGBY [4] and FALLBÖHMER [5], they believe that between 20 - 38% of the labor costs and also the delivery time of the product is deeply influenced by this manual finishing process.

Even so, the cutting parameters are the ones that definitively influence the execution of parts at the required quality and with economic efficiency (high productivity). The optimal choice of these parameters (machining centers, cutting tools and cutting parameters) lead to obtaining the desired results [6].

A special case is the execution of molds for precision injection of lenses made of thermoplastic materials, used in lighting systems in the automotive industry (headlamps, rear lens, DRL – Daytime running lamp, CHSML – Center High Mounted Stop Lamp and interior lighting). A lens is a component made of a transparent material (glass, plastic, etc.), with two opposing surfaces, generally curved, used alone or with other similar parts to focus or diverge light and form images of objects. Lenses are based on the phenomenon of light refraction, i.e., changing the direction of propagation of the passage from one transparent medium to another. Due to the advantages related to the execution of complex shapes as well as the production costs (injection), the use of plastic lenses becomes a very important alternative for glass lenses.

As can be seen from above the key factor for these injected products are presents the quality of the injected surfaces, namely the roughness surface.

Worldwide, in addition to the International Organization of Standards (ISO) that regulates the definition of roughness, the companies and associations of manufacturers in the plastics and automotive industry have created their own standards regarding the condition of surfaces roughness, which have been taken over worldwide by companies. These standards are not in contradiction with the ISO standard, they go in parallel and complement the needs of companies in the plastic injection sector and automotive industry.

Automotive mold manufacturers from all over the world use 3 standards regarding the roughness of the mold surfaces, each standard with its own specifics and applications:

- SPI Mold Finish (SPI Surface Finishes) – set by SPI (Society of the Plastic Industry) represents an American standard regarding the condition of processed surface (surface finishing). The standard comprises 12 SPI grades for polished surface: starting with SPI A1 to SPI D3(Ra 0.012 µm Ra 18.00 µm) focus on „FINISH”.

- VDI 3400 texture Standard – refers to the texture surface (process carried out mainly by Electrical Discharge Machining - EDM) set by VDI (Verein Deutscher Ingenieure). The standard covers 12 grades of texture surface: VDI 12 to VDI 45 - focus on „ROUGH” - Mold – Tech injection mold surface texture – refers to the surface (it is mainly processed by chemical etching or laser – based alternation of the mold cavity) set by Standex Engraving Mold – Tech. The standard Mold-Tech provides the most types of texture in the world (over 500,000 textures).

According with the standards Table 1 shows the 12 degrees of surface roughness according to the SPI standard, as well as their correspondence related to Ra and Rz. Also, the relation with the VDI3400 standard where there is correspondence. The typical application and the polishing process for surface roughness can also be observed.

Table 1

Table 1. Mold surface classification SPI vs VDI

Mold Surface Classifications - SPI vs VDI					
SPI	Guide	Typical Application	Roughness Average (µm)	Root Mean Square (µm)	VDI 3400 (CH)
A-1	Grade #3 Diamond	Lens/Mirror	0.012 to 0.025	0.013 to 0.027	-
A-2	Grade #6 Diamond	High Polish	0.025 to 0.05	0.027 to 0.055	-
A-3	Grade #15 Diamond	High Polish	0.05 to 0.10	0.055 to 0.11	0 to 5
B-1	600 Grit Paper	Medium Polish	0.05 to 0.10	0.055 to 0.11	6
B-2	400 Grit Paper	Medium Polish	0.10 to 0.15	0.11 to 0.18	7 to 8
B-3	320 Grit Paper	Medium to Low Polish	0.25	0.27	9 to 10
C-1	600 Stone	Low Polish	0.3	0.33	11 to 12
C-2	400 Stone	Low Polish	-	-	13 to 15
C-3	320 Stone	Low Polish	-	-	16 to 17
D-1	Dry Blast Glass Bead	Satin Finish	-	-	18 to 19
D-2	Dry Blast #240 Oxide	Dull Finish	-	-	20 to 29
D-3	Dry Blast #24 Oxide	Dull Finish	-	-	30 to 45

To be able to identify these standards, sample cards (steel or plastic) can be used.

Figure 1 shows some examples of surface roughness types according to the previously presented standards. Can be see the roughness surface of the injected parts, the quality of the injected mold surface.

a) b) c)

Fig.1. Examples of surface roughness standards
a) SPI b) VDI 3400 c) Mold – Tech

All these dedicated standards have special recommendations for mold manufacturers and for injection companies, which types of steel should be used to obtain the necessary roughness, as well as the types of plastic materials that can be injected.

At the same time, depending on the injected material, certain values used in the design of the molds are recommended, such as the contraction coefficient, the deformation angle as well as the injection temperatures.

3. THE EXPERIMENTAL METHOD

As a way to achieve the proposed objective, two types of pretreated tool steel are used for the experiments to investigate the effect of the technological parameters of milling on surface roughness. Experiments are carried out at the headquarters of S.C. Evopart Solutions S.R.L. in close connection with the Faculty of Mechanics from Timisoara. The first material, 1.2312, will be used for the part named P0 and the second material, 12714 HH will be used for the parts named P1-P2-P3-P4.

Both steels are recommended for the execution of the active zones of the injection molds, sliders or active elements of the injection molds.

The tables below present or analysis of the most important characteristics of the two materials, similarities and differences, as well as recommendations of the steel manufacturers. Tables 2 and 3 present an analysis of the important characteristics of this two materials, similarities and differences, as well as recommendations of the steel manufacturers.

Table 2

Material equivalence according standards

Standard	1.2312	1.2714 HH
DIN	40 CrMnMoS 8-6	55 NiCrMoV 75,85
AFNOR	40 CMD 8.S	55 NCDV 7
AISI	P20 + S	L6

The chemical composition (%) of the 2 pretreated steels used in experimental method can be seen in Table 3.

Table 3

The chemical composition

1.2312 [%]					
C	Si	Mn	Cr	Mo	S
0,40	0,40	1,50	1,90	0,20	0,06
1.2714 HH [%]					
C	Cr	Mo	Ni	V	
0,56	1,10	0,50	1,70	0,10	

Steels show high machinability, good dimensional stability, wear resistance and thermal conductivity suitable for the plastic mass injection process, Table 4. In addition to these characteristics, the materials also have good properties for polishing, grinding or surface treatment(nitriding).

Table 4

Strength and thermal conductivity

Material	Strength [HRC]	Thermal conductivity at 100 °C
1.2312	28-34 HRC	35 W/m K
	(≈ 950 - 1100 N/mm²)	
1.2714 HH	41 - 45 HRC	35 W/m K
	(≈ 1300 - 1450 N/mm²)	

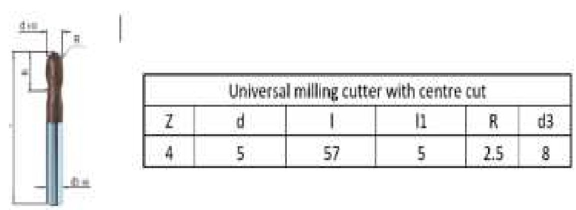
The experimental work was carried out with the experimental machining system and the milling cutter presented in Figure 2. Experimental machining system is a 3-axis CNC milling center HAAS VF2, with maximum spindle rotation 8100 [rpm] and 22,4 KW maximum rating and Max torque 122. Nm@ 2000 rpm. [*1]

Fig.2. The milling machining center used for experiments

Travels:

- X Axis 762 mm
- Y Axis 406 mm
- Z Axis 508 mm
- Spindle Nose to Table (~max) 610 mm
- Spindle Nose to Table (~min) 102 mm

To carry out the experiment was used an end ball mill with a diameter of 5 mm (r=2.5mm), this cutting tool can be named: spherical carbide milling cutter for roughing and finishing, short model (l=57 mm – total length, active length l1=5 mm). The dimensional characteristics and technical information of ball end milling cutter are presented Figure 3, specifying that Z=4 represents the number of teeth. The milling cutter is a dedicated tools made of Carbide, TiAlSiN multi-layer coated [*2].



Universal milling cutter with centre cut					
Z	d	l	l1	R	d3
4	5	57	5	2.5	8

Fig.3. The dimensional characteristics and technical information of ball end milling cutter

The first who analyze and study the milling process with a ball-end mill cutter was Hosoi, he experimentally showed that using this type of cutting tool a spiral cut is made, and this type of cutting leads to a highly productive machining without edge chipping. The studies were continued by others, for example Yang and Park [10] created a force model that could predict and analyze the cutting forces that appear in ball-end milling. They used for this model, an orthogonal cutting theory was applied to the plane of the cutting velocity and the chip velocity at an arbitrary point on the cutting edge.

For this case study, an injection mold was designed for the injection of a product that represents a lens used in the fog lights of vehicles. A main characteristic of this product is the most accurate and correct transmission of the light of the bulb, and consequently the condition of the injected surfaces must have an adequate roughness. In automotive industry this type of surface has a specific name, namely: "Class A surface". The state of the final surface before injection must be polished with 0.3 microns paste, resulting in the resulting roughness after milling being as optimal as possible from the point of view of the polishing and injection process.

The production of free-form optics has a technology that includes prototype design, final design, manufacturing, injection molding, measurements and evaluation (quality and optimal performance functional) [8]. Injection molding is the most widely used process for mass production.

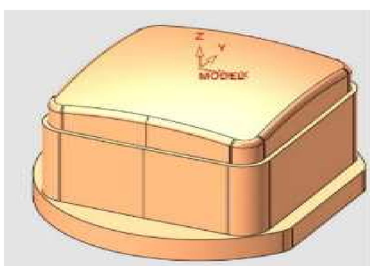


Fig.4. The 3d definitions of core insert

The injection cavities for the injected lens consists of 2 parts: cavity and core. Cavity is the upper half of the injection mold, and most of the time it is the visible part of the finished product (the shape is concave). The lower half of the mold is called Core and is manly convex.

For the case analysis in this paper, only the core inserts were selected for milling, and the experimental analysis taking into account only for upper milling finishing and (Figure 4). The rest of processing being included for future case studies.

Advanced manufacturing technologies are increasingly used due to CAM software's. The NC program was made in a special CAM software, a specific CAM program dedicated to the execution (sperate modules for CAD, CAM and CAE) of molds and dies for the injection, Figure 5.

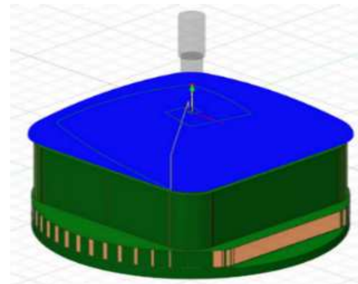


Fig.5. NC program for upper milling finishing

The CAM software used to calculate the tool-path must allow control of 2 parameters:

- Do not deform the topography of the surface. So, must be fixated the parameter of software for the tool-path to a value lower than 2 microns and make sure that the machine includes this parameter.

- For the calculation of the tool-path can´t overpass 4 microns of the surfaces optically sensitive.

The HSM - high speed milling - machine allows better control about minimum steel-shave (0,05 mm.) than the classical milling on CN. In this case, we´ll get the final surface sooner saving polishing time and with a better fidelity and precision [11].

The HSM machine must:

- Compensate vibrations
- Excellent command managing
- Excellent rigidity of milling (part, machine, fixation…) [12].

By using a suitable range of parameters, the pilot experimentations were performed for all 5 inserts core.

The starting point of the case study takes into account the milling parameters recommended by the tool company. To improve the accuracy of the experiment, new milling cutting tool are used for each part.Fig.6 shows the sample parts used in the experiments according with the pre-treated material chosen (insert core P0 – 1.2312 steel and inserts core P1-P2-P3-P4 – 1.2714HH steel).

Fig.6. Working pre-treated steel parts

The experiments are carried out in 2 stages:

- First stage – one identical set of cutting parameters are used for P0 and P1.

- Second stage – different sets of cutting parameters are used for P2-P3-P4.

On overview of the milling parameters used in actual case study is given in Table 5.

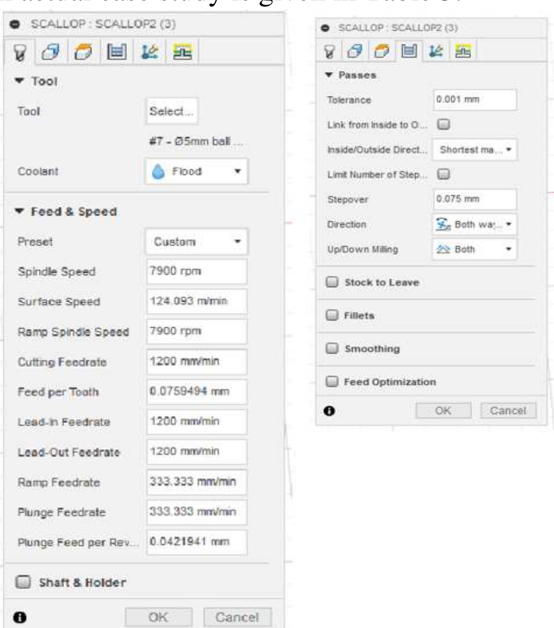


Fig.7. Cutting parameters for upper surface finishing for P3 core insert

Table 5

Cutting parameters of the case study

Cutting parameters/Inserts	P0	P1	P2	P3	P4
Material	1.2312	1.2714 HH	1.2714 HH	1.2714 HH	1.2714 HH
Tolerance [mm]	0.001	0.001	0.001	0.001	0.001
Spindle speed [rpm]	7000	7000	7000	7900	7900
Feed per tooth fz [mm]	0.085	0.085	0.15	0.085	0.15
Feed [mm/min]	1200	1200	1200	1200	1500
ae [mm]	0.075	0.075	0.15	0.075	0.075
ap[mm]	0.1	0.1	0.1	0.1	0.1

In Figure 7 are presented the cutting parameters for upper surface finishing for P3 core insert.

Similar programs are used for the rest of the parts, but with different values for spindle speed [rpm], Feed rate [mm/min], Feed per tooth [mm]) and stepover (radial depth of cut) ae [mm] and also de ap [mm] (axial depth of cut) according with the Table 5. For technological reasons, the rest of the cutting parameters remained unchanged.

For this experimental work, a tester brand “Taylor Hobson” UK made is used for surface roughness (Ra and Rz) measurements as shown in Figure 8.

Fig.8. Taylor Hobson tester

For the measurements of surface roughness (surface finishing) in this case study, the parameters Ra and Rz (DIN 4762, 4768, ISO 4287/1-2. 4288) within the evaluation length was chosen because are simple and the most widely distributed as indicators for surface roughness.

For each machined sample a measurement procedure was applied using 2.4 mm instrument probe movement. The measurement process consists in holding the part in a position that allows the achievement of five measurement points, perpendicular to the direction of the tool's movement. According with the standard for roughness measure the average of these five measurements represents the surface roughness of the respective part.

In Table 6, following the collection of the measured data, the results of the measurements are presented.

Table 6

Surface roughness values

Part	P0					P1					P2				
Ra [μm]	0.48	0.48	0.48	0.46	0.44	0.42	0.44	0.44	0.42	0.42	0.55	0.60	0.62	0.60	0.54
Rz[μm]	2.80	2.70	2.80	2.80	2.70	2.70	2.80	2.70	2.70	2.70	3.40	3.00	3.10	2.90	3.40
Part	**P0**					**P3**					**P4**				
Ra [μm]	0.48	0.48	0.48	0.46	0.44	0.36	0.33	0.32	0.38	0.40	0.44	0.44	0.48	0.48	0.42
Rz[μm]	2.80	2.70	2.80	2.80	2.70	2.10	2.00	2.00	2.30	2.70	2.70	2.80	2.80	2.70	2.50

According to Table 6, the roughness of the resulting surfaces shows that the milling samples with an end ball mill tool help to accurately observe the influence of milling parameters depending on the hardness of the material.

A more detailed analysis of some of these results can be seen in the graphs of Figures 9.

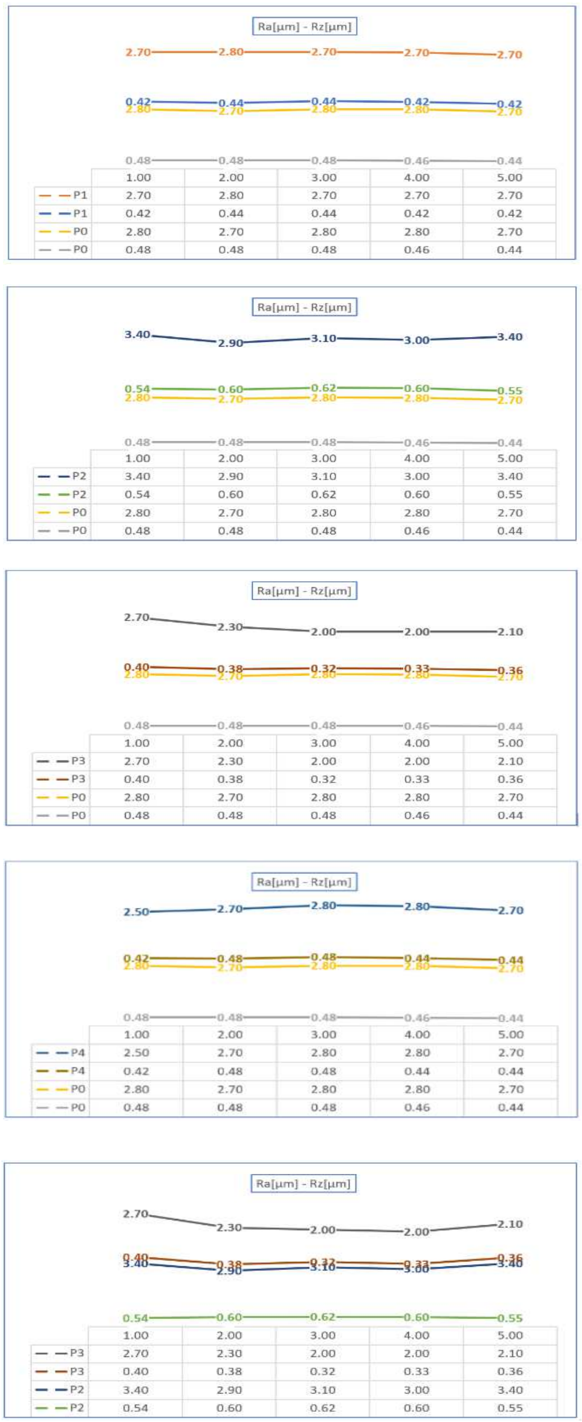


Fig.9. Graphs with Ra and Rz values

The first 4 graphs show the surface roughness ratio in microns between the 1.2714HH core inserts and 1.2312 core insert material. A separate graph was made for each insert, namely:

- Graphic 1 – comparison between P0 - P1,
- Graphic 2 – comparison between P0 - P2,
- Graphic 3 – comparison between P0 - P3,
- Graphic 4 – comparison between P0 - P4.

In the last graph is related the ration for the same material used, 1.2714HH, but with different cutting parameters.

4. CONCLUSION

Based on what exists in the specialized literature regarding the 1.2312 material, but also information from the steel producers, a series of experiments were conducted for the new 1.2714 HH material.

According to the first graph, when the milling parameters were identical, the difference in hardness of the 2 materials (10 HRC units) did not drastically influence the surface roughness. This means that for pretreated steels the milling parameters are relatively similar, with small differences.

According to the second and the last graphs, the stepover ae[mm] have an important influence on the surface roughness also for the same material, but also for the both types of pretreated steels.

In milling process (HSM) several parameters lead to the quality of machined surface. In this paper work for the experiment (a ball-end milling cutter was used), only the following parameters were analyzed: the feed-rate, the stepover, the spindle rate.

According to the results, the stepover parameter (ae) is the one that most influences the surface roughness.

By establishing cutting regimes for this new material, future researchers will have new information and a database.

For future research, other factors and parameters that influence the condition of the machined surface of the material 1.2714 HH will be analyzed.

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Influenta parametrilor de frezare asupra rugozității suprafețelor pentru oteluri de scule pretratate

Principalul obiectiv al acestei lucrări este de a analiza experimental influenta parametrilor de frezare 3d asupra rugozității suprafețelor pentru noul material pretratat 1.2714HH (55 NiCrMoV 75,85) utilizat în execuția părților active ale matrițelor de injecție. Principalul avantaj al otelului 1.2714 HH este duritatea crescuta(41-45 HRC) cu aproximativ 10 unități HRC fata de 1.2312(29-34 HRC). Analiza experimentala are ca punct de plecare otelul pretratat 1.2312,un oțel larg utilizat și analizat în execuția pieselor active ale matrițelor de injecție de plastic. Pe baza datelor experimentale rezultate, la parametrii de frezare identici, diferența de duritate a celor 2 materiale (10 unități HRC) nu a influențat drastic rugozitatea suprafeței. Valoarea parametrului ae[mm] are o influență importantă asupra rugozității suprafeței și pentru același material, dar și pentru ambele tipuri de oțeluri pretratate.

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