Surface Roughness of Hardened Steel Parts Machined with Round Inserts Face Mills

Larysa Ye. Hlembotska, Lubomir V. Dimitrov, Valerii A. Kyrylovych, Oleksandr L. Melnyk, Natalia O. Balytska

Abstract—When machining hardened steels with multi-blade tools, problems arise that have a negative impact on the surface quality and process productivity. This is especially true when finishing flat workpiece surfaces by face milling. The surface roughness, as one of the geometric indicators of surface quality, primarily depends on the shape and geometric parameters of the cutting edges of the mill. The expediency of using round inserts of face mills for machining parts made of hardened steels has been substantiated. New results concerning the quality of machined surfaces were obtained when machining with a face mill with a flat front surface of round inserts and a face mill with a cylindrical front surface of inserts. The influence of cutting modes on the machined surface roughness has been studied, which made it possible to recommend optimal cutting modes for face mills with round inserts according to the criterion of minimum surface roughness. It was found that at the maximum cutting modes, a face mill with cylindrical front surfaces of inserts produced a lower machined surface roughness than a face mill with flat front surfaces of round inserts. At the same time, when machining with a face milling cutter with cylindrical insert fronts, by 1.27 times increase in productivity is achieved.

Index Terms— **cylindrical front surface, face milling, hardened steels, process productivity, surface roughness.**

I. Introduction

In various engineering industries, about 40% of steel used for parts is heat-treated. Hardened steels are difficult-to-machine materials characterised by special physical and mechanical properties (high hardness and specific strength, corrosion resistance, etc.) and low machinability. According to the material classification in [1], hardened steels (HRC>40) are classified as group H, which are used to manufacture critical parts of machines and mechanisms that can withstand significant loads.

Machining of hardened steels is accompanied by significant power stresses and high temperature in the cutting zone, increased wear of the cutting tool, which negatively affects the quality of the machined surface and machining performance [2], [3].

One of the main areas of research in the field of machine and instrumentation engineering is the influence of surface quality indicators of parts on their operational properties (wear resistance, vibration resistance, contact stiffness, joint strength, joint tightness), especially when machining flat precision surfaces that may be mated.

Surface roughness is one of the most important geometric indicators of surface quality and has a significant impact on both the durability and reliability of machines and the cost of manufacturing parts. The finishing of flat surfaces of parts by face milling with roughn[1]ess requirements within Ra=0.63-1.25 μm primarily depends on the geometric parameters and shape of the cutting edge of the cutter inserts [2], [4]-[6], which encourages the improvement of cutter designs.

Given the above, an urgent scientific and technical task is to ensure the required roughness of machined flat surfaces of hardened steel parts with a simultaneous increase in machining performance by improving the design of face mills.

II. Literature Review

Today, face milling is the most common method of machining flat surfaces of parts. At the same time, face milling is accompanied by unevenness of the cutting process, shock loads, vibrations and increased tool wear, high loads on the technological system, which negatively affects the stability of the cutter, the quality of the machined workpiece surfaces and machining performance. This is especially true for machining flat surfaces of hardened steel parts, which places high demands on the process equipment and cutting tools.

The quality of flat surfaces of workpieces during face milling depends on the choice of processed and tool materials, shape and geometric parameters of the tool cutting elements, cutting modes, cutting pattern, rigidity of the technological system, etc. [7], [8].

Increasing the productivity of flat surface machining during face milling can be achieved by increasing the feed rate and/or cutting speed. To increase the cutting speed, it is necessary to use superhard tool materials, which, when used in the design of face milling cutters, significantly increases the cost of machining. In turn, hard alloys are resistant to abrasive wear and can be used for face milling of hardened steels with a hardness of up to 55 HRC, and are also a more economical option. In turn, the intensification of cutting modes also leads to a deterioration in the dynamic state of the technological machining system, which prompts the development of new designs of end mills with the ability to process with increased feeds, ensuring the stability of the cutting process and the required surface quality [5].

These face mills include those with round inserts, which

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L. Hlembotska, V. Kyrylovich, O. Melnyk, N. Balytska are with the Zhytomyr Polytechnic State University, Zhitomir, Ukraine (gle.tmkts@gmail.com, kiril_va@yahoo.com o.l.melnyk@ukr.net, balytskanataliia@gmail.com)
L. Dimitrov is with the Technical University of Sofia, Sofia, 1000, 8 Kl. Ohridski Blvd, Bulgaria (lubomir_dimitrov@tu-sofia.bg)

are versatile and the most commonly used cutting inserts for complex face milling applications. This insert shape is used for machining hard-to-machine materials, including hardened steels, has the strongest cutting edge, can operate at high feeds, provides smooth operation and reusability [6], [9]-[10]. However, many designs of face mills use inserts with flat front surfaces.

At the same time, scientists at the V. Bakul Institute for Superhard Materials of the National Academy of Sciences of Ukraine studied the finishing of hardened steel parts with a tool with a cylindrical front surface of the inserts. Comparative studies were conducted on the effect of the front and rear angles of the tool using flat and cylindrical front surfaces on the roughness of the machined surface [11]. As a result of these studies, the effectiveness of using a cylindrical front surface of the cutters in machining hardened steels, obtaining a low height of micro-irregularities and increasing machining performance by using high feeds was confirmed [11], [12].

In the previous works of the authors [13], a deep systematic analysis of the design and operation of a face mill with round inserts was carried out, which showed the need to develop a new tool. As a result, several design options were proposed, including a stepped arrangement of inserts on the cutter body, inserts with a cylindrical front surface, equal overhang relative to the body, and uniform load distribution on each insert. At the same time, work [5] provides recommendations for selecting rational design parameters of a face mill by modelling the load on the edges of each insert.

Therefore, in continuation of the previous studies by the authors [5], [13], [15], it is advisable to investigate the influence of the shape of the front surface of round inserts of face mills on the roughness of the machined surfaces of hardened steel parts.

Therefore, the aim of this article is to ensure minimum surface roughness of hardened steel parts by improving the design of face mills with round inserts and increasing machining productivity.

To achieve this goal, the following tasks were set:

1) to carry out experimental studies of face milling of flat surfaces of hardened steel parts with cutters with round inserts.

2) to compare the obtained results and determine the optimal cutting modes of face mill with round inserts.

III. Methods

For the experimental studies of face milling, the same machining conditions were selected: cutting modes, tool material, processed material, machined surface width, cutter diameter, number of inserts, and depth of cut.

TABLE I
CHEMICAL COMPOSITION, %

C	0,34–0,42
Si	1-1,4
Mn	0,3–0,6
Ni	up to 0,3
S	up to 0,035
P	up to 0,035
Cr	1,3–1,6
Cu	up to 0,3
Fe	~95

TABLE II
PHYSICO-MECHANICAL PROPERTIES

Hardness	HRC 40–45
Tensile strength σb , MPa	735
Impact strength KCU, kJ/m²	59
Thermal conductivity coefficient I, W/(m*grad)	28…38
Material density ρ, kg/m^3	7640
Specific heat capacity C, J/(kg*grad)	466…663

Experimental studies of machining flat surfaces were performed on a vertical milling machine XL5032. The workpiece is hardened 38CrSi steel to a hardness of 40-45 HRC (chemical composition and physical and mechanical properties are given in Tables 1 and 2). Dimensions of the workpieces: 80×250×80 mm. 38CrSi steel is characterised by high hardness and strength and is used to manufacture parts that operate under high loads and dynamic influences.

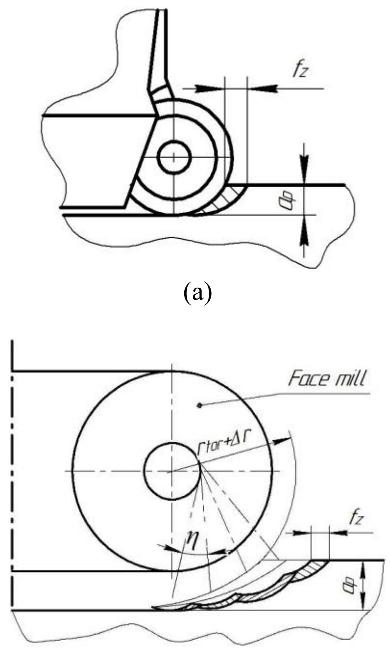
The tool material of the cutting inserts is a hard alloy WC-Co 8% (ISO 513:2012), which is used for machining high-strength steels and for interrupted cutting, including face milling.

The diameter of the face mills is 200 mm, the number of inserts is $z=12$.

The face mills with round inserts with:

1) flat front surfaces (front angle γ = -8°, rear angle α = 8°, main cutting edge angle λ = 8°, d = 12.7 mm) - **mill 1** [14];

2) with cylindrical front surfaces (front angle γ = -16°, rear angle α = 16°, angle of inclination of the cutting units η - 6°, d = 11 mm) - mill **2** [5], [13], [15]. Previous studies [5] made it possible to propose rational values of the main design parameters of mill 2 depending on the required depth of cut.



(a) (b)

Fig. 1. Cutting schemes with face mill 1 - (a) and face mill 2 - (b).

The machining was carried out in accordance with a non-composite second-order plan for three factors (cutting speed, feed rate, and depth of cut) (Table 3) in order to evaluate the effect of cutting modes on surface roughness when using different shapes of the front surface of round face mill inserts. In a 3^k type plan, each variable varies at three levels: +1, 0, -1. To simplify the experiment, a constant depth of cut was assumed, so the number of experiments was reduced to 9. Based on the experimental studies, the levels and intervals of variation of the factors were selected (Table 3).

TABLE III
LEVELS AND INTERVALS OF VARIATION OF FACTORS

Factors	Levels of factors		
	(+1)	(0)	(–1)
v – cutting speed, m/min	157,1	125,7	100,5
f – feed rate, mm/min	80	63	50
a_p – depth of cut, mm	3	3	3

A surface profile study in accordance with ISO 4287-2012 to assess the surface roughness of Ra was carried out using a mode profiler. Calibre 170311, equipped with a computerised measuring system.

TABLE IV
RESULTS OF THE MACHINED SURFACE ROUGHNESS TEST

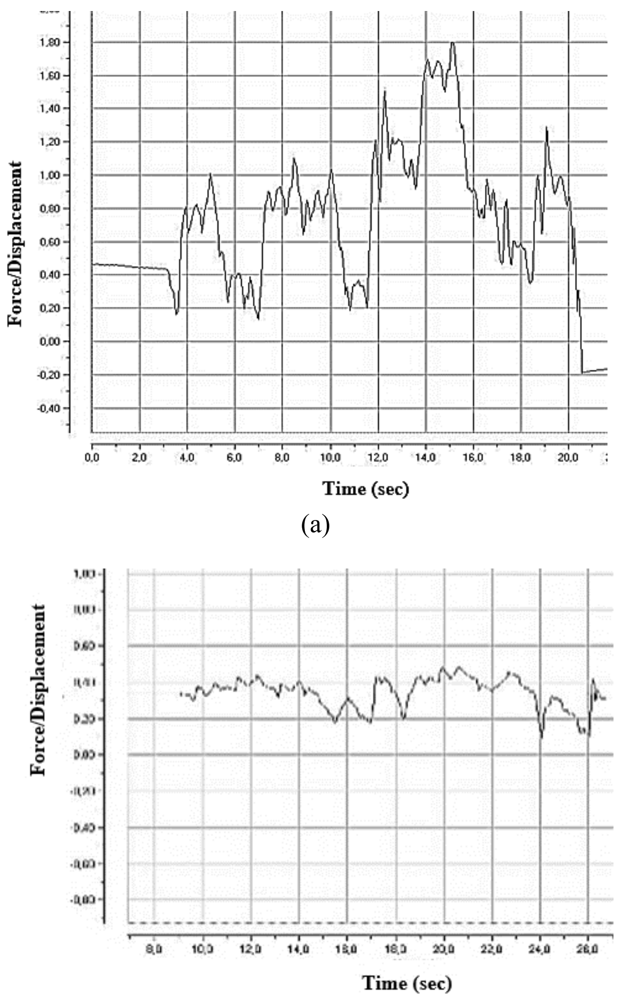
N	x_0	x_1	x_2	*v*, m/min	*f*, mm/min	Ra, µm	
						Mill 1	Mill 2
1	+	+	+	157,1	80	0,82	0,42
2	+	+	–	157,1	50	0,73	0,57
3	+	–	+	100,5	80	1,15	1,14
4	+	–	–	100,5	50	1,72	1,58
5	+	0	0	125,7	63	0,66	0,62
6	+	0	+	125,7	80	0,85	0,72
7	+	+	0	157,1	63	0,81	0,43
8	+	–	0	100,5	63	1,06	0,96
9	+	0	-	125,7	50	1,04	0,75

IV. RESULTS

For the conditions of machining hardened steels with the two proposed face mills, the matrix and the results of the study are presented in Table 4.

When machining with a face milling cutter 1, a minimum surface roughness value of Ra 0.66 µm was obtained (cutting conditions: f = 63 mm/min, v = 125.7 m/min), and when machining with a face mill 2 - Ra 0.42 µm (cutting conditions: f = 80 mm/min, v = 157.1 m/min).

At the maximum cutting conditions, cutter 2 provides a lower surface roughness (Ra 0.42 µm) than when machining with mill 1 (Ra 0.82 µm). The profilograms are shown in **Fig. 2**.

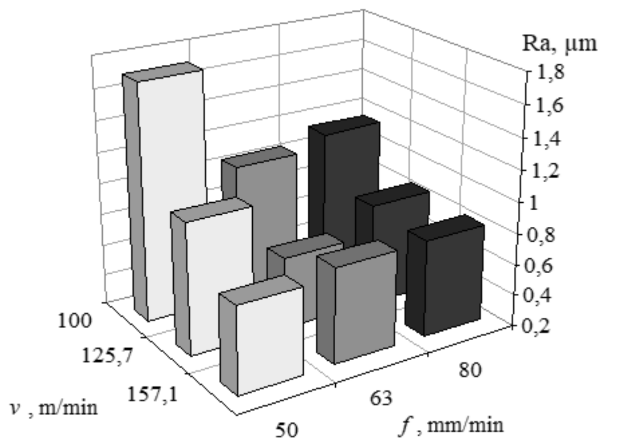


(a)

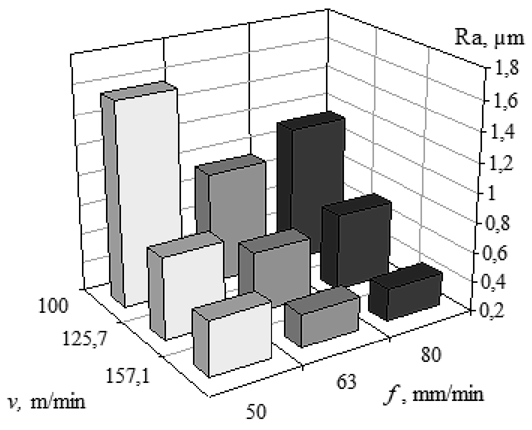
(b)

Fig. 2. Profilogram of the machined surface (rotational speed *n* = 250 min^{-1}, f = 80 mm/min, ap = 3 mm): *a* - by mill 1 (Ra 0.82 µm), *b* - by mill 2 (Ra 0.42 µm)

Figure 3 shows a diagram of the influence of cutting modes on the surface roughness of the machined flat of parts.



(a)



(b)

Fig. 3. Effect of cutting modes on surface roughness: (a) - mill 1, (b) - mill 2

Thus, when machining hardened steels with cutter 2, the minimum surface roughness - Ra 0.42 µm - is achieved at higher feed rates f = 80 mm/min compared to cutter 1 - Ra 0.66 µm at feed rates f = 63 mm/min.

The productivity of the process of face milling of hardened steels was determined for the entire range of changes in cutting modes. The results obtained are shown in **Fig. 4.**

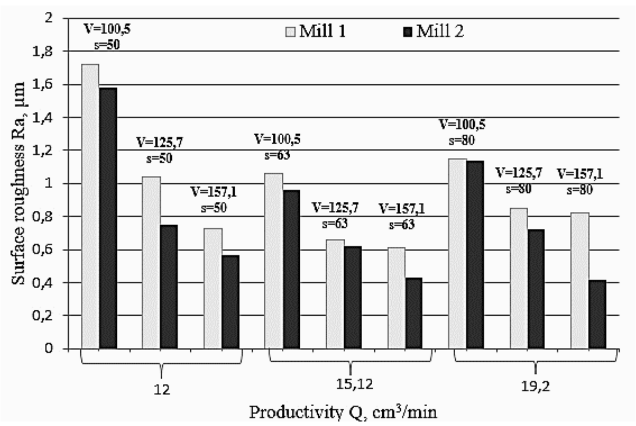


Fig. 4. Effect of cutting modes on surface roughness and machining performance (v - m/min, f - mm/min)

Based on the research results, it was found that the optimal cutting modes for machining hardened steel with a face milling cutter 2 according to the criterion of surface roughness (Ra 0.42 µm) are f=80 mm/min, *v=157*.1 m/min.

At the same time, the productivity of machining hardened steel increased by 1.27 times due to the use of cutter 2 compared to machining with cutter 1, and the minimum values of surface roughness were obtained - Ra 0.42 µm and Ra 0.66 µm, respectively.

Thus, the use of face mills with a cylindrical front surface of the inserts ensures the minimum surface roughness values with a simultaneous increase in the productivity of machining hardened steel parts.

V. Conclusion

When machining flat surfaces of hardened steel parts with a face milling cutter with a cylindrical insert face, a 1. 27 times increase in machining performance is achieved while obtaining minimum values surface roughness Ra due to an increase in feed rate (from 63 to 80 mm/min) compared to machining with a face milling cutter with flat round insert faces. At maximum cutting modes, a face mill with a cylindrical insert face provides lower surface roughness values than a face mill with flat insert faces - Ra 0.42 and Ra 0.82 µm, respectively. This is due to the design features of the cutter: a stepped arrangement of inserts with a cylindrical front surface, a torus shape of the body with the same insert overhang. Machining with such a cutter ensures a uniform load on each insert, reduced shock loads when the insert is plunged into the workpiece, the tangential component of the cutting force, vibration levels, the area of contact between the chips and the front surface of the inserts, plastic deformation of the layer to be cut along the cutting edge, etc.

Thus, when machining parts made of hardened steels, it is expedient and promising to use face mills with a cylindrical front surface of the inserts.

In the future, it is planned to study the effectiveness of machining with face mills with round inserts made of superhard tool materials when machining other grades of hard-to-machine materials.

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