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A Brief Review of Milling Hard Metals

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Abstract. The development of technology in recent years, as well as the need to obtain high precision surfaces and in the shortest possible time, has led to the search for new cutting methods. CNC machine tools show high productivity, high precision pieces can be obtained from one or two positions, and materials with high hardness can be processed. Milling is a manufacturing process that allows the processing of flat surfaces and complex surfaces. In recent years, numerous studies have been carried out regarding the milling processing of hard materials. This paper presents a short review regarding the researched materials, the parameters of the cutting, the tools used, and the analyzed parameters

Keywords: milling, hard metals, milling tools, cutting parameters, cutting force.

INTRODUCTION

Hard metals have been used in many industrial applications such as the manufacture of machine parts, molds, and aircraft for their good fatigue strength, corrosion resistance, and good high-temperature behavior.[1], [2] In order to obtain pieces with high precision, and good surface quality, researchers have carried out studies on the milling processing of hard materials.

The correlation of the cutting parameters and the appropriate choice of tool are elements that essentially influence the precision and quality of the milled surfaces. For the rational use of hard milling, the choice of cutting parameters and the choice of cutting tool are important steps. Cutting parameters are essential in cutting operations, because they are related to milling performance such as the precision and quality of surfaces, the size of cutting forces, etc.

In practice, both the tool and the cutting parameters are chosen based on the recommendations of the tool manufacturers, but the results are not always expected.

This paper determines the influence of milling regimes on tool wear and surface quality when milling hard materials. In the following I will present several types of materials analysed in different articles, as well as methods and means used in machining hard materials. At the end of the paper, the parameters studied and their influence on the quality of the machined surfaces and on the tools will be presented.

MATERIALS AND TOOLS

Nowadays, more and more types of materials are being discovered. Due to their properties, hard materials are of great interest for many industrial applications. Hard materials studied recently are presented below. Their chemical composition, physical and mechanical properties can be found in the articles listed in Table 1.

Table 1. Summary of hard materials

Material	Reference
2205 DSS, 2507 SDSS	[3]
AISI 4340	[4]
AISI H13	[5]; [6]–[12]

Material	Reference
AISI 316L	[13]
AISI D2	[14]
AISI 301, AISI 1042	[15]
SKD 61	[16]
NiCr20TiAl-6, Inconel 718	[17]
C-22 HS	[18]
Ti-6Al-4V	[19]
Inconel 718	[20]
SS-304	[21]
P20 HH	[22]
C/SiC composites	[23]

The machining of materials is a group of machining procedures to which the semi-finished product is subjected in order to obtain the finished piece by removing the excess material in the form of chips (machining allowance) with the help of tools called milling cutters. The durability and wear of the tool depends on the cutting parameters, its type and the material from which it is made.

During the cutting process, the wear phenomenon occurs due to thermal and mechanical stresses on the active faces of the tool. Wear is a continuous and evolving process that causes the state of the tool's performance parameters to gradually decrease and reduces the cutting capacity of the tool and lowers the quality of the milled surface.

For machining 2205 DSS and 2507 SDSS alloys, materials with a hardness of 30 HRC, respectively 32 HRC, a Ø16mm tool with tungsten coated TiCN carbide inserts was used. The type and description of the tool are given in Table 2.

Table 2. Tool description[3]

Tool type	Description
Holder	Ø16mm
Cutter	EAP300R-16D-160L-2 T-W
Insert	APMT 1135PDR-YBG 205

AISI 4340 is a hard-to-machine steel with a hardness of 40-42 HRC. After several researches coated tools were chosen AlTiN, TiAlN, TiN and TiCN have been widely used in high speed cutting of high strength steel. Three types of tools were used in this work for milling of AISI 4340, and together with the type of bodies are shown in Table 3. Figure 1 shows the scheme of the milling process.

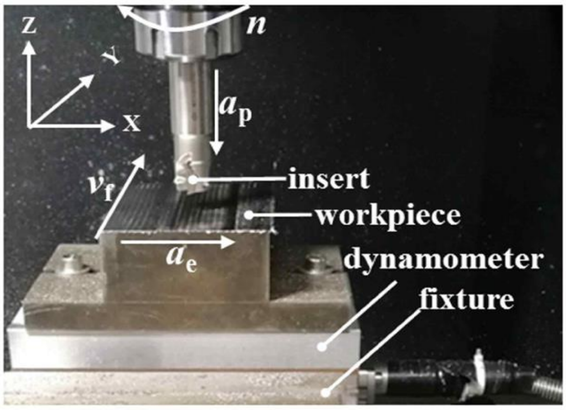

Figure 1. Scheme of the milling process[4]

Table 3. Tool description[4]

Grade no.	Inset type	Cutter type	Manufacturer
KC522M	EDCT10T304PDERLD	20A03R028A20ED10	Kennametal, America
PR830	BDMT-11T308ER-JT	MEC25-S20-11T	Kyocera, Japan
ACM300	AXMT123508PEER-E	WEX 2020E	Sumitomo, Japan

Figure 2. Tool with carbide inserts[15]

A Ø63mm tool with carbide inserts was used for machining AISI301 alloy, austenitic stainless steel with a hardness 80 HBS, and the inserts. These were produced by Zhuzhou Cemented Carbide Cutting Tools Co. Ltd, (Figure 2).

The type and code of the tools used are presented in table 4

Table 4. Tool description [15]

Tool type	Description
Holder	HSK-A63-XM40-70 [15]
Cutter	FMA01-125-B40-SE12-08 [15]
Insert	YBG202 SEET12T3-DF/SEETT4(2.5)-DF

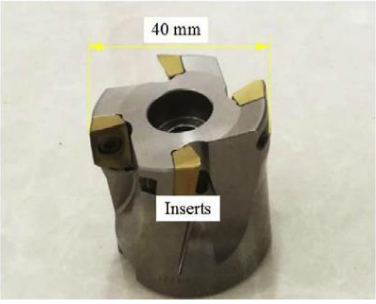

Figure 3. Ø40 milling cutter with cemented carbide inserts[17]

NiCr20TiAl-T6 is widely used as a material of construction for turbine blades. Face milling experiments were performed on a CNC DMU 80. The tool used is a Ø40 milling cutter with cemented carbide inserts (Figure 3). The tool and pad data are given in Table 5. [17]

The paper analyzes the influence of the cooling and lubrication liquid on the mechanical properties of the milled surface.

Table 4. Tool description[17]

Tool type	Description
Pad name	XOMX120408TR-ME08 F40M
Cutter	PVD coated cemented carbide
Tool diameter (mm)	40
Console length (mm)	50
Axial displacement angle (°)	10,4°
Radial angle (°)	15°
Pads number	4
Corner radius (mm)	0,8

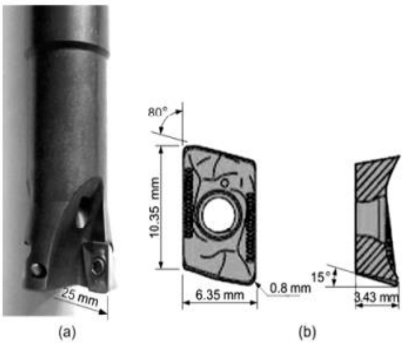

Figure 4. Tool geometry used

AISI H36 tool steel has a hardness of 50 HRC and is resistant to high temperatures. It is processed by milling with the help of a tool of 20 mm diameter produced by Seco. [7]

The same type of tool and the same inserts are also used for milling the Ti-6Al-4V alloy. [26] It has a hardness of 334 HB and is used in various industries for its characteristics (high-temperature resistance, corrosion resistance) Figure 4. The insert geometry and dimensions and tool body characteristics are presented in the Table 5.

a) Tool body b) Non carbide coated insert[26]

Table 5. Tool description[26]

Tool type	Description
Tool holder	R217,79
Pad name	XOMX 090308TR
Tool body material	H25
Pad clamping	Screw
Tool diameter (mm)	25
Plate thickness (mm)	3,13
Plate length (mm)	10,35
Plate width (mm)	6,35

Table 6 summarises existing data in the literature on types of materials processed, tools used, processing procedures and output sizes analysed.

Table 6. Bibliographic synthesis

Alloy	Used tool		Milling type	Output reponse (value)	References
	Inserts coated	Inserts geometry			
2205 DSS / 2507 SDSS	TiN - Coating W	Parallelogram	Front milling	Cutting force (620N)	[3]
AISI 4340	AlTinN,TiAlN+TiN,TiCN	Parallelogram	Front milling	Cutting force (360N)	[4]
AISI H13	(Ti, Al)N–TiN	Parallelogram	Front milling	Cutting force (644.3N) Surface roughness (0.27 µm)	[7]
AISI 301, AISI 1042	TiN - Coated CVD	Square	Front milling	Vibrations	[15]
AISI D2	PVD TiAlN - Coated tungsten carbide	Parallelogram	Front milling	Temperature (495.78°C), Surface roughness (0.28 µm) Cutting force (536.3N)	[14]
NiCr20TiAl-T6	Cemented carbide PVD	Parallelogram	Front milling	Cutting force (140N)	[27]
SUS304	ACM300 PVD coated	Round	Milling	Cutting force (530N)	[28]
Iconel 718	Carbide	Round	Milling	Cutting force (400N)	[29]
Ti-6Al-4V	H25(No carbide cover)	Parallelogram	Front milling	Milling time (63.5min)	[26]

From the presented synthesis, it appears that tools with covered inserts were used in all cases, and the shape of the inserts was parallelogram or round. The output variables analyzed were especially the cutting forces, but also the quality of the surfaces and the wear of the tools. It can be seen that the quality of the surfaces of the parts made of hard materials processed by milling is very good (0,27 µm).

The force varies from 140 N to 644.3 N and depends on the cutting parameters and the hardness of the material.

OUTPUT REPONSE IN HARD METAL MILLING

In the case of 2205 DSS and 2507 SDSS material processing, the impact of feed and rotation were more noticeable. Therefore, a constant milling depth 0.7 mm, was maintained. The rotational speed varied from 1400 to 5600 rpm and the milling speed was 50,100 and 150mm/min. These parameters are presented in Table 7. [3]

Table 7. Design of experiments ([3]

No.exp.	**Speed [rpm]**	**Feed [mm/min]**	**Depth [mm]**	**Milling force [N]**	
				2205 DSS	**2507 SDSS**
1	1400	50	0.7	319.53	486.13
2	2800	50	0.7	293.95	464.25
3	4200	50	0.7	275.30	458.44
4	5600	50	0.7	356.21	522.60
5	1400	100	0.7	333.42	500.21
6	2800	100	0.7	307.42	495.35
7	4200	100	0.7	287.45	486.92
8	5600	100	0.7	411.35	546.21
9	1400	150	0.7	376.91	521.43
10	2800	150	0.7	336.16	513.38
11	4200	150	0.7	301.33	506.12
12	5600	150	0.7	491.97	621.56

When cutting the AISI 316L steel, the experimental research carried out took into account the effect of the cutting parameters on the surface roughness and flank wear. A Taguchi-type design of experiment was used for these determinations. Both the set of parameters used and the obtained roughness are shown in Table 8.

A minimum roughness Ra=1.14 μm was obtained using the following parameters: cutting speed 170m/min, feed rate 0.10mm/rot and milling depth 0.15mm. [30]

Table 8. Milling regime parameters (AISI 316L)[30]

No. exp.	**Feed [m/min]**	**Speed [mm/rot]**	**Depth [mm]**	**Roughness [μm]**	**Flank wear [mm]**
1	150	0.05	0.15	1.42	0.252
2	150	0.07	0.20	2.73	0.295
3	150	0.10	0.25	2.32	0.212
4	170	0.05	0.20	1.94	0.103
5	170	0.07	0.25	2.66	0.105
6	170	0.10	0.15	1.14	0.118
7	190	0.05	0.25	3.22	0.305
8	190	0.07	0.15	2.15	0.242
9	190	0.10	0.20	1.94	0.333

The maximum wear of the tool (0,333 mm) was obtained for the cutting parameters with the highest values.

In the paper [4], three types of insert coatings are analyzed, table 6 in order to identify the optimal inserts for milling AISI 4340. At the same time, the milling parameters are analyzed in order to obtain a minimum force cutting, tool wear and roughness.

The machining of AISI4340 alloy was carried out using three carbide-tipped tools and the milling parameters are shown in Table 9. [4]

Table 9. Milling parameters (AISI4340)[4]

Parameter/Milling	**1**	**2**	**3**	**4**	**5**
Feed (m/min)	280	320	360	400	440
Feed per tooth (mm/ turn/tooth)	0.02	0.04	-	-	-
Depth (mm)	0.2	0.4	-	-	-
Radial depth of milling (mm)	2	4	-	-	-

The conclusion was that the tools with insert coated with several layers are the ones recommended for milling the material AISI 4340. In this case the wear of the tool was the lowest.

For a feed of 280 - 440 m/min, feed per tooth of 0.02 mm/tooth, depth of 0.4 mm, and depth of 2 mm, the milling surface roughness of AISI 4340 obtained by multi-layer coated insert tool could reach 0.2 μm.

The machining of AISI301 alloy, using a Ø63 mm tool with carbide inserts, which were cemented, was carried out under the following conditions:

- ❖ milling speed 190 m/min;
- ❖ constant milling feed of 150mm/min;
- ❖ axial milling depth 0.25 mm;
- ❖ radial milling depth was divided into 3 groups as shown in Figure 5.

I. a maximum of one alternatively engaged gear tooth, ae=8mm, 16mm, 24mm;

II. one or two alternately engaged teeth, ae=32mm,40mm,48mm,56mm;

III. two or three teeth alternately interlocked, ae=64mm,72mm,80mm.

It turned out that the number of teeth simultaneously in the chip has a great influence on the vibrations. As the radial depth increases, the surface roughness also increases due to the occurrence of vibrations.

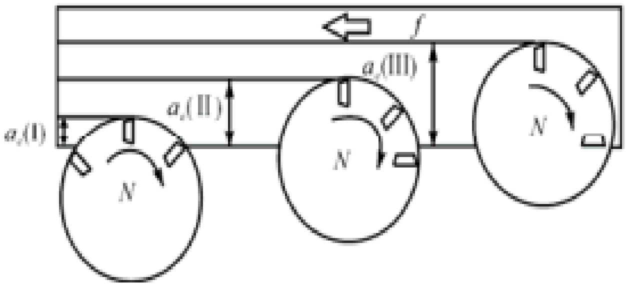

Figure 5. Experimental settings[15]

The paper [26] investigates tool wear, and surface roughness in high-speed milling with uncoated carbide inserts under dry cutting conditions.

During milling, the feed direction of the workpiece was along the negative x-axis, while the pass direction was along the positive y-axis, Figure 6.

The parameters used in this research are listed below:

- ➢ milling feed 100 m/min (correspondingly rotational speed was speed=1273 r/min);
- ➢ feed per tooth 0.05 mm/tooth;
- ➢ axial and radial milling depth 2 mm.

It turned out that the roughness of the surface increases with the increase of the milling time and implicitly of the wear of the tool

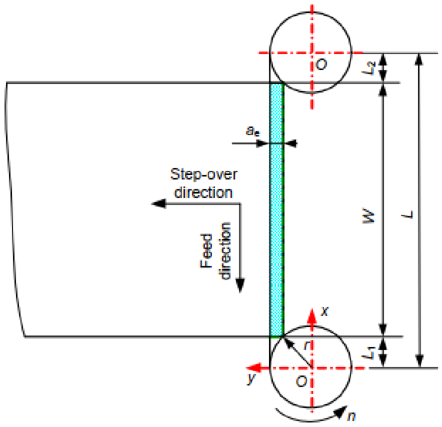

Figure 6. Scheme of the milling process[26]

A curved piece of Iconel 718 alloy steel was used to study the phenomena of chipping a surface whose generator is a sinusoidal curve. To reduce the stress, the samples were annealed for 30 minute at 800°C. [29]. It is recommended that when milling pieces with curved surfaces from Inconel 718, the cutting speed should be chosen in the range of 4000-4500rpm.

Table 10 summarizes data on the milling parameters studied in the papers.

Table 10. Sumary of milling parameters

Material	Speed [m/min]	Feed per tooth [mm/tooth]	Axial depth [mm]	Depth [mm]	Design of Exp.	Roughness min., Ra [μm]	Reference
AISI4340	280~440	0.02 [mm/tooth]	0.4	2		0.2	[4]
AISI301	190	150 [mm/min]	0.25	variable	Taguchi	0.4 [a_e=40mm]	[15]
Ti-6Al-4V	100	0.05 [mm/tooth]	2	2	Taguchi	1.36	[26]

Material	Speed [m/min]	Feed per tooth [mm/tooth]	Axial depth [mm]	Depth [mm]	Design of Exp.	Roughness min., Ra [μm]	Reference
AISI 316L	170	0.10 [mm/tooth]	0.15	2	Taguchi	1.14	[30]
SKD61	75	0.01 [mm/tooth]	0.2	2	Taguchi	0.122	[16]
Inconel 718	40-50-60	0.8-1.2-1.6	0.1-0.25-0.40	-	Taguchi	0.325	[20]

CONCLUSIONS

This paper shows that by selecting specific milling conditions (proper tools and parameters), superior surface quality can be achieved during machining of hard materials. In addition to roughness, if CNC milling machines are equipped with special equipment, both cutting forces and vibrations can be measured during machining.

Several types of materials, tools and processing technologies were presented. A compromise must be chosen between cutting force, chip type and optimum durability.

For the given values of cutting speed and feed rate, the results show that roughness increases with feed rate due to increased cutting forces and deformation. For low values of the cutting speed, the roughness decreases. Similarly, for high values of cutting speed and feed rate, the roughness Ra increases due to vibrations that increase forces and stresses. If the cutting speed is limited by the maximum speed of the machine, it also increases the tool life, production time or production cost.

If CNC milling machines provide high pressure cooling, higher cutting parameters can be used because the cutting edge of the tools would not be subjected to high temperatures. In most of the analyzed experiments, machining was performed dry because the coolant would have greatly influenced the results.

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