MACHINABILITY INVESTIGATION OF AISI W1 TOOL STEEL BY HARD FACE MILLING

Irina BEŞLIU[1]

ABSTRACT: Hard milling is considered to be an expanding field. This paper studies some machinability aspect and process viability of hard face milling AISI W1 tool steel with different hardened states. The process performances are determined in terms of surface quality, cutting force and chip formation mechanism. The outcomes suggest that these machining processes can compete with other finishing techniques.

KEY WORDS: hard machining, machinability, hardened tool steel, cutting force, surface integrity.

1 INTRODUCTION

Milling hardened tool steels with geometrical defined cutting edges was considered to be extremely difficult until recent decades. The achievements in the tool materials area and in machine building and the development of new cutting technologies like high speed machining had opened new opportunities for cutting these kinds of materials. The term used nowadays for describing the cutting processes of materials with hardness higher than 45 HRC is hard machining (Beşliu et al., 2011). Hard machining and especially hard milling is considered to be an extremely efficient machining technique in the die and mold industry, because of the significant machining time reduction and improved surface qualities that can be obtained. The work of various authors when reporting investigations carried out in the field of hard milling of tool steels had shown that shapes with high dimensional tolerance, good surface finish and often with complex geometry can be generated and that these cutting techniques are a more economic alternative for machining dies and molds in comparison with electro-discharge machining.

Usually, hard machining is carried out in air, being considered an environmental friendly machining technique. Considering the characteristics of hardened steels, the applicable cutting tools should have high hardness high hardness-to-modulus ratio, high thermal conductivity, high abrasive wear resistance and high thermal, physical and chemical stability (Suresh et al., 2013).

[1]Universitatea Ştefan cel Mare din Suceava, Departamentul de Mecanică şi Tehnologii, Universităţii 13, Corp B, Suceava, România

E-mail: irina.besliu&yahoo.com

The cutting tool used when hard milling tool steel must be machined is usually made of single phase ceramics or composite ceramics, coated carbide tools, CBN (cubic boron nitride) and PCBN (polycrystalline cubic boron nitride).

Machinability is the characteristic of a material that refers to the ease or difficulty with which that material can be machined to an acceptable surface finish and also achieving satisfactory final economic results (Picoş et al., 1980). The economic performance is measured by the technological cost or the performance parameters that depend mostly on the elements of the cutting conditions.

In recent decades, several investigations have been carried out to study the performance of the cutting hard materials with geometrical defined cutting edges. Most of the researches focused on the turning process and hard milling with ball nose mills. In the area of face milling, there are few investigations.

This paper proposes to investigate some machinability issues of the hot worked tool steel AISI W1 in hard face milling operations by means of cutting forces, surface integrity and chip formation mechanism.

The cutting forces involved in hard machining operations are usually lower than the ones generated in traditional machining processes. This is a result of higher shear angles in saw toothed chip forming, mechanism that is an important aspect in the case of the poor ductility of hardened tool steels. Cutting force level can offer important information of the power requirements and also for machine safety and for assuring high accurate cutting processes. In some cases, if the proper tool material and geometry are not well chosen, the cutting of the hard material can conduct to extreme wear of the cutting tool that can cause also an increase of the cutting forces, followed by generating machining errors.

In hard machining there are several factors that can conduct to poor surface integrity, including subsurface plastic deformation, phase transformations, intergranular attack, thermal softening or hardening, redeposited layers, cracks, recrystallization and residual stress distribution (Suresh R. et al., 2013).

Surface quality and topography influence the functional performance of a manufactured component and is consider being one of the main performance parameters in evaluating a machining process. Typical surface integrity problem includes machining burns, untempered martensite, cracks on the surface, lower fatigue strength of parts, distortion and residual stresses The profile of the machined surface reflects also the cutting tool deviations and the cutting tool wear. The integrity of the machined surface profile is also affected by the high local temperature due to the plastic deformations. Most of the heat generated in this cutting process is carried out by the chips that are rapidly evacuated from the cutting area.

2 THEORETICAL CONSIDERATIONS

Machinability of metallic materials by chip removal can be affected by many variables such as: properties of the workpieces materials, cutting tool material and geometry, cutting parameters (cutting speed, feed rate, and depth of cut), machining conditions like the rigidity of machine components, the cooling conditions provided etc.

The properties of the materials that may affect their machinability are: microstructure, chemical composition, grain size, material hardness, yield, and tensile strength, physical properties such as the modulus of elasticity, thermal conductivity and thermal expansion. In order to increase a material machinability, the microstructure of a metal can be modified by annealing and normalizing, which will change its ductility and shear strength or by addition of some specific chemical elements.

The most common evaluation criterions for describing a material machinability by cutting usually refers to the following: *a)* tool wear; *b)* cutting process forces; *c)* surface roughness; *d)* machined surface accuracy; *e)* chips shape resulted from cutting process etc. Depending on the needs of a technological machining process, some criterions may have a primary or secondary role in evaluation of material machinability. The machinability of a material represents a complex technical characteristic and usually is determined by comparing the values obtained for the process output variables exposed in the criterions with those that characterize the cutting processes of often used metallic materials.

AISI steel grade W1 is one of the more common forms of tool steels produced; it has moderately high carbon content relative to other tool steel grades and is designed to be hardened through water quenching. These steels can attain high hardness (above HRC 60) and are rather brittle compared to other tool steels. Typical applications of this steel grade are: hand operated metal cutting tools, cold heading, embossing taps and reamers as well as cutlery etc.

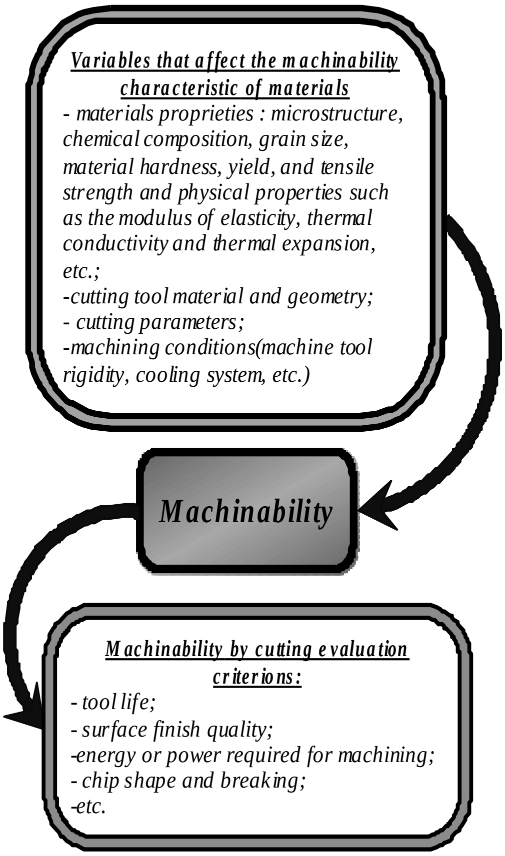


Figure 1 Material machinability characteristic analyze

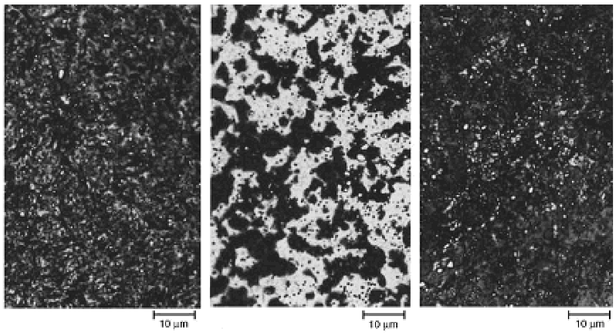
AISI W1 is a hypereutectoid carbon tool steel and its structure contains only cementite, which is easily dissolved. To properly heat treat AISI W1 tool steel, the steel needs to be taken through a thermal cycle that includes annealing, stress relief, preheating, hardening, quenching and tempering.

Table 1 Chemical composition of AISI steel grade W1

Element	C	Mn	Si	Cr	Ni	Mo	W	V	Cu	P	S
Weight %	0.7-1.5	0.1-0.4	0.1-0.4	0.15	0.2	0.1	0.15	0.1	0.2	0.025	0.025

The microstructure corresponding to the different hardness states of the AISI W1 tool steel is presented in figure 1. Due to the cementite shape, it is expected that the higher cutting forces to be achieved when machining AISI W1 with medium hardness state.

The quenched material microstructure will consist of martensite and residual cementite. A small amount of retained austenite will also be present, but it will not be detectable with a light microscope, if the proper austenitization temperature is used. Martensite is an unstable constituent in quenched steel, resulting as a solid solution of carbon in alpha-iron. Due to the martensite presence in the treated material structure, the machinability of the hardened AISI W1 tool steel is considered to be very low, cutting processes of this material resulting in high tool wear. Even if its hardness is lower than the martensite hardness, cementite is considered one of the main factors that determine tool wear when machining different types of steel. The values of the cutting forces developed in the machining processes of hardened tool steel will be dictated by the shape of the cementite structure. The globular shape usually has a negative impact on this process parameter.



a b c

Figure 2 AISI W1 (1.05% C), 19 mm diameter bars, brine quenched: (a) Hardened case microstructure. 64 HRC. Case contains as-quenched martensite and undissolved carbides. 4% picral; (b) Transition zone. 55 HRC. Martensite is light and undissolved, carbide is outlined, and pearlite is dark. 4% picral; (c) Core microstructure. 42 to 44 HRC. 4% picral etch reveals fine pearlite matrix (black) containing some patches of martensite (white) and undissolved carbides (outlined white particles). 1000x

3 EXPERIMENTAL SETUP

In order to investigate the machinability of AISI W1 hardened tool steel by face milling machining, tests were conducted using a Taguchi design approach. The experimental design method permitted the investigation of the effects of different parameters on some performance characteristics, like cutting force, surface quality and chip shape. For the experiments, four control factors were chosen: workpiece material hardness, cutting speed, cutting feed and depth of cut. For each of this control factors, three levels were selected therefore an orthogonal array layout of L9(3^4) was performed. In table 2, there are presented the experiment runs and the levels that were selected for each control factor from the orthogonal array.

Table 2 Experiments runs and the control factors and their levels

Nr. Exp.	Material Hardness HRC	s [m/min]	f [mm/min]	ap [mm]
1	50	336	20	0.2
2	50	470	25	0.3
3	50	672	32	0.5
4	55	336	25	0.5
5	55	470	32	0.2
6	55	672	20	0.3
7	62	336	32	0.3
8	62	470	20	0.5
9	62	672	25	0.2

The machining operations were made on rigid plant milling machining FU 32. The cutting forces developed were measured using a Kistler 9257B specialized dynamometer. The signal from the dynamometer was processed by using Dynoware software. The software also allowed the generation of some specific rapports. The machined surface integrity was investigated by analyzing SEM images capture with a scanning electron microscope Vega II Tescan LSH. Chip shape images were obtained with a stereomicroscope commercialized by Optika. The experiments were conducted using an indexable milling tool with a diameter of 210 mm, with only one round cutting insert mounted. For each run, a different cemented tungsten insert was used. The cutting geometry of the inserts was the following: rake angle 0^0, radial relief angle 15^0, and angle of inclination 0^0.

4 RESULTS AND DISCUSSION

The maximum cutting forces levels obtained in the test were situated in the following ranges:

- Fx_{max}~53-100 N;
- Fy_{max}~34-56 N;
- Fz_{max}~190-400 N.

Figure 3 presents the rapports and the graph of the cutting force values obtained for the 9 experiments that were carried out in the study. The graphs that show the evolution of the cutting force components during the machining test were generated with the Dynowave software.

The branchy aspect of the graphs is the result of face milling with a single cutting insert. The values obtained for the cutting force components were strongly influenced by the tool insert wear and material quality. The influence of material quality could be observed in some of the graphs from figure 3 that illustrate the evolution of the cutting force parameters during machining. For instance, the section highlighted in the graph corresponding to the six runs from the Taguchi design of experiments matrix show a decrease of the three machining force components that could be a result of the unequal proprieties of the material along the cutting area. Also for most of the graphs, we can observe that the cutting forces are slowly increasing with cutting time. This can be an effect of the wear mechanism of the cutting insert.

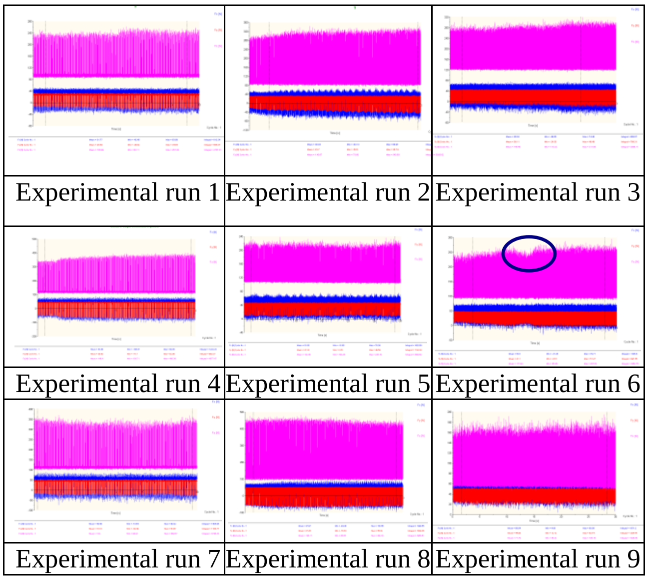


Figure 3 Reports showing the cutting force components evolution during machining generated with Dynoware specialized software

Figure 4 shows images of the shape of the chips generated in the experiments obtained with the Optika microscope. The chip shape can offer meaningful information about the cutting processes physical and mechanical phenomena and is consider an adequate machinability evaluation indicator. The chips obtained in the experiments are characteristic for machining ductile materials. Most of the chips obtained in the experiment have spiral and comma shape and show high plastic and thermal deformations. Most of the heat generated in the machining process was eliminated through chips that had a red color and that were easy removed from the cutting area.

Figure 5 shows the aspect of the machined surface generated in the experiments. As we can observe, the machined surface obtained when machining with higher cutting speeds and feeds of AISI W1 tool steel grade with high hardness has a good integrity.

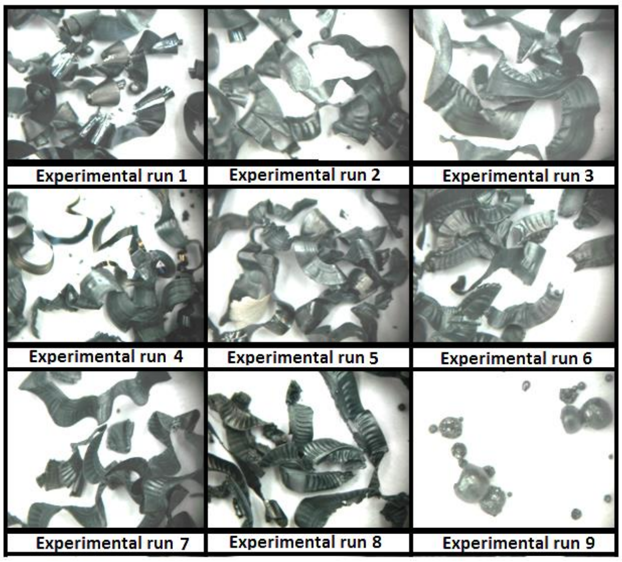


Figure 4 Chip shapes obtained in the experiments 8X magnitudes

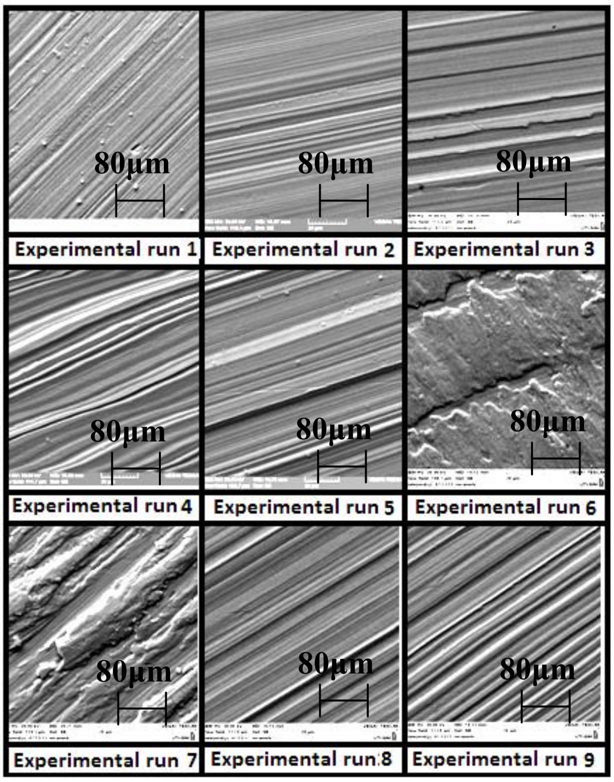


Figure 5 SEM micrographs of the machined surface obtained in the experiments

The striations observed are a result of the tool insert accuracy that affects the surface roughness. The image that details the machined surface aspect obtained in the fourth experiment run shows laced striation that could have been caused by vibrations of the tool during machining. The lower surface integrity was obtained in the sixth and seventh experiments, when the surfaces present scales due probably to the high cutting temperatures involved. The phenomena of the flowing of the highly plasticized material through the worn trailing edge to the side of the tool can also be observed in the machined surface obtained on the third experiment run. The side flow of workpiece material is a result of high temperature in the cutting zone and of the behavior of the workpiece material at chip-tool interface and workpiece - tool interface as a viscous fluid.

5 CONCLUSIONS

In most of the machining processes, chips are generated as a result of strong plastic deformations followed by the shearing of the workpiece cutting layer. In most cases, the strong plastic deformations of the material and other machining conditions have consequences on the process performance. One of the main factors that have to be taken into consideration when discussing the performance of a process is the workpiece material machinability. The process has specific aspects in the case of high speed milling of workpieces made of hard materials. The paper proposal is to investigate some aspects referring to the machinability of AISI W1 tool steel in different hardened states by hard face milling. From the results obtained in the study, the following conclusions can be drawn:

1. Majority of the researchers found that the force conditions in hard machining are different from that of conventional cutting processes.

2. The chips obtained in the experiments are characteristic for machining ductile materials; most of the chips have spiral and comma shape and show high plastic and thermal deformations.

3. The machined surface aspect seems to be qualitative for the case of machining with the extreme values that were considered in the study.

4. High speed face milling of hardened tool steel AISI W1 can be carried out in economical conditions and can lead to satisfactory surface quality.

In the future, there is the intention to develop a research about the possible correlations that could exist between the cutting tool material and other machining parameters and the machinability characteristics of the workpiece material, in the case of machining different hardened tool steel.

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7 NOTATION

The following symbols are used in this paper:
s = cutting speed;
f=cutting feed;
a_p=depth of cut
Fxmax= maximum radial thrust force;
Fymax= maximum tangential cutting force;
Fzmax= maximum feed force.