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INFLUENCE OF COOLING AND LUBRICATION ON CHIP FORMATION AND ITS FORM IN TURNING

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Abstract

Machining with the use of cooling and lubrication liquids (called wet machining) is still the primary method of shaping constructional materials. However, economic and ecological factors cause that wet machining is being replaced by processes which use minimal quantities of cooling and lubrication liquids (MQL machining) or do not use them at all (dry machining). Eliminating cooling and lubrication from cutting processes results in higher temperatures during the cutting process and worse tribological conditions around the moving surfaces between the tool and workpiece. This, on the other hand, causes changes of the conditions in which the chip is formed and a different form of the chips. Another consequence is problems related to hot chips and difficulty measuring hot workpieces. The form of the chip is an important factor particularly noticeable in automated part manufacturing lines, where the chip has to be easily removable from the cutting zone - especially if the parts are made of difficult-to-machine materials. This paper presents results of an investigation into the conditions of chip formation and its form in dry, MQL turning as well as in turning with emulsion. The machined materials include constructional steel C45 and austenitic stainless steel X2CrNiMo 17-12-2. The obtained results confirm a significant role of cooling and lubrication conditions which, however, depends on the selected cutting parameters and the properties of the workpiece material. The results also helped to select cutting conditions which are most suitable for automated machining.

Keywords: cutting chip formation, form, turning dry, MQL, emulsion

1. Introduction

Machining with the use of cooling and lubrication liquids, called wet machining, is still the primary method of shaping constructional materials. However, economic and ecological factors cause that this type of machining is being replaced by processes which use minimal quantities of cooling and lubrication liquids (MQCL) or do not use it at all (dry machining) [1,10,12,15]. Eliminating cooling and lubrication liquids from the cutting process means that their basic functions such as cooling, lubricating and chip removal from the cutting zone are not performed. This fact constitutes the primary drawback of such methods. In practice it means that the cutting temperature is higher and the tribological conditions on the moving surfaces of the tool and workpiece are highly unfavorable. This further leads to quicker tool wear, uneven distribution of the surface layer properties and worse dimensional and shape accuracy of the part. It also changes the conditions of chip formation and its form as well as causing problems related to hot chips and measurements of a hot part. The high temperature melts the chips which stick to the cutting edge and the machined workpiece. The lack of lubrication means increased friction on the tool and flank faces and greater adhesion of the chip to the tool. This causes adhesion and blockage of the chip area and, in consequence, difficulty removing the chip. Higher temperatures of the cutting process also result in the chip being more prone to deformations, assuming a ribbon-like, snarled form [3,5,6,7,9]. That is why one of the conditions of a successful implementation of dry and MQCL cutting is obtaining acceptable chips in terms of their form and easiness of removal from the cutting zone.

The conditions of chip formation and its shape have a significant influence on cutting efficiency and reliability as well as operators' safety. In terms of chip removal possibilities, uninterrupted machine operation, machine operator's safety and machined surface quality, chips can be divided into acceptable (ribbon-shaped short, helical, tubular, conical and washer type short, arc, connected, loose) and unacceptable (ribbon shaped long, helical, tubular and conical long) [8,13]. The form of the chip is strictly connected with the state of deformations and stresses in the chip formation zone. The factors influencing it include material strength and hardness, which contribute to the state of deformations and stresses in the chip formation zone and its form [4,7]. Apart from the properties of the machined material also the cutting parameters and cooling and lubrication conditions play a crucial role in determining the conditions for chip formation and its form [2,4,9,16].

The research and industrial practice show that eliminating entirely cooling and lubrication liquids from machining processes of certain materials or from certain types of machining requires an appropriate selection of cutting conditions - ones which will result in an acceptable form of the chip and will not cause difficulty in unattended removal from the cutting zone [7]. This problem is especially important in machining difficult-to-machine materials such as e.g. austenitic stainless steels.

The first aim of the research presented in this paper was to determine the impact of the cooling and lubrication mode and cutting parameters on chip formation conditions as well as its form in machining constructional steel C45 and austenitic stainless steel X2CrNiMo 17-12-2. Secondly, it was attempted to determine which cutting conditions will lead to formation of the chips which are acceptable in automated machining.

2. Experimental procedure

Cylindrical turning tests were carried out on carbon C45 and austenitic stainless steel X2CrNiMo 17-12-2 bars. The chemical composition and mechanical properties is presented in table 1.

The sintered carbide inserts SNMG 120408TF grade IC907 with a TF chip breaker covered by PVD method with (TiAlSi)N coating (produced by ISCAR) were employed. They were fixed in a tool holder MSS 2525-12-EB (produced by Mircona AB) with cooling channels for an internal lubrication system (Fig. 1). The following cutting point geometry was applied: the orthogonal rake angle $\gamma_0=5^0$, orthogonal clearance angle $\alpha_0=10^0$, cutting edge angle $\kappa_r=45^0$, cutting inclination angle $\lambda_s=0^0$ and corner radius r_ε=0,8 mm. The quoted inserts were recommended for machining of stainless steel as well as soft steels machined with medium cutting speeds.

The following cooling and lubrication techniques and their designations were used in the experiments:

D - dry cutting, without cooling or lubrication,

MQL - minimum quantity lubrication, executed by a Minibooster II applicator (produced by Accu-Lube Manufacturing GmbH) for coolant fed tools (Fig.2). Biodegradable vegetable oil Accu-Lube LB 8000 was used as a lubrication medium. The oil consumption by the MQL system was adjusted at a level of 0,014 mm^3/s.

E - overhead flood application of 6% emulsion with 0,07 dm^3/s flow volume, made on the basis of emulsifying oil ARTEsol Super EP (produced by W.O.P. ARTEFAKT).

Tab. 1. Chemical composition and mechanical properties

Steel	Chemical composition, %								
	C	Si	Mn	P	S	N	Cr	Mo	Ni
X2CrNiMo 17-12-2	<0,03	≤1,0	<2,0	≤0,045	≤0,015	≤0,011	16,5-18,5	2-2,5	10-13
C45	0,42-0,50	0,17-0,37	0,5 - 0,8	≤ 0,04	≤ 0,04	-	≤ 0,30	≤ 0,10	≤0,30

	Mechanical properties			
	R_e, MPa	R_m, MPa	A_5, %	HB
X2CrNiMo 17-12-2	200	500-700	40	215
C45	340	620	16	207

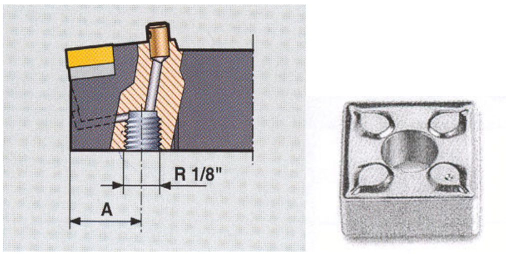


Fig. 1. Tool holder Mircona AB MSS 2525-12-EB and cutting insert SNMG 120408TF grade IC907

The experiments were carried out with the cutting parameters presented in table 2.

Tab. 2. Experimental cutting parameters

X2CrNiMo 17-12-2									
v_c (m/min)	82			164			255		
f (mm/rev)	0,08	0,27	0,47	0,08	0,27	0,47	0,08	0,27	0,47
a_p (mm)	1								
C45									
v_c (m/min)	76			190			237		
f (mm/rev)	0,08	0,27	0,47	0,08	0,27	0,47	0,08	0,27	0,47
a_p (mm)	1								

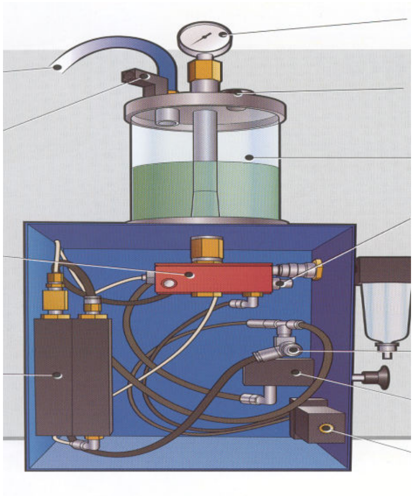


Fig. 2. Accu-Lube Minibooster II

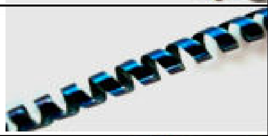
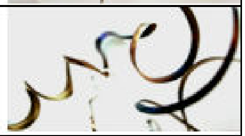
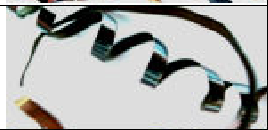
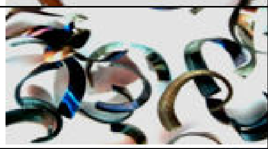
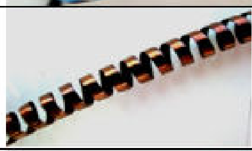
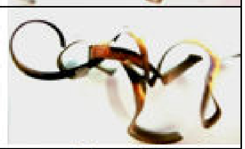
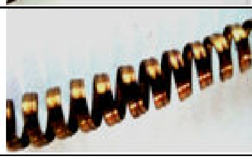
The chips generated in the process of turning were studied with an optical microscope MWP manufactured by PZO Warsaw, under 10x magnification.

3. Results and discussion

The form of the chips after turning C45 steel dry, with minimal cooling and lubrication in the cutting zone and with a conventional supply of emulsion in the range of employed cutting parameters was presented in table 3. Assessing it for the needs of automated machining systems, it can be concluded that the most desired chip form is loose arcs and short helical pieces [13]. The formation of helical tubular chips or washer type long and snarled is less acceptable because of the problems with removing them from the cutting zone or unacceptable because they may wrap around the tool and machined workpiece, which makes the elimination of the cooling and lubrication liquid impossible.

The interaction of cooling and lubrication conditions of the cutting zone largely depends on the applied cutting parameters. In the range of low and medium feed rates (0,08 and 0,27 mm/rev), the influence of cooling and lubrication in the cutting zone on changes in the chip form is limited. In turning steel C45, the most common are helical tubular long chips or ribbon snarled chips which are, however, difficult to remove. An increase in the feed rate causes a change of the chip form into one that is easier to remove from the cutting zone.

Table. 3. Chip forms after turning C45 steel (PL-ISO 3685)

Cutting parameters			Chip form		
v_c (m/min)	f (mm/rev)	a_p (mm)	D	MQL	E
76	0,08	1			
	0,27				
	0,47				
190	0,08	1			
	0,27				
	0,47				
237	0,08	1			
	0,27				
	0,47				

Elimination or reduction of the cooling and lubricating liquid results in a higher cutting temperature [11] and the friction between the chip and tool edge causes increased compression and curling of the chip [2,9]. In dry and MQL turning, at a feed rate of 0,47 mm/rev, the helical tubular long or helical washer type snarled chip changes its form into a helical tubular short or elemental one. The increase of the feed rate leads to a larger cross-section of the chip and, in consequence, its greater stiffness. This, in connection with a higher cutting speed, renders the chip more breakable. An application of a minimal quantity of a lubricating liquid changes the conditions for chip formation and its removal along the tool face. The penetration of the oil fog onto the chip contact surfaces prevents adhesion and changes the character of the chip-tool contact: rubbing turns into plastic flow, which results in lower compression and curling of the chip. As a result, the length of the chip-tool face contact surface decreases [2,4,9]. The obtained chip is characterized by lower pulverization, compared to that after dry machining. An increase of the cutting speed at a low feedrate (0,08 mm/rev) causes the chip to be longer and snarled.

A microscopic analysis of the surfaces of the obtained chips performed at a 10x magnification shows that depending on the cooling and lubrication mode, elimination of the emulsion causes larger compression of the chip as a result of greater friction and adhesion between chip surface and the rake face of the tool (Fig. 3). This has also been confirmed in the study [14]. The back surface of the chip after dry turning is rough and dull, with clear signs of discontinuity of the chip material. It is dark blue in color, which clearly points to a high cutting temperature. The chip surfaces after MQCL machining are smoother and lighter, which is a result of a lower cutting temperature and lower chip compression as well as better chip flow conditions.

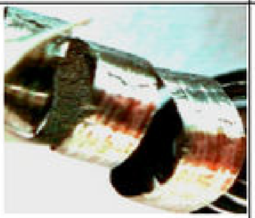
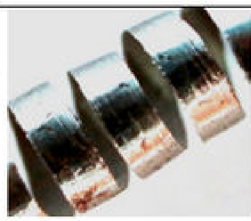
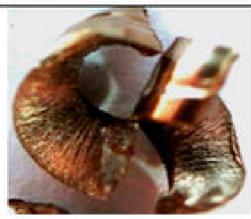
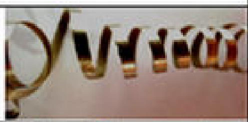
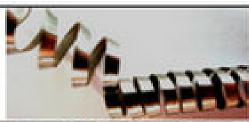
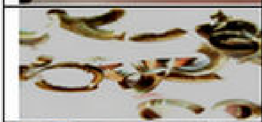
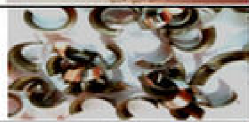
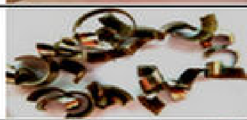
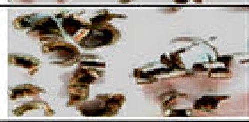
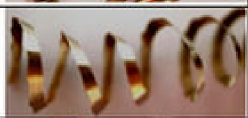
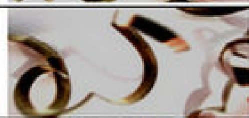
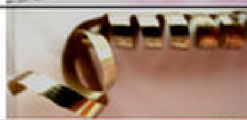
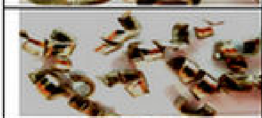
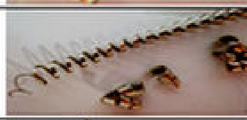
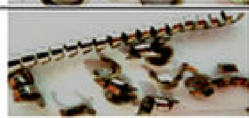
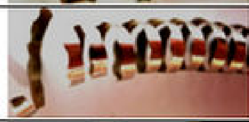
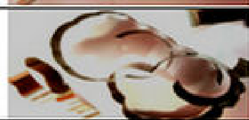
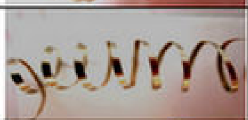
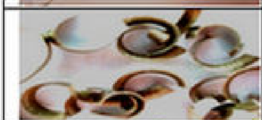
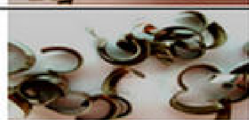
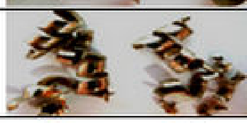
Cutting parameters			Chip form		
v_c (m/min)	f (mm/rev)	a_p (mm)	D	MQL	E
76	0,08	1			
237	0,27				
	0,47				

Fig. 3. Influence of cooling and lubrication on the chip form (C45 steel)

Eliminating a cooling and lubricating liquid from the machining of the X2CrNiMo17-12-2 steel does not influence the change of the chip form as much as it does in machining the C45 steel. Upon analysis it can be seen that both in dry machining and in machining with emulsion in a wide range of the used cutting parameters, the chips look similar and are more readily removable than these after MQL machining. The desired form (for the needs of unattended machine operation) includes: arc loose or connected chips as well as helical conical short chips. Replacing the emulsion with oil fog causes that machining generates undesired chip forms: instead of arc loose or connected chips, they are helical conical long and snarled or helical tubular long (tab. 4). Based on the obtained chip forms, it can be concluded that similar conditions of chip formation are also present in dry turning and in turning with emulsion, whose penetration of the chip-tool face contact area is limited - it is proved by a similar structure of the back part of the chips which come in contact with the tool rake (Fig. 4). The tendency of stainless steels to become hardened during machining causes greater compression of the chip, which means that at a lower feed rate (0,27 mm/rev) the obtained chip is arc loose or helical conical short in form.

Similarly to the C45 steel, it is the feed rate that has the greatest influence on the chip form. With its increase the chip form changes favorably in all the used modes of cooling and lubrication of the cutting zone. The cutting speed and depth of cut influence the chip form to a smaller extent. The analysis confirmed the results of the work [14], which pointed that the influence of the cutting speed on the chip form at large feed rates is negligible.

Table. 4. The forms of chips after turning X2CrNMo17-12-2 steel (PL-ISO 3685)

Cutting parameters			**Chip form**		
v_c (m/min)	f (mm/rev)	a_p (mm)	**D**	**MQL**	**E**
82	**0,08**	**1**			
	0,27				
	0,47				
164	**0,08**	**1**			
	0,27				
	0,47				
	0,08	**0,5**			
		2			
255	**0,08**	**1**			
	0,27				
	0,47				

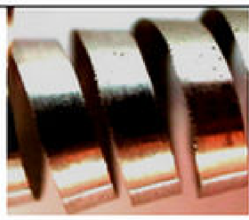
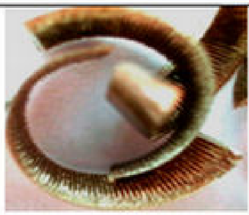
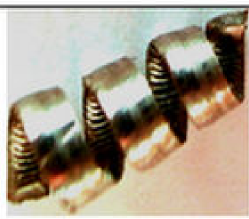
Cutting parameters			Chip form		
v_c (m/min)	f (mm/rev)	a_p (mm)	D	MQL	E
82	0,08	1			
255	0,27				
255	0,47				

Fig. 4. Influence of cooling and lubrication on the chip form (X2CrNMo17-12-2 steel)

Conclusions

The analysis of chips after turning C45 and X2CrNiMo17-12-2 steels showed a large influence of the cooling and lubrication mode on their form and, in consequence, on the conditions in which they were formed and removed from the machining zone.

Eliminating or minimizing the application of cooling and lubricating liquids in the cutting process may favorably influence the chip form and cannot hinder the practical implementation of dry and MQL turning of the C45 steel. However, reaching an optimal form of the chip requires increased feed rates and cutting speeds.

Dry cutting of the X2CrNiMo17-12-2 steel facilitates achieving the chip form which is very similar to that after cutting with emulsion. A higher cutting zone temperature in dry turning causes lower strength and hardness of the machined material, which is connected with better conditions of chip formation. Reaching a satisfactory chip form in MQL turning requires increased cutting speeds and most of all, higher feed rates.

In the case of finishing turning of aforementioned steel in dry conditions at a low feed rate (0,08 mm/rev), eliminating or minimizing the use of cooling and lubrication media does not significantly influence the chip form, as compared to turning with emulsion. The analysis of the topography of back side of the chips obtained in dry and MQL turning as well as in turning with emulsion indicates on large plastic deformations, which become more intense as the feed rate increases as well as making the chip more brittle.

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