Proceedings of the International Conference on Environmental Pollution and Remediation
Ottawa, Ontario, Canada, 17-19 August 2011
Paper No. 210

Dry and Wet Machinability of Hardened Mould Steels

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Abstract **–** Dry machining is being proposed as a sustainable manufacturing process since it can help to respect both economical and environmental issues by avoiding the use of lubricants. However, some manufacturers are still hesitating to adopt dry machining, especially for steels, due to fears related to excessive tool wear and forces. The present paper attempted to compare the machinability and the surface integrity of three prehardened mould steels in dry and wet cutting conditions. The tested steels (P20-AIR MELT, P20-ESR and DIN 1.2711 ESR) were obtained using Air Melt and Electro-Slag Remelting (ESR) processes. For the tested conditions, results show that dry machining performs better than wet machining regarding tool wear and surface finish. These improvements depend significantly on melting process and chemical composition of the machined steels.

Keywords: Machining, lubrication, steels, surface integrity, tool wear, cutting forces, residual stresses.

1. Introduction

Nowadays metal cutting industry and particularly the mould manufacturing sector is looking for producing parts with improved machinability and surface integrity using environmental friendly processes. Besides, to compete with price and lead time, mould steels are increasingly machined in the hardened state (Tonshoff, Arendt et al. 2000). However, the machining of hardened steels results to higher cutting temperatures and consequently high cutting tool wear rates. To overcome these problems, manufacturers most of the times used wet machining to reduce cutting temperature and improve the tool life and surface quality (Dhar, Kamruzzaman et al. 2006). The use of lubricants has been widely criticized because their usage poses threat to ecology and health of workers (Vamsi Krishna, Srikant et al. 2010) (Sutherland, Kulur et al. 2000). Thanks to the development of new cutting tool materials and advanced techniques in metal processing (Chandrasekaran 2006), dry machining of hardened mould steels becomes possible. Songmene et al (2007) showed that dry machining is appropriate for cost reduction and for protecting the environment and the worker's health. Zaghbani et al (2010) have proposed a model for establishing the sustainability indexes (PSI) of products and applied it to the machining of mould steels. The proposed model was based on the tool life, cutting forces, surface finish, energy consumption, operation cost and the acoustic emission during machining mould steels, but not on surface texture.

Despite its direct impact on the functional performance of the parts, surface integrity and particularly residual stresses were less studied in the case of machined mould steels. In the present study, we focus on the machinability and surface integrity of pre-hardened mould steels machined in dry and wet conditions.

2. Experimental procedure

Three pre-hardened steels (38-42 HRC) that are widely used in plastic injection molds were evaluated in terms of machinability and surface integrity. The tested materials were low alloy steels produced with Air melt and ESR melting processes. The steels are referenced as P20-AIR MELT, P20-ESR and DIN 1.2711 AIR MELT. The P20 steel grades were commercial steels supplied by a mould steel maker. The typical compositions as provided by the supplier are listed in Table 1. The Sulphur and phosphor contents were consecutively (wt% <0.010) and (wt% <0.015) for all the tested steels.

Table -1 Typical compositions of tested steels.

Element	*C*	*Mn*	*Si*	*Ni*	*Cr*	*Mo*	*Al*
P20	*0.36*	*1.00*	*0.40*	*0.5*	*1.85*	*0.53*	*0.023*
DIN 1.2711 AIR MELT	*0.55*	*0.80*	*0.26*	*1.70*	*1.10*	*0.49*	*0.020*

Rough face milling operations were performed on the steel block in order to evaluate the tool life. All tests were conducted on CNC machining using an automated procedure. Additionally, Drilling operations were realizing to evaluate the thrust force on each of the tested steels. These tests consisted of recording the thrust forces (Fz) during the drilling operation. Finish end milling was performed for surface finish evaluations. All the experiences were performed in dry and wet cutting conditions. The test conditions are summarized in Table 2.

Flank wear patterns and machined chips were analyzed using optical microscope. Cutting forces were recorded during drilling tests using a Kistler dynamometer. Surface roughness was measured using Mutotoyo-SJ400 instrument. The machined surface texture was examined using scanning electronic microscope (Hitachi S-3600N). Surface residual stresses were measured using X-ray diffraction method.

Table -2 Test conditions

Test	**Operation**	**Tooling**	**Speed [m/min]**	**Feed**	**Depth of cut [mm]**
Tool wear	Rough Face milling	TiAlN coated carbide tool. Ø38mm	100,125,150, 200,225	0.1016 mm/tooth	Radial depth: 12.7 Axial depth:2.54
Cutting forces	Drilling	HSS drill Ø 10mm	7	57.15 mm/min	Hole depth: 12.7
Surface finish	End milling	TiN coated carbide tool. Ø 38.1 mm	125	0.1016 mm/tooth	Radial depth: 19 Axial depth:0.5

2. 4. Results and Discussion

2.4.1. Machinability study

The machinability of mould steels is most of the time evaluated in terms of tool life, chip morphology and cutting forces (Zaghbani, songmene et al. 2009). Other performance indicators such as surface texture can also be studied. In this work, in addition to traditional indexes, the machinability is discussed regarding the melting processes by which the alloys were obtained.

- **Tool wear analysis**

Figure-1 shows the tool life recorded during dry and wet face milling of the three steels tested. It can be seen that the tool life depends significantly on cutting speed and cutting mode (dry or wet). Dry machining can leads to higher tool life compared to wet machining (Figure 1). The P20-AIR MELT steel exhibits the highest tool life during dry machining at lower cutting speed however at higher cutting speed it is P20-ESR steel that performs better. In fact, the high tool life recorded during dry machining can be due to the lower wear rates induced during machining compared to wet machining (Figure-2). Cutting speed affects the wear rates in different ways for the three steels tested particularly during dry machining which gives evidence to the interaction between work materials, speeds and cutting modes (dry or wet). However, for wet machining (Figure-2-b), the cutting speed affects the wear rates in the same way for the cutting speed ranging between 150-225 m/min. The lowest wear rate values recorded during machining P20-ESR steel can explain the higher tool life obtained during wet machining for this steel.

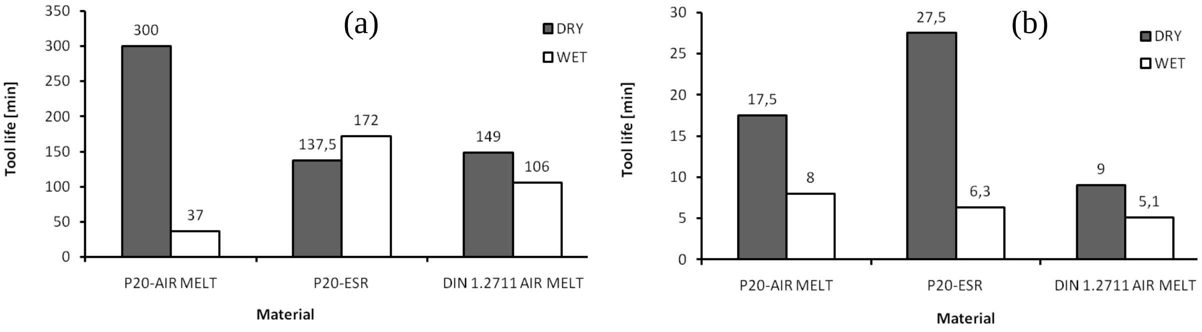


Figure -1 Tool life for VB =0.3 mm criterion at a) Vc=100 m/min and b) Vc =225 m/min

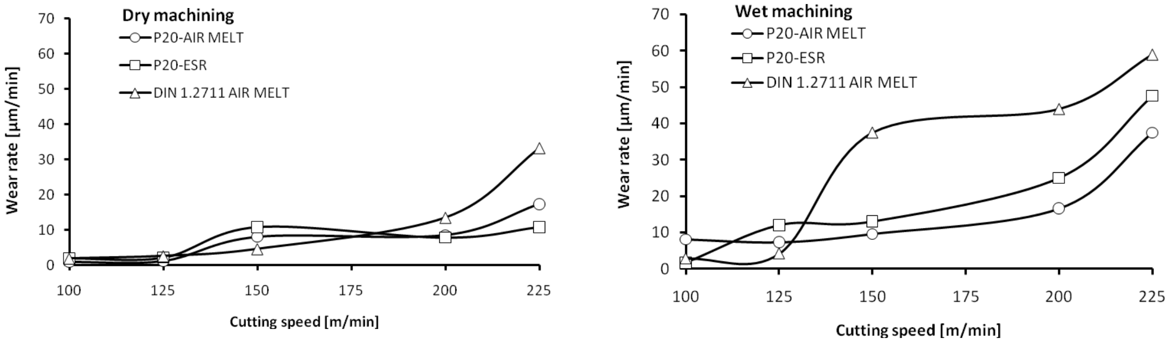


Figure -2 wear rates versus cutting speed.

Tables 3 and 4 show images of the flank wear recorded on tool during dry and wet machining. One can observe that dry machining exhibits a uniform and progressive flank wear rise (Table 3) compared to wet machining (Table 4) for all the steels tested. The tool life is limited by the maximum flank wear mode during dry machining. The longer tool life recorded during dry machining is attributed, essentially, to the resistance to coating flaking and chipping and the improved abrasive wear resistance of the multi-layer PVD-TiAlN coating of the tool (Prengel, Santhanam et al. 1997; Jindal, Santhanam et al. 1999). Whereas, when wet milling is performed (Table 4), the edge chipping is the failure mode that dominates which results in noticeable decrease of the tool life compared to dry milling. The chipping of the tool during wet milling is initiated by thermal cracks and the wear of the tool is preceded by microchipping of the insert edge accompanied by uniform flank wear (Prengel, Jindal et al. 2001).

Table -1 Flank wear evolution during dry machining at cutting speed Vc = 100 m/min

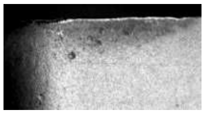
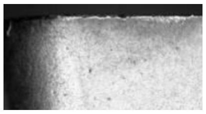
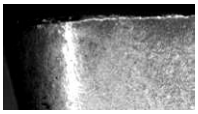
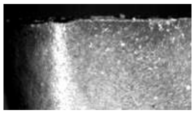
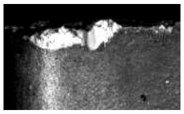
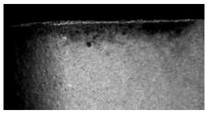
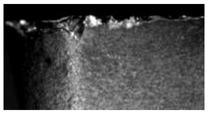
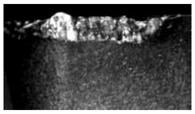
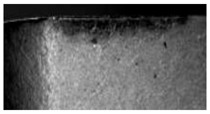
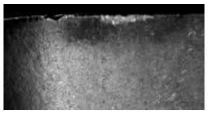
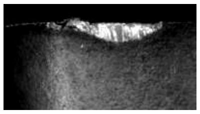
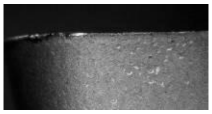
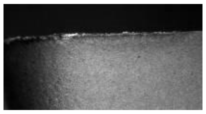
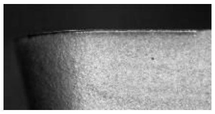
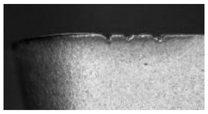
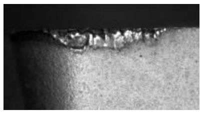
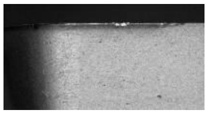
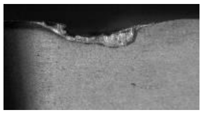
MATERIAL	***Time (min)***				
	43	*114*	*158*	*184*	*316*
P20-AIR MELT					
P20-ESR					
DIN 1.2711 AIR MELT					

Table -2 Flank wear evolution during wet machining at cutting speed Vc = 225 m/min

MATERIAL	***Time (min)***			
	1.1	***3.2***	***6.4***	***9.6***
P20-AIR MELT				
P20-ESR				
DIN 1.2711 AIR MELT				

From a material point of view, although the three steels have the same hardness they exhibit different tool life for each cutting modes. Hence, we considered that the melting processes can explain the different behaviours of the cutting tool observed during the testing. The melting process leads to different microstructures, sizes and distribution of inclusions and carbides which affects differently the wear of the cutting tool (Poulachon 2003) (Chandrasekaran 2006). Although the DIN 1.2711 grade steel was obtained using air melt technique, it exhibits lower tool life compared to the P20-AIR MELT. The difference in tool life could be explained by the higher amount of Carbon and nickel elements of the DIN 1.2711 AIR MELT steel compared to P20-AIR MELT steel.

- **Chip morphology**

The chips produced during rough face milling are typically elemental chip type for almost steels tested and for the high and low cutting speed as showing in Table -5. Oxidized chips with brown colour are produced during wet machining due to the rapid cooling by the cutting fluid during machining. However, the chips produced during dry machining are blue colour and the chips produced at higher cutting speed were obviously deformed compared to those produced at lower cutting speed.

Table -3 Chips produced during rough face milling

Machining mode		Steel		
		P20-AIR MELT	P20-ESR	DIN 1.2711 AIR MELT
Vc = 100 m/min	Dry			
	Wet			
Vc=225 m/min	Dry			
	Wet			

- **Cutting forces**

Cutting forces are a significant parameter for the evaluation of the cutter’s penetration ease during machining. They are reliable indicators of the cutting power consumption. Drilling tests were performed and penetration force were recorded during wet and dry cutting modes. Observing Figure 3, one can conclud that penetration forces are almost equal regarding machined steels and cutting modes. These results indicate clearly that the wear behavior of the cutting tool is most probably governed by the microstructure of the machined steel as previously mentioned. Also, the little increase of the penetration force obtained when drilling DIN 1.2711 steel give evidence of the effect of the higher amount of carbon and nickel elements as compared to the P20-steel grades.

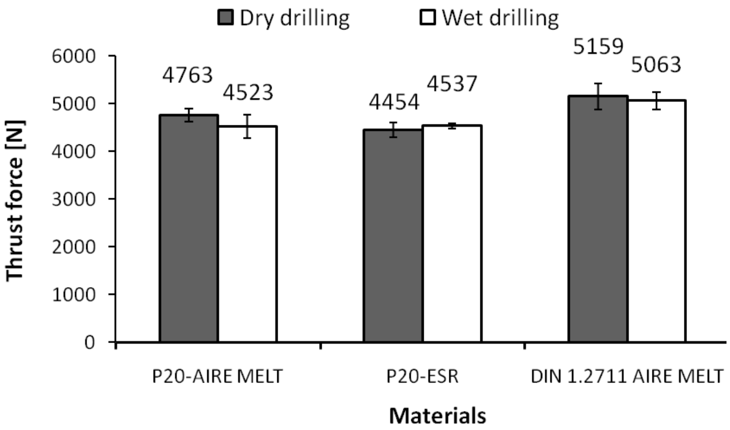


Figure -3 Effect of machined steels and cutting mode on Penetration forces

2.4.2. Surface Integrity

- **Surface texture**

Surface integrity and particularly residual stresses of machined parts have direct impact on their functional performance and life cycle. The machining process and conditions can affect the part machining surface texture. End milling tests were performed using a TiN coated carbide tool in order to evaluate the surface texture of the machined parts under dry and wet conditions. The arithmetic surface roughness produced during wet machining are about three times higher than those obtained during dry machining for almost tested steels (Figure -4). A close examination of the machined surfaces under scanning electron microscope (SEM) reveals that distinguishing features over dry and wet conditions can be identified (Table -6). The dry machined surfaces seems smoother with less feed marks as compared to wet machined surfaces which experience deeper and crossed feed marks. In fact, this phenomenon has been reported and most of the times was attributed to the accelerated flank wear and notch wear on the auxiliary tool edge under wet machining conditions (Dhar, Kamruzzaman et al. 2006).

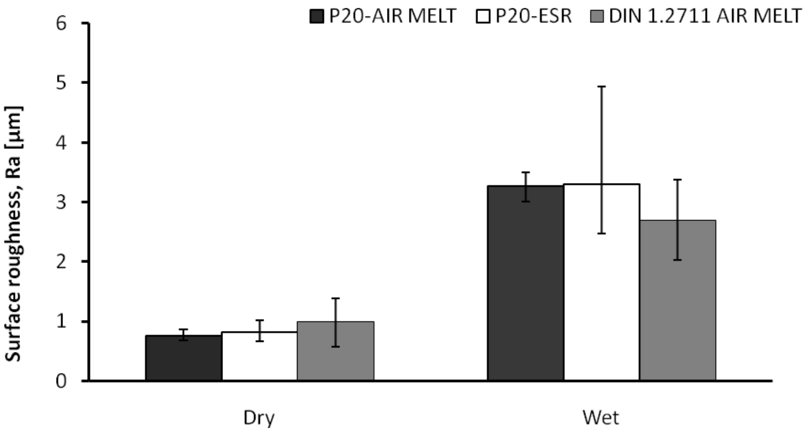
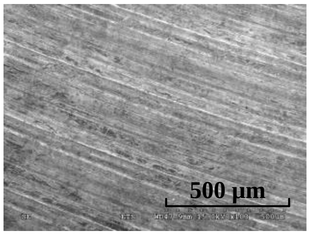
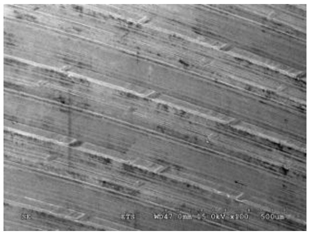
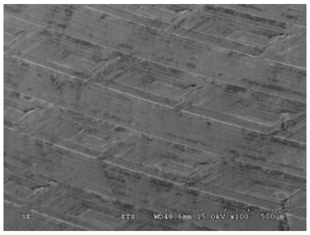
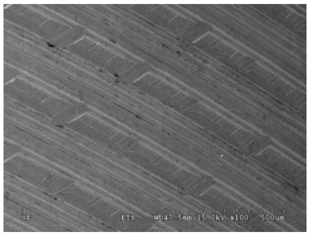
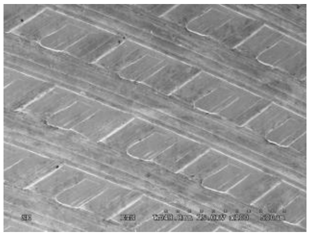
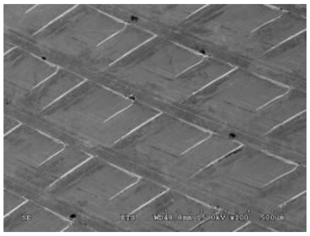


Figure -4 Average surface roughness obtained during dry and wet machining.

Table -4 Surface texture of the machined surfaces

Cutting mode	**Steels**		
	P20-AIR MELT	P20-ESR	DIN 1.2711 AIR MELT
Dry			
Wet			

- **Residual stresses**

Surface residual stresses were measured in two direction (Figure -5) using an X-ray diffraction technique. Figure -6 and 7 shows clearly that cutting mode (wet or dry) affect differently the residual stresses state depending on the machined steel grade. In fact, the milling of the P20-AIR MELT steel results to tension residual stresses in the two directions and also for dry as well as for wet cutting mode. Whereas, compressive residual stresses were obtained in the case of P20-ESR steel in the transversal direction (Figure -7) and also for DIN 1.2711 AIR MELT steel in longitudinal direction (Figure -6). The highest compressive residual stress values in dry as well as in wet conditions (respectively -433 MPa and -436 MPa) were obtained in the longitudinal direction which could be explained by the higher plastic deformation and mechanical loading induced by the advance of the cutting tool during milling in the feed direction.

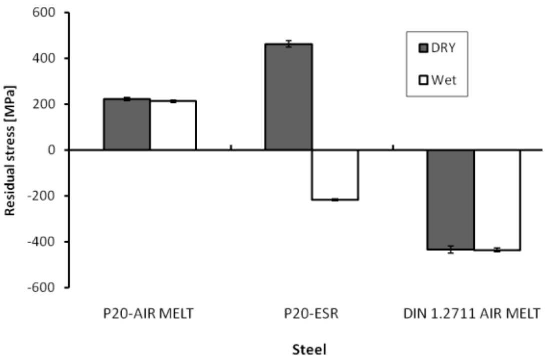


Figure -6 Longitudinal residual stresses.

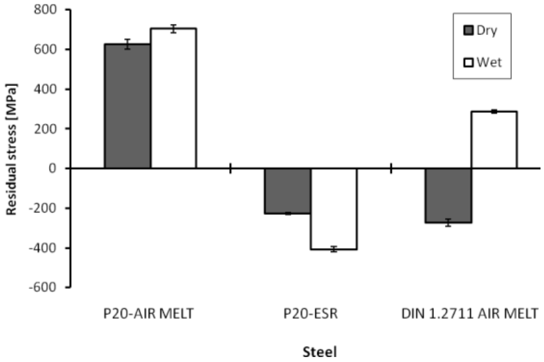


Figure -5 Transversal residual stresses.

3. Conclusion

The machinability and surface integrity of three mould steels were investigated during dry and wet machining in this work. The results show that:

- Dry machining of hardened mould steels can perform better in terms of tool wear and surface finish compared to wet machining, depending on cutting speed used;
- The residual stress state is highly influenced by the cutting mode and the melting processes of the machined steels.
- Compressive residual stresses were obtained in the case of P20-ESR and DIN 1.2711 AIR MELT steels whereas tension residual stresses were produced during dry and wet machining of P20-AIR MELT steels in the two directions.
- The encouraging results obtained in the present work makes the dry machining a sustainable machining process for the tested steels.
- Further investigation over a larger range of cutting parameters should be made in order to optimize the residual stress state of the tested steels.

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