International Journal of Civil Engineering and Building Materials (ISSN 2223-487X) Vol. 2 No.3 2012

Investigation on Tool Wear During Dry and Wet Machining of Hardened Mould Steels

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Keywords: mould steels, melting process, lubrication, milling, tool wear.

Abstract. The development of new melting processes for mold steels demands a great attention from steel manufacturers to improve the machinability of such steels. One of the important parameters that affect machinability is the tool wear. An insightful understanding of tool wear behavior can lead to better process economics, increased process stability, improved tool life and reduced tooling costs. The present paper attempted to study the tool wear mechanisms of a PVD-TiAlN coated carbide tool during face milling of two hardened mold steels in dry and wet 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. The results show that although the tested steels have comparable hardness, the tool wear behavior is different regarding the cutting mode, melting processes and chemical composition of the tested steels. For the tested steels and conditions, the dry machining performs better than wet machining. The tool life is limited by the maximum flank wear mode during dry machining. Nevertheless, when wet milling is performed, the catastrophic tool wear is the failure mode that dominates which results in noticeable decrease of the tool life compared to dry milling.

Introduction

The machinability of materials is usually evaluated using indicators such as tool life, surface finish, cutting forces but the tool wear is the criteria the most used. Recently, Zaghbani *et al.* [1] demonstrated that the tool life is one of the most important parameters that affect the machinability rating of mould steels. With the development of new steels and cutting tool materials, further efforts should be made in order to understand the basic tool wear and tool failure mechanisms during machining. Cho and Komouvopolos [2] observed that the different wear mechanisms are not mutually exclusive; they may occur simultaneously at different locations on the same tool surface. The tool surface state is greatly dependent on the coatings used. Klocke *et al.* [3] summarized the fundamental research works on advanced coatings effect on contact conditions and wear mechanisms during the machining of different ferrous metals. The latter may be affected deeply by the use of metal cutting fluids. Haron *et al*. [4] investigated the effect of cutting fluid on the coating performance during turning operations. The authors [4] proved that the tool wear mechanisms can change from mechanical to thermal when the cutting fluids are applied. This change is principally due to different tribological effects. Khrais and Lin [5] investigated the tribological influences of PVD-applied TiAlN coatings on the wear of cemented carbide inserts and the microstructure wear behaviours of the coated tools under dry and wet turning of hardened steels. The study reveals that when the material hardness rises above 40 HRC the material machinability decreases due to shortened tool life either in wet or dry conditions. Zaghbani *et al.* [6] showed that the cutting mode (dry or wet) has a significant effect on tool wear mechanisms during the machining of hardened mould steel tools. Hardened steels often contains a high amount of abrasive carbides which can leads to high mechanical loads and cutting temperatures and consequently the tool life can be extremely shortened [7]. Poulachon *et al*. [7] studied the effect of the microstructure of four hardened materials with the same hardness on the cutting tool wear. The results showed that, in spite that they have the same hardness, the machined materials exhibit different tool wear behaviours due to different types and sizes of carbides existing in each steel. Chandrasekaran and M'Saoubi [8] studied the effect of melting processes and alloying on the dry machinability of hardened steels. The study showed that at a given hardness, the materials microstructure has a strong effect on the resulting machinability during hard milling.

In the present paper a comparative study of tool wear mechanisms when machining mould steels manufactured using two different melting processes is investigated under dry and wet milling conditions. The paper starts with a brief description of the experimental protocol followed by a presentation of the important results on tool wear mechanisms. In the last section a summary of the realized work are presented.

Experimental procedure

Two hardened P20 (with trace elements) and DIN 1.2711 steels that are widely used in plastic injection moulds were used in this work. The tested materials were produced with Air melt and ESR melting processes. The steels tested are referenced as P20-AIR MELT, P20-ESR and DIN 1.2711 AIR MELT and have approximately the same hardness (38-42 HRC). The typical compositions of these steels as provided by the supplier are listed in Table 1.

Table 1 Typical compositions (wt %) of tested steels.

Element	***C***	***Mn***	***Si***	***Ni***	***Cr***	***Mo***	***Al***	***S***	***P***
P20	*0.36*	*1.00*	*0.40*	*0.5*	*1.85*	*0.53*	*0.023*	*0.005*	*0.012*
DIN 1.2711	*0.55*	*0.80*	*0.26*	*1.70*	*1.10*	*0.49*	*0.020*	*0.003*	*0.012*

Dry and wet end milling tests were conducted on CNC machining using an automated procedure. An end mill with two PVD-TiAlN multilayer coated carbide inserts was used in the experiments. The cutting cutting speeds (V_c) was set at 100, 125, 150, 200 and 225 mm/min at a constant feed (f_z) of 0.1016 mm/tooth with an axial depth of cut (a_a) of 2.54 mm and a radial depth of cut (a_r) = 12.7 mm. The maximum flank wear was measured using optical microscope while crater and flank wear lands were analyzed using scanning electron microscope (ESM). The most important findings during this study are presented in the following section.

Results and analysis

The tool wear of coated inserts was evaluated in dry and wet milling of three steels. Figure 1 shows the progression of the maximum flank wear as function of cutting time for the three materials tested at a cutting speed of 100 mm/min under dry and wet conditions. Visibly, in term of tool life, the three materials perform better under dry conditions than under wet conditions. The lowest wear rate is recorded during dry machining of the P20-AIR MELT steels at cutting speed of 100 mm/min. At the same conditions, the wear curves of the P20-ESR and DIN 1.2711 AIR MELT steels are nearly identical. Inversely, at wet conditions, the P20-ESR steel performs better than the P20-AIR MELT steels and DIN 1.2711 AIR MELT shows intermediate wear behaviour.

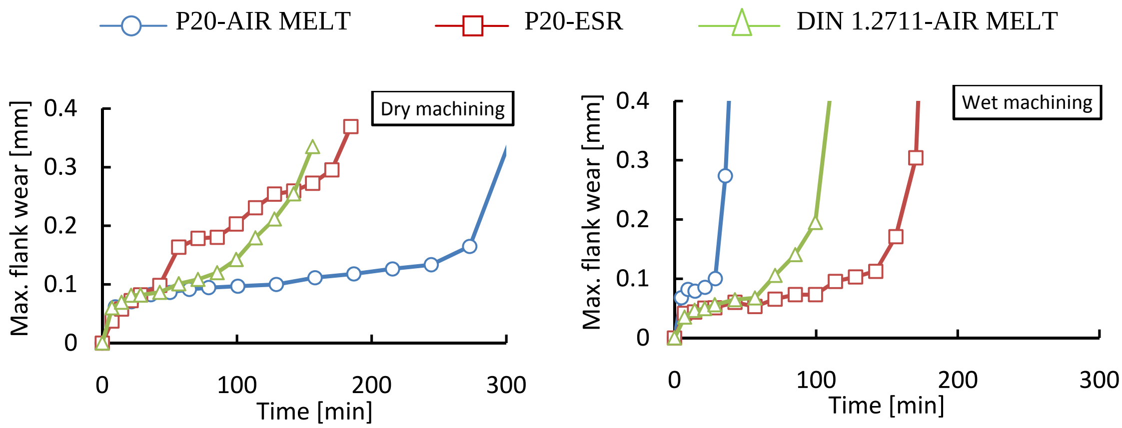


Fig. 1 Maximum flank wear (mean from 2 inserts) as function of cutting time; V_c= 100 m/min; f_z = 0.1016 mm/tooth; axial depth = 2.54 mm and radial depth = 12.7 mm.

The TiAlN coating of the inserts experiences a pronounced resistance to flank wear when dry machining the P20-AIR MELT steel at a cutting speed of 100 m/min. In these conditions, the tool wear progresses through three stages as follow:

- The wear of the cutting tool started by a localized plastic deformation of the tool edge (Figure 2.a). The plastic deformation of the edge is characterized by a slight change of the edge radius without any significant edge chipping. The occurring of plastic deformation may be caused by the high level of stresses induced by the combination of high mechanical load and small contact surface.
- The second stage is characterized by the formation of a uniform microchipping along the tool edge (Figure 2.b and 2.e). The microchipping grow progressively and slowly to reach the value of 0.15 mm after about 270 min (Figure 1-Dry machining). This behavior may be attributed to the improved abrasive wear resistance that characterize the PVD-TiAlN coating of the cutting tool used in the experiments [9] [10]. It can be noted that the coating burns out at the flank and rake faces as shown in figure 2.a and 2.e. The final color of the coating is a good indicator of the reached temperature level. The darker is the coating color, the higher is the temperature.
- Finally, when the flank wear reaches a given level (about 0.15-0.2 mm), the cutting temperature and stresses rise dramatically which accelerate the delamination of the coating before the failure of the cutting tool. In fact, the edge micro-chipping breaks the heat barrier that was created by the coating, leading to a "voided-heat-barrier". When the created voids in the heat barrier reach a critical dimension, the heat transfer from the chip to the insert become significant and can increase the adhesive wear. This heat transfer affects the properties of the existing bonds between the carbides causing their failure. This phenomenon becomes more important as the coating goes away and makes the exposed uncoated area becomes larger.

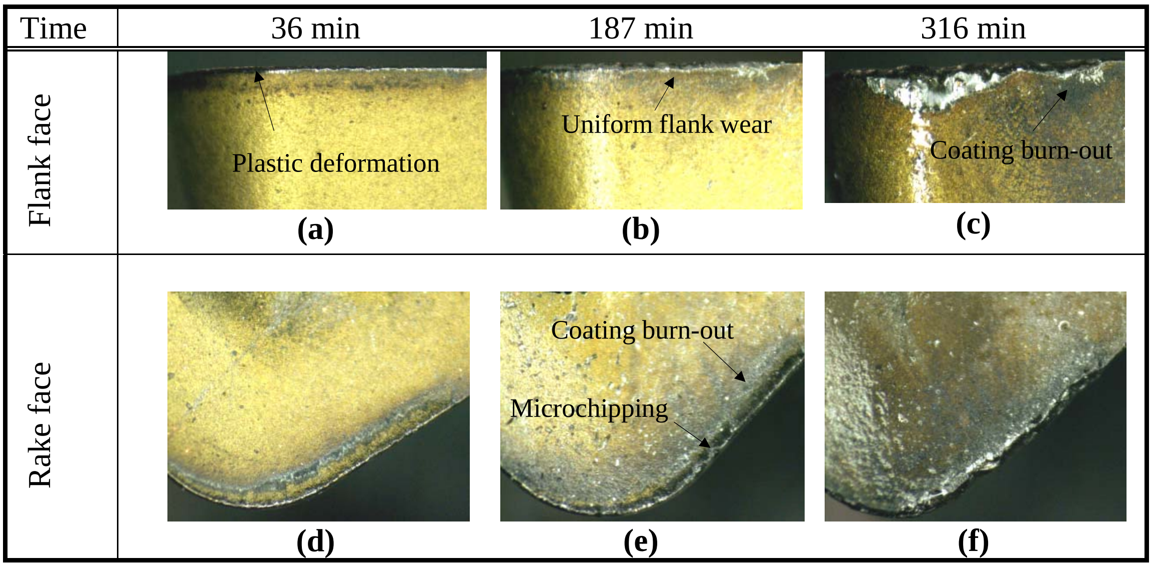


Fig. 2 Tool wear evolution during dry machining of P20-AIR MELT steel at cutting speed of 100 mm/min.

In the case of dry machining of the P20-ESR steel at a cutting speed of 100 m/min, the tool wear starts by chipping near the tool nose (Figure 3.a) which then propagates along the tool edge (Figure 3.b). The propagation of the edge chipping was irregular and sudden in some cases. It can be observed in the Figure 1-Dry machining, that there is a sudden increase of the tool wear after 40 minutes of machining. This sudden increase is explained by the appearance of comb cracks at this stage. The comb cracks are induced by thermal shock stresses taking place because of the intermittent cutting process. The shock stress is more important when the insert temperature is higher and the cooling rate is higher too. In dry condition the cooling rate is controlled by the ambient air surrounding the insert. The increase of the insert temperature when milling the P20-ESR may be due to two reasons: either the P20-ESR material has a lower thermal conductivity which causes a less heat transfer to the work piece material or the P20-ESR steels has lower sulphur content than the P-20AIR MELT which will cause an increased wear that will raise the insert temperature as explained above.

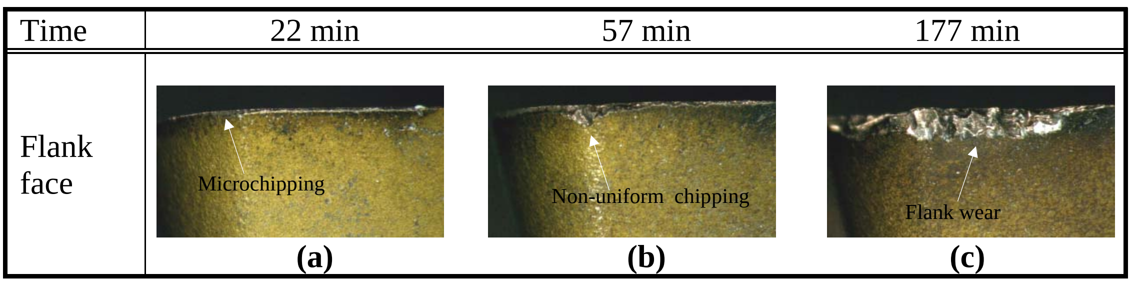


Fig. 3 Flank wear evolution during dry machining of P20-ESR steel at cutting speed of 100 mm/min

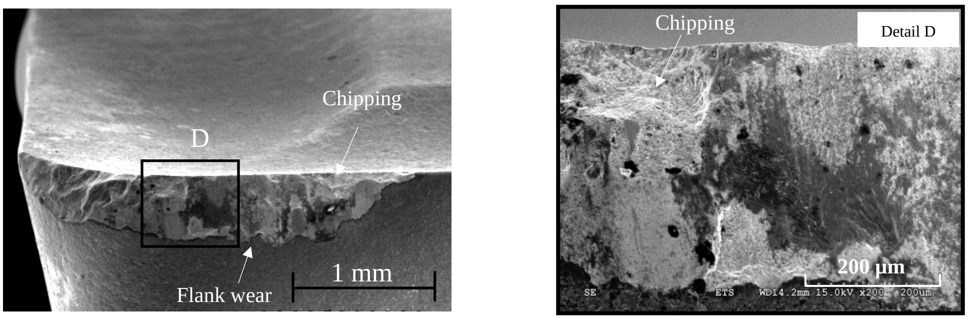


Fig. 4 SEM micrographs of tool wear (insert 1) after dry machining of P20-ESR at cutting speed of 100 mm/min and t=185 min.

The inserts were observed under scanning electronic microscope (SEM) at their end of life. It was observed that the P20 in both version AIR MELT and ESR didn't lead to adhesive tool wear at low cutting speed of 100 m/min (Figure 4 and Detail D). At the opposite, adhered layers were observed into the wear land during dry machining DIN 1.2711 AIR MELT steel at lower speeds (Figure 5 and Detail D).

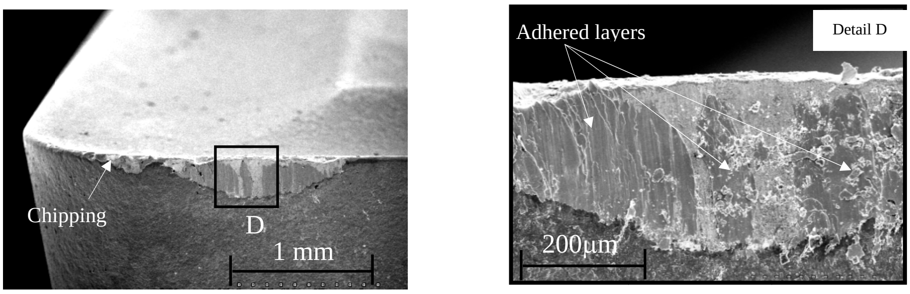
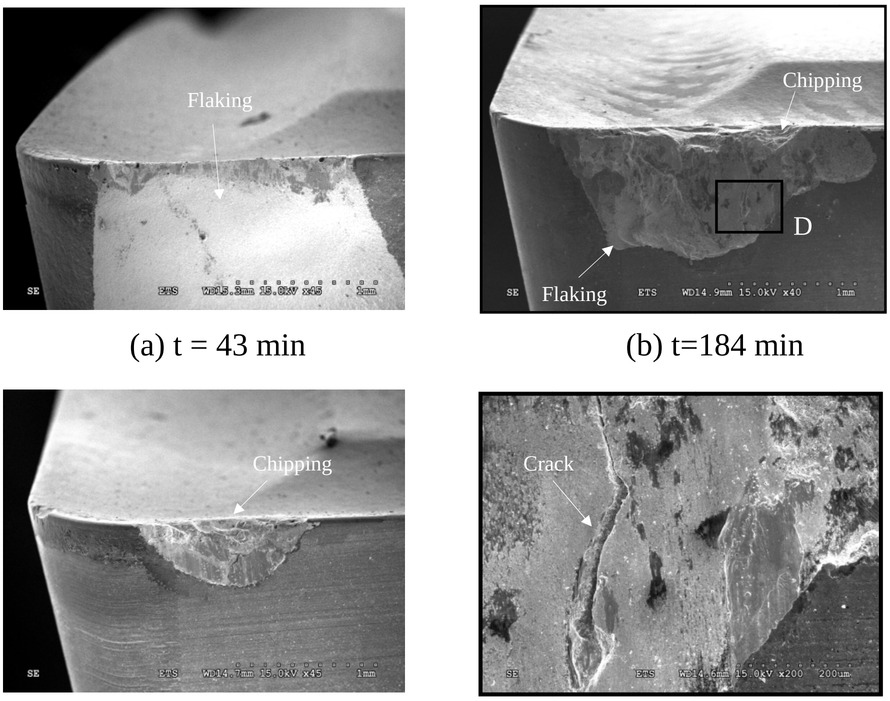


Fig. 5 SEM micrographs of tool wear (insert 1) after dry machining of DIN 1.2711 AIR MELT at cutting speed of 100 mm/min and t = 156 min.

The adhered layers may alter the geometry and the properties of the cutting edge. The cutting edge becomes similar to the cut material which induce a similar thermal properties and more heat transfer from the chip to the insert increasing by this way the wear rate. The presence of adhered layers when machining the DIN 1.2711 AIR MELT might be due to its chemical composition that made the adhesion favourable.

In the case of wet machining of the P20-AIR MELT steel at lower cutting speed (100 m/min), a non uniform chipping grow progressively until a value of about 0.1 mm (Figure 1), after that a rapid tool failure was observed (Figure 6.a). However, the rapid tool failure was observed when flank wear reaches about 0.2 mm in the case of wet machining of P20-ESR and DIN 1.2711 AIR MELT steels (Figure 1). Figures 6.a and 6.b show a severe flaking (peeling) and chipping of the inserts in the case of P20-ESR and P20-AIR MELT steels. The flaking was preceded by the appearance of comb cracks along the cutting edge after 3 minutes of continuous milling. These comb cracks were large and deep. They are due to thermal shock caused by the high cooling rate. The high cooling rate of the cutting fluid is significantly higher than the cooling rate of the air. Thus, high thermal stresses were created in the inserts leading to flaking phenomena. The flaking causes a premature failure of the inserts.

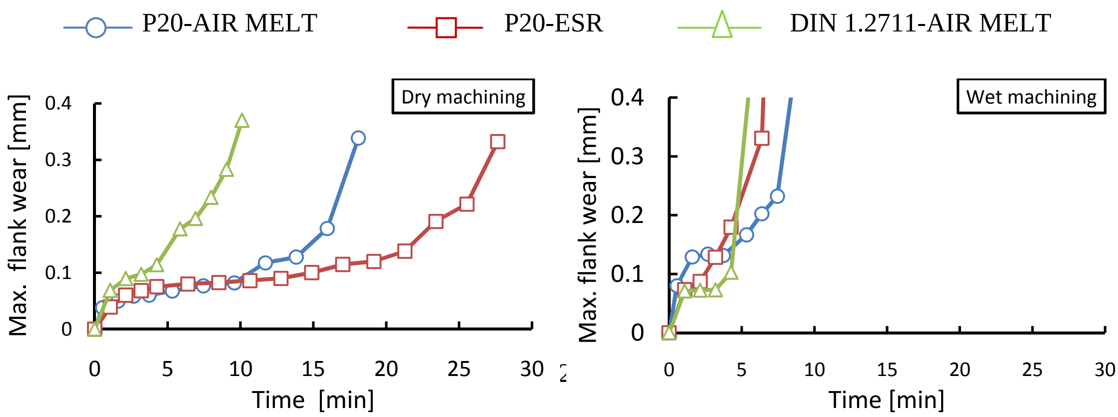


(a) t = 43 min (b) t=184 min

(c) t = 114 min Detail D

Fig. 6 SEM micrograph of tool wear (insert 1) after wet machining of a) P20-AIR MELT, b) P20-ESR and c) DIN 1.2711 AIR MELT at cutting speed 100 mm/min.

At higher cutting speed (225 m/min), the P20-ESR steel performs better than DIN 1.2711 AIR MELT steel in dry conditions (Figure 7) and the P20-AIR MELT steel has intermediate wear behaviour. At this regime, the wear mechanisms seem to be the same for the three materials tested. In fact, microchipping on the tool edge has been observed in the beginning of the machining. Due to higher cutting temperatures, adhered layers (Figure 8) were formed particularly in the chipping zones. The adhered layers grow progressively and accentuate the delamination of the tool coating and most probably may induce catastrophic flaking in the end of the machining (Figure 8.b). Additionally, the cracks observed on Figure 8 (Detail D) give evidence of the higher cutting temperatures and stresses induced when dry machining at higher cutting speeds. The three steels exhibit practically the same behavior during wet machining at higher cutting speed (Figure 7). Catastrophic tool failure was observed after a few minutes of machining for all tested steels.



International Journal of Civil Engineering and Building Materials (ISSN 2223-487X) Vol. 2 No.3 2012

Fig. 7 Maximum flank wear progressions (mean from 2 inserts); Vc = 225 m/min; f_z = 0.1016 mm/tooth; a_a = 2.54 mm and a_r = 12.7 mm.

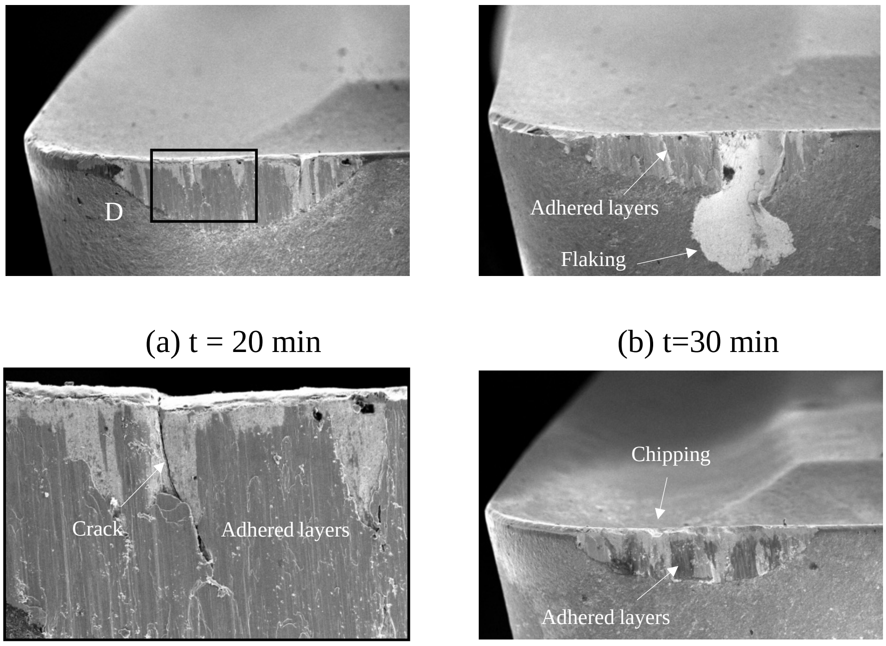


Fig. 8 SEM micrographs of tool wear (insert 1) after dry machining of a) P20-AIR MELT, b) P20-ESR and c) DIN 1.2711 AIR MELT at cutting speed of 225 mm/min.

The previous tests were repeated for other cutting speeds (up to 225 m/min) under both dry and wet conditions. The obtained results are summarized using the Taylor's law for tool life. Figure 9 illustrates the behavior of the materials under wet and dry conditions for wide band of cutting speeds.

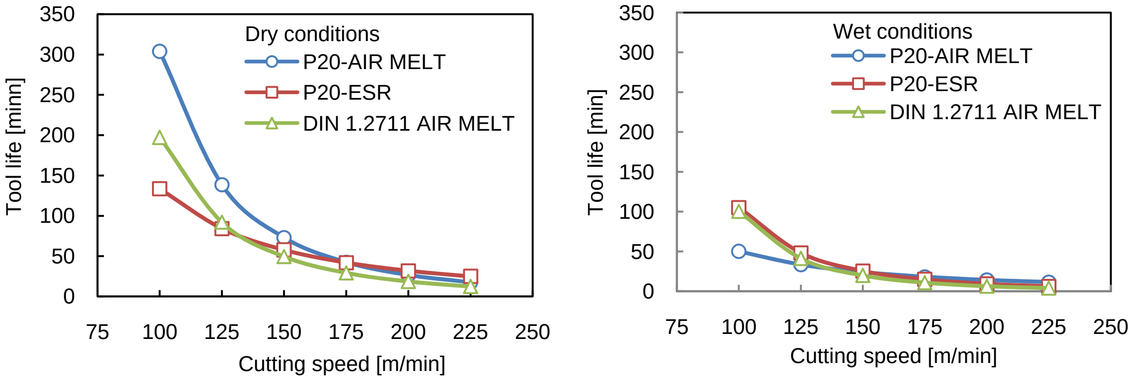


Fig. 9 Taylor models of tool life for dry machining and wet machining.

Figure 9 shows that although the three steels have the same hardness they exhibit different tool life for each cutting modes. The melting process leads to different microstructures, sizes and distribution of inclusions and carbides which affects differently the wear of the cutting tool [7] [8]. In fact, the melting process has a significant effect on the P20 steels. Particularly, when dry milling at lower speed (100 m/min) the AIR MELT grade performs better than the ESR one and the inverse is true in wet conditions (Figure 9). Although the DIN 1.2711 and the P20 were obtained with the same melting process (AIR MELT), they exhibit different wear behavior regarding the cutting modes at lower speeds. 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. While the high speed milling the three materials exhibit some differences in tool life but without being as significant as that. The flaking of the inserts during wet milling was the main cause of shortened tool life, in both ranges low and high cutting speeds.

Conclusion

The melting process has a significant influence of the tool life in milling process. The latter is characterized by an intermittent cut that causes different wear mechanisms. These mechanisms were investigated and analyzed during dry and wet milling. The observed mechanisms are different between the two milling modes, while the dry milling exhibits a progressive wear, the wet milling shows a sudden tool failure. The obtained results proved that it is possible to obtain a higher tool life when machining mould steels under dry conditions, if the right cutting speeds are selected.

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