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High Strength Steel solutions for powertrain applications : Machinability testing for gear hobbing applications

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Abstract

ArcelorMittal focuses on both mechanical performances and machinability while designing new steel grades. ArcelorMittal has developed specific programs for machinability testing in turning, low and high speed drilling and gear machining. Machinability is evaluated through cutting forces, chip shape, surface quality and tool life. Gear machining is one of the main machining operations involved in powertrain manufacturing operations. The literature proposes many papers dealing with this process however there are too few studies interested in steel machinability evaluation while gear machining. This paper focuses on a particular gear manufacturing process, i.e. gear hobbing, and more precisely on steel machinability for gear hobbing applications. Tools as well as kinematics of gear hobbing are quite complex. This paper proposes a comprehensive experimental protocol for machinability testing. This protocol is based on a European standard. Tests are performed on a machine tool using a commercially available cutting tool. Tests provide the range of cutting conditions for five different steel grades. Both steels have a ferrite-pearlite structure with yield stress from 530 to 800 MPa and ultimate tensile stress from 680 to 900 MPa. Four grades are devoted to bar machining. The last one is devoted to forming and then machining operations. Many metallurgical solutions are investigated to enhance machinability such as lead addition or increase in sulfur content or calcium treatment. This paper analyses the influence of steel composition and structure on machinability. It shows the relevance of metallurgical solutions for machinability enhancement even for powertrain applications. Cutting conditions clearly depend on the metallurgical solution even if specific cutting force is finally close. The main difference is found on tool wear with tool life ratio from 1 to 1.5.

Keywords: Engineering steels, machinability, gear hobbing, the Couple Tool-Material.

1. Introduction

The gear hobbing process investigations started due to a ArcelorMittal customer assistance request. Literature proposes numerous studies devoted to gear hobbing. Most of them are concerned with hobbing modelling (chip section and/or tool wear and/or cutting forces prediction) or hobbing testing (i.e. wear distribution along the cutting edges and/or performance evaluation for substrate or coating or edge preparation) [1] [2] [3] [4] [5]. One of the main difficulties in gear manufacturing studies is that gear cutting machines are production machines where classical instrumentation is difficult to implement. Several authors have proposed relevant techniques to perform hobbing or hobbing-like operations. The experiments performed are so called fly hobbing, a technique widely used by researchers [1] [2] [4] [6] [7].

Few papers are dealing with the influence of metallurgical solution on machinability in gear hobbing. ArcelorMittal develops a research program focusing on the influence of metallurgical solution on machinability within a whole manufacturing process involving both forging and/or heat treatment [8]. Many machining processes have already been investigated: turning, drilling, gun drilling [8] [9] [10]. This paper proposes results concerned with hobbing.

2. Steel grades investigated

Machinability is investigated for five low alloy steel grades devoted to powertrain applications. The steel grades investigated are called G1, U1, U2, K1 and K2. Their chemical composition and mechanical properties are listed in the Table 1. G1 is a steel grade commonly used for automotive gear applications. U1, U2, K1 and K2 are steel grades used in swiss machining applications. The steel grade U is available with two different structures. U2 is cold drawn. A partial spheroidization heat treatment is applied to U1 before cold drawing. K1 and K2 global chemical composition are very close. A machinability enhancement treatment using both metallic and non-metallic inclusions is applied to K2.

	HV ₃₀	Rp _{0.2}	Rm	chemical composition (ppm)			
				C	Mn	S	Si
U2	315	750	900	419	1545	185	215
U1	225	584	676				
K1	265	715	833	390	1715	222	177
K2	265	788	842	388	1533	247	109
G1	320	534	846	200	1250	35	300

Table 1 : Steel grades investigated

3. Machinability evaluation

Machinability is evaluated based on experiments led according to the Couple Tool Material methodology [11]. It is a standardized experimental protocol devoted to evaluate machinability in turning, milling and drilling. The experiments are to be done for each association workpiece / cutting tool / machining operation. The result is an operating range i.e. the whole acceptable machining conditions for the association workpiece / tool / operation. A machining condition is regarded as acceptable when:

- specific energy values are acceptable,
- chips are regular and fragmented,
- tool wear is regular and controllable,
- surface roughness is compatible with other similar machining applications,

The Couple Tool Material standard proposes to measure the specific energy and to determine the operating range from its variations versus either the cutting speed or the feed. Specific energy measurement is not relevant for fly hobbing experiments. The contact time between cutting edge and workpiece is very low (between 5 and 100 ms depending on the cutting conditions). The most convenient system for this purpose is the piezoelectric dynamometer. The operating range is also determined not from specific energy but from a very close physical quantity: the specific cutting force k_C . An usual value of feed per tooth is arbitrarily chosen. The cutting speed varies within a large range (about from 10 to 250 m/min).

k_C clearly depends on chip thickness however a curve $k_C = f(V_c)$ can be drawn for a particular chip thickness value, and $V_{c_{min}}$ can be deduced. Specific energy as well as specific cutting force usually decreases when cutting speed increases. An asymptotic trend often appears when drawing the curve $k_C = f(V_c)$. $V_{c_{min}}$ is considered as the minimal cutting speed value required getting low and constant values of k_C .

On one insert engagement, the specific cutting speed can be drawn as a function of the chip thickness which is linked to the feed. That involves the possibility to determine the minimum feed f_{min} without doing tests with various feed (such as the determination of $V_{c_{min}}$).

Physical phenomena in tool wear lead to an alteration of the tool geometry [13], and then the machined parts geometry is perturbed. Standard details how to characterize this geometry damages on both the relief and rake face. The steel grades machinability can be compared by many ways such as the tool life (T) until a VB value about 200 μm is reached. Three cutting speeds from the operating range are arbitrarily chosen for the wear tests of each steel grade and the lengths hobbled are computed. Taylor equation is simplified, the cutting speed being the predominant factor, the influence of the feed has not been considered.

4. Experimental device

Fly hobbing operations are performed on a 4-axis NC machining centre Ernault FH 45. Forces are measured using a Kistler 9257 3 component dynamometer. The tool is a Sandvik side milling cutter with indexable inserts. The outer diameter is 80 mm. The width is 5 mm. One GC4040 or GC4240 coated carbide insert is used for fly hobbing tests. It enables to reduce workmaterial quantity for tool wear tests. It also simplifies cutting forces analysis and insures a regular tool wear.

5. Experiments and results

Milling kinematics is quite complex. The cutting edge trajectory (i.e. a cycloid) leads to a continuous variation in cutting geometry and instantaneous chip thickness. Edge geometry variations are not considered in the analysis of cutting forces. Chip thickness is approximated using:

$$h(\phi) = fz \times \sin(\phi) \times \sin(\kappa_R) = fz \times \sin(\phi) \text{ with } \phi \in \left[\pi - \cos^{-1} \left(1 - \frac{2 \times ae}{D} \right), \pi \right] \quad (3)$$

All experiments consist in down milling operations. Down milling is commonly used during roughing operations.

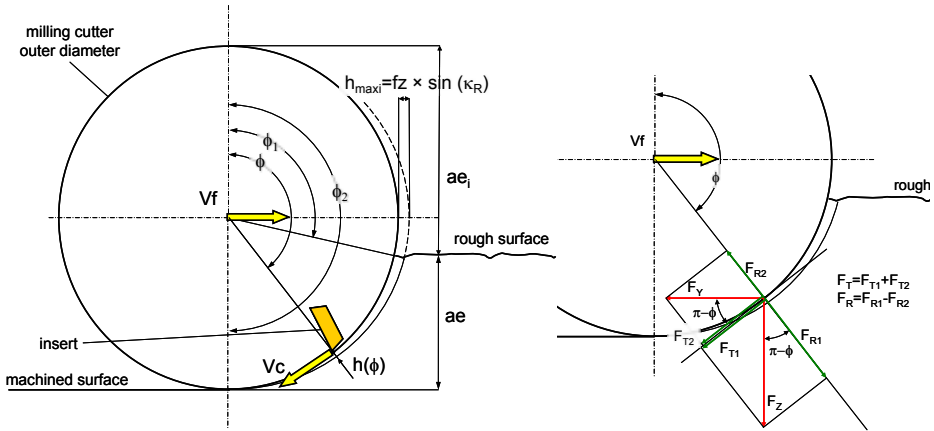


Figure 1 : Milling kinematics - Chip thickness

Cutting forces values F_x , F_y , F_z are computed to get the tangential and radial forces, respectively F_T and F_R . F_x and so axial force are still negligible due to the tool geometry (inclination angle is zero). Cutting forces time curves and the cutting insert angular position are fitted thanks to a FFT analysis. It provides both the actual rotating speed of the spindle and the phase shift between tool angular position and time. The cutting tool geometry is extremely simple and prevents cutting force discretization along cutting edge. Models provided are mechanistic [12] :

$$F_T(\phi) = k_C \times h(\phi) \times ap \qquad F_R(\phi) = k_R \times h(\phi) \times ap \quad (5)$$

k_C and k_R simple models are used to

$$k_C(\phi) = k_{C\text{ref}} \times \left(\frac{h_{\text{ref}}}{h(\phi)} \right)^{n_C} \qquad k_R(\phi) = k_{R\text{ref}} \times \left(\frac{h_{\text{ref}}}{h(\phi)} \right)^{n_R} \quad (7)$$

$k_{C\text{ref}}$ n_C $k_{R\text{ref}}$ n_R are determined for each experiments from cutting forces curves using a least square method. a_p is constant for the whole experiments and is equal to the tool width.

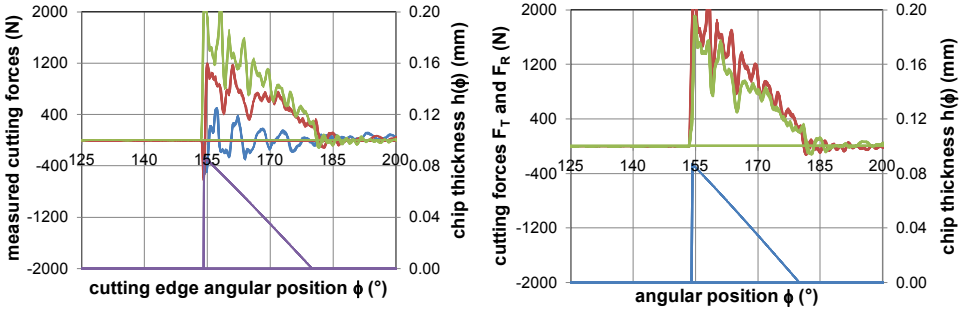


Figure 2 : Forces measurements and chip thickness (G1 steel grade, $V_C = 150$ m/min, $f = 0.2$ mm/rev)

For variable cutting speed value, k_C computations lead to graphs such as :

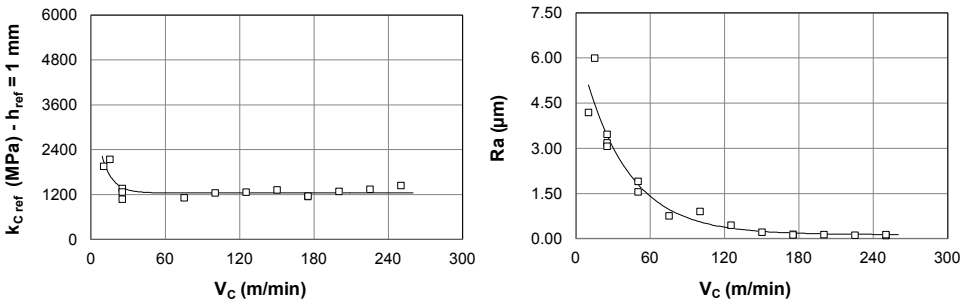


Figure 3 : $V_{C\text{min}}$ determined from k_C computations and R_a measurements (G1 steel grade, $f = 0.2$ mm/rev)

Roughness is one of the most important specifications on gear surfaces. Roughness levels depend on the gear's precision class. The longitudinal roughness in the groove is then measured. When machining with a constant feed, the roughness is supposed to remain almost constant. Measurements highlight that roughness depends on cutting speed value and decreases with an increase of cutting speed. A specific cutting speed value, i.e. $V_{C\text{min}}$ or minimal cutting speed, should be defined based on roughness or specific cutting force considerations. A synthesis for both steel grades is presented in Table 2.

A mean apparent friction coefficient is calculated within the chip thickness range used to determine $k_{C\text{ref}}$ value.

Steel grade	HV ₃₀	Vc _{min} (m/min)	k _{C ref} (N/mm ²) at Vc _{min}	μ
U1	225	60	1330	0.90
U2	315	35	1350	0.91
K1	265	50	1075	0.78
K2	265	50	955	0.79
G1	320	55	1200	1.00

Table 2 : Synthetic table of the values Vc_{min} and μ

Minimum cutting speeds are almost equivalent for both steel grades and are extremely low compared with cutting speed values recommended by cutting tools manufacturers. The decrease in hardness due to the U2 heat treatment tends to increase Vc_{min}.

Specific cutting pressures as well as apparent friction coefficient are significantly lower for both K steel grades. K2 induces a lower specific pressure than K1. K2 machinability is metallurgically improved using specific inclusions.

Specific cutting pressures are similar for U1 and U2 despite heat treatment. Even if specific cutting pressures are similar for U1, U2 and G1, tool chip contact seems more severe when machining G1. U1 and U2 machinability has been enhanced using specific non metallic inclusions unlike G1. These results should be correlated with tool wear tests before proposing a reliable machinability ranking.

6. Tool wear tests

Tool wear tests are based on standardized protocols [14]. Tool wear tests are also performed with a single insert on the milling cutter. Pictures are taken along the tool life and VB is measured from time to time. Tool wear criterion choice is based on several tool wear curves. The maximum value allowed is VB = 200 μm.

The whole wear curves show a running in of the tool. The tool wear rate is slow until the tool coating is removed. When the tool substrate is in contact with the material machined, global tool wear rate significantly increases and some cracks appear across cutting edge. They are assumed to be related to oxidation wear process.

Tool life is evaluated based on a Taylor simplified model i.e. $V_c \cdot T^n = C$. Tool life model coefficients are determined through least square analysis. The model perfectly fits to experimental data. Even if two tests only are required to estimate the Taylor model coefficient, the investigations are done with at least three cutting speeds to improve precision.

	U1	U2	K1	K2	G1
n	0.235	0.283	0.291	0.302	0.510
C	1100	1260	1180	1300	3050
r ²	0.999	0.998	0.989	0.999	0.999

Table 3 : Taylor coefficients (f= 0.2 mm/rev, tool life criterion VB = 200 μ m)

Correlation coefficients are pretty high for both steels grade. A major difference should be observed for G1 steel grade since C and n are higher. Tool life should decrease faster when increasing cutting speed. Tool lives about 400 and even 600 min have been measured for U and K steel grades. The higher tool life encountered for G1 is only about 200 min. Cutting speed range should then be narrower for G1. The following graphs synthesize tool wear tests for the steel grades.

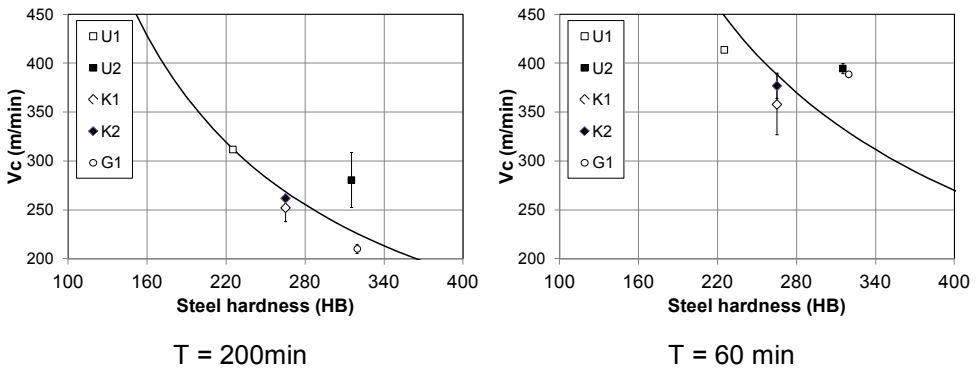


Figure 4 : Tool life comparison graph
(f = 0.2 mm/rev, tool life criterion VB = 200 μ m)

Cutting speeds are estimated for each steel grade and two tool lives (i.e. 60 and 200 m/min). Cutting speeds are ranked according to steel hardness. The higher the cutting speed is, the better the steel machinability is. There is an overall trend: when the hardness increases, the cutting speed decreases. A solid line shows it for many steels tested. However phenomena should occur at the tool / material interfaces, such as Built-Up Layer for instance, which tends to increase tool life in a more or less narrow cutting range. It is frequently observed when machining such steels. K steels machinability is similar when observing tool wear rate (for both high and low tool lives or respectively low and high cutting speeds). However U2 tool wear rate seems lower especially for low tool lives (i.e. higher cutting speeds). It may be explained as an occurrence of Built-Up Layers provided by non-metallic inclusions provided in this steel grade.

7. Conclusions

This paper proposes an application of the Couple Tool Material approach to gear hobbing operations. Cutting forces, surface quality, friction intensity and tool wear

are measured and enable to propose relevant operating range. Chip morphology analysis as well as allowed chip thickness ranges confirms the previous results.

The protocol enables to rank five steel grades G, U and K specifically developed by ArcelorMittal for gear hobbing applications. Experimental results show the influence of machinability metallurgical enhancement especially at high cutting speeds. They show that U2 steel has a good behaviour in machining since its machining conditions can be chosen in a wide range. Concerning the tool wear tests, U2 is the one which wears the tool the less. K1 and K2 steels are the most wearer grades among the steels with improved machinability. However cutting forces as well as tool – chip contact severity are lower.

8. Acknowledgment

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