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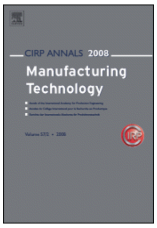

The Contribution of Microstructure and Friction in Broaching Ferrite-Pearlite Steels

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Ferrite-Pearlite (FP) steels are used in many automotive components. However, their machinability in low cutting speed processes appears to be highly dependent on their metallurgical state. An experimental approach combining broaching and tribological tests under machining-like conditions was developed to determine the key FP features driving machining performance. Fundamental tests were performed on fifteen variants so as to cover a wide range of microstructural properties under dry and lubricated conditions using both uncoated and TiN coated High Speed Steel (HSS) tools. The correlation between the microstructure, tribology and outputs such as machining forces and chip thickness ratio is presented.

Cutting, Micro structure, Friction, Chip

1. Introduction

Carbon steels are used in many automotive components especially transmission shafts, gear wheels, pinions or wheel hubs, where the core of the workpiece is primarily composed of a Ferrite-Pearlite (FP) microstructure.

FP steels are considered as conventional materials but they are not the easiest materials to machine. The low deformability and greater hardness of pearlite has been reported to cause significant abrasive wear and high resultant forces [1][2]. On the other hand, pearlite promotes the formation of favourable chips and limited burrs, improved surface quality [3], to reduce adhesion tendency and the occurrence of built-up edges [4].

Broaching is widely used in industry, however there is little published research on this process when compared to turning, milling or drilling. The few studies found in the literature have been conducted to identify the process parameters affecting cutting forces [5], surface integrity [6], surface roughness [7,8], the influence of different coatings and lubrication [9] and the development of innovative monitoring techniques [10]. Moreover, very little work exists on broaching [11] or even micro cutting [11] of FP steels. To date, no study has been found which specifically investigates the effect of FP microstructural parameters, i.e. ferrite content, grain size and hardness, on machining forces or chip formation in the broaching process.

In addition, findings from [4] and [9] suggest that tribological phenomena could play a major role in governing the cutting behaviour. Whereas many attempts have been made over the years [13] to improve the understanding of friction in cutting, whether by using the cutting process itself [14][15] or laboratory tests [16][17], no study has clearly reported the exact correlation between friction and the FP microstructure.

This work thus aims to identify (i) the exact contribution of FP microstructure on machining outputs, (ii) the influence of FP microstructural parameters on friction and (iii) the correlation between friction and machining outputs in a broaching framework. To this end, an experimental approach was developed combining one tooth fundamental broaching tests with tribological tests under machining-like conditions.

2. Experimental approach

2.1. Investigated materials

Five steel grades, 16MnCr5, 27MnCr5, C45, C60 and C70 with increasing carbon content were selected to generate ferrite ratios from 6 to almost 70%. C70 was also investigated as a fully pearlitic steel for reference purposes. Homogeneous FP microstructures (Fig. 1a) were obtained by a standard isothermal annealing cycle. Processing and heat treatments (Fig. 1b) were applied on each grade to extend the range of microstructural characteristics (Fig. 1c). A specific heat treatment was designed to increase the material grain size (Fig. 1d) whereas globular annealing was developed to achieve an overall softening and increase the ferrite ratio. Cementite lamellas were transformed into spherical particles, uniformly distributed in the predominant ferrite matrix (Fig. 1e). In total, 15 different materials were manufactured and analysed to properly define the ferrite ratio (F%) and macroscopic Brinell hardness. The ferrite ratio was measured using statistical image analysis based on 30 to 40 images taken at a 200x magnification in 10 random locations within the sample. For all the variants except one, a relatively constant grain size was achieved ranging reasonably between 10 and 20µm, limiting its potential effect.

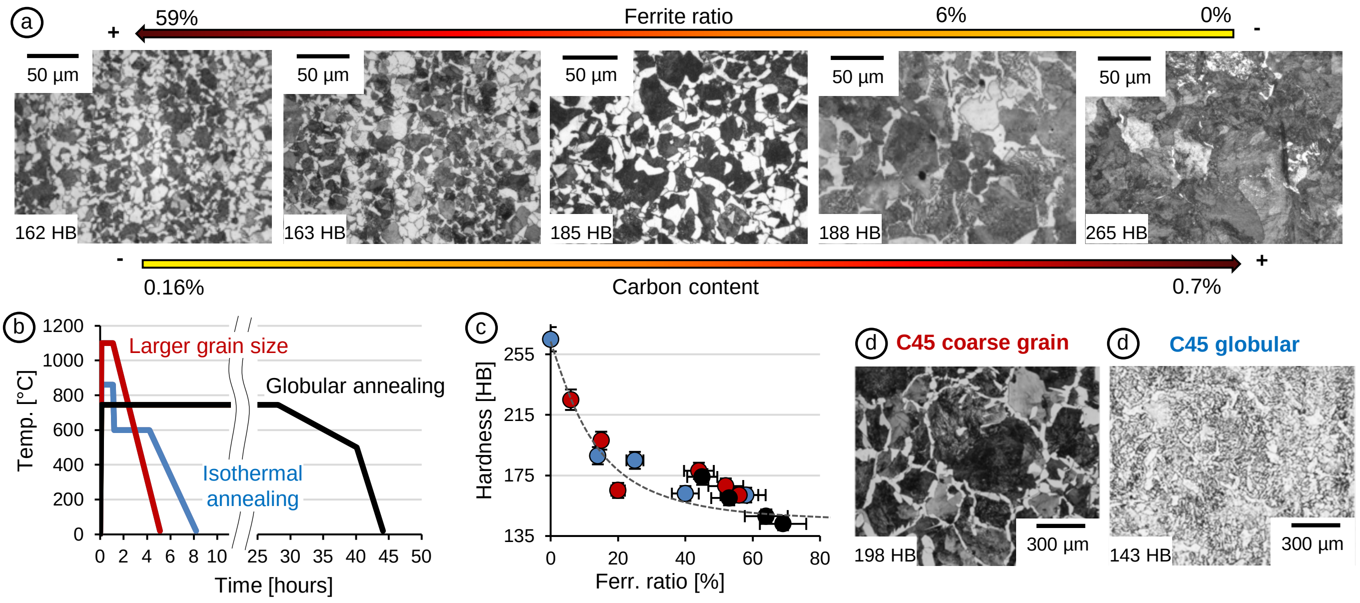

Figure 1. a) Examples of microstructures obtained when increasing the carbon content/ferrite ratio, b) heat treatment cycles applied to generate the various FP microstructures, c) correlation between ferrite ratio and macroscopic hardness and d,e) examples of corresponding micrographs when applying the heat treatment cycles to C45.

2.2. Fundamental broaching test

A dedicated experimental set-up, developed in previous studies focusing on surface roughness [7,8], was used to perform fundamental tests up to 60m/min. To alleviate any lack of stiffness, the experimental campaign was conducted with a single tooth broaching tool. Steel specimens were manufactured with a cutting width b = 3mm and fitted in the spindle via s specific holder while a HSS M35 broaching tool was fixed to the machine table. A dynamometer was used to record the main cutting force Fc and normal force Fn.

The broaching tool was designed with a rake angle γ of 17°, a clearance angle α = 1°, a cutting edge radius r_β = 5µm and an edge inclination angle λs = 0°, resulting in orthogonal cutting conditions.

Experiments were run at cutting speeds v_c = 2, 20 and 60m/min, with an uncut chip thickness h = 10 and 40µm, under both dry and straight oil lubricated conditions. The results show the average and standard deviation of 5 consecutive runs.

2.3. Tribological tests

The tribological investigation was based on an open tribometer mounted on a CNC lathe [17]. The tool-material interaction was tested by scratching a pin with a spherical geometry, made of HSS M35 (uncoated or TiN coated), against a cylindrical bar of each studied variant. After each friction test, a cutting tool refreshed the scratched surface to remove the affected layer of work material, and a belt finishing operation was then applied.

The sliding velocity V_{sl}, defined by the rotation speed of the spindle, ranged from 2 to 60m/min, and the normal load was set to 1000N via a hydraulic jack, leading to a contact pressure of around 1.5GPa. Friction pins were ground and polished to achieve a roughness Ra of around 0.3µm.

The apparent friction coefficient was computed as the ratio of the tangential force to the normal load measured by a piezoelectric dynamometer. The results set out the average and standard deviation of three repetitions performed for each sliding condition, each with a new pin.

3. Interaction under uncoated dry conditions

Broaching tools are usually fully coated and then ground on the rake face in order to accurately control the cutting edge radius. This leads to a specific configuration with a coated flank face and uncoated rake face. To simplify the cutting configuration and dissociate the effect of the microstructure, uncoated tools were first selected under dry conditions.

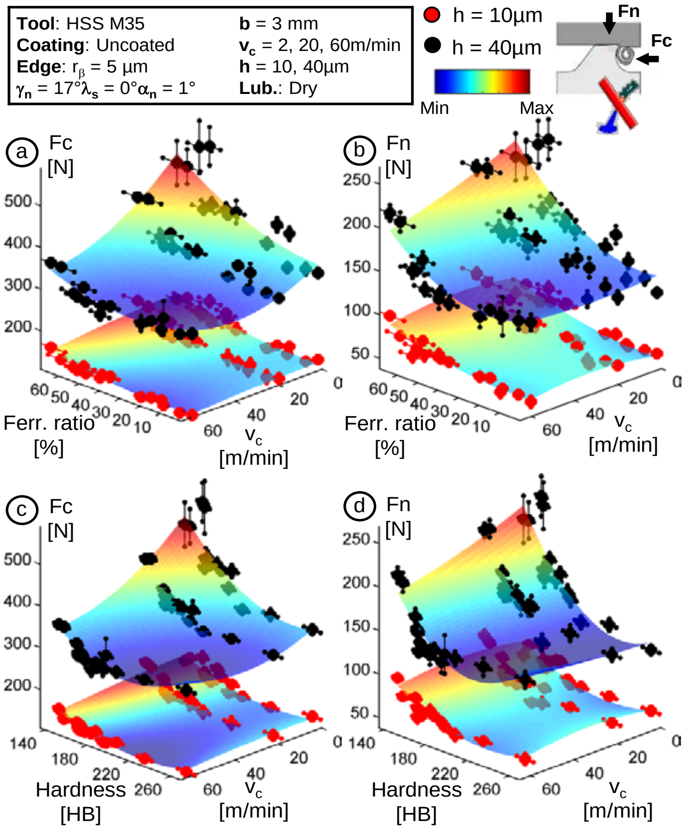

Figure 2. Influence of ferrite ratio and macroscopic hardness on the cutting force Fc (a,c) and normal force Fn (b,d).

The results of this campaign are displayed versus F% (Fig. 2a,b) and macroscopic hardness in terms of normal force only (Fig. 2c). Considering the large amount of data, second order polynomial equations were fitted to each of the datasets in order to analyse the main trends as presented in Figure 2.

The following quantitative comparisons are given based on this surface fit with a range of F% from 5 to 70% and hardness from 140 to 260HB. Figure 2 summarises the effects of both FP microstructural parameters and cutting conditions.

It first shows that at both *h* and low cutting speed, increasing F% (Fig. 2a) led to an increase in the main cutting force *Fc*. At *h* = 40µm, increasing F% generated an increase of 40% in *Fc*. This effect was reduced significantly when increasing the cutting speed up to 60m/min. Indeed, a 10% variation of *Fc* was observed with the same increase in F%. Materials with a larger ferrite content F% = 70% were found to be more sensitive to the cutting speed with a decrease of nearly 20% in *Fc* when changing from 2 to 60m/min, as opposed to only 5% with a material with a lower ferrite ratio F% = 5%.

When *h* was reduced from 40 to 10µm, similar amplitudes were reported at 2m/min. An increase of 36% in *Fc* was observed when increasing F%. Tests conducted at 60m/min exhibited larger variations (+28%) showing the limited effect of the cutting speed with a small uncut chip thickness.

As regards the normal force *Fn*, a similar trend to *Fc* was noted with *h* = 40µm characterised by significant increase of 70% when increasing F% at v_c = 2m/min and 36% at v_c = 60m/min. This behaviour was seen again to be less dependent on the cutting speed with *h* = 10µm. In the case of the latter, *Fn* still increased by 50 to 60% when increasing F% (Fig. 2b), however the cutting speed no longer appeared to play a major role. *Fn* was indeed reduced by 35% at both 2 and 60m/min when decreasing F% from 70 to 5%. Finally, if machining forces generally increased when increasing F%, *Fn* appeared to be more affected compared to *Fc*.

All the previous observations can be easily transposed in terms of hardness as a direct relationship exists with the ferrite ratio (Fig. 1c). As an example, Figures 2c,d highlight the specific finding that cutting a FP steel with a higher hardness can result in lower machining forces. The normal force *Fn* can be reduced by 46% by increasing the hardness from 140 to 260HB. To analyse this, one has to keep in mind that for a given rake angle, friction and work hardening are established as governing the machining forces via their influence on the chip thickness and shear angle [18]. Tribological experiments were thus performed to assess the friction contribution and extend the data already collected on some of the variants in a previous work [8].

As generally reported in metals [8,17], the friction coefficient μ_{app} decreased when the sliding velocity increased (Fig. 3). Moreover, μ_{app} was seen to follow the same trends as machining forces when varying the ferrite ratio.

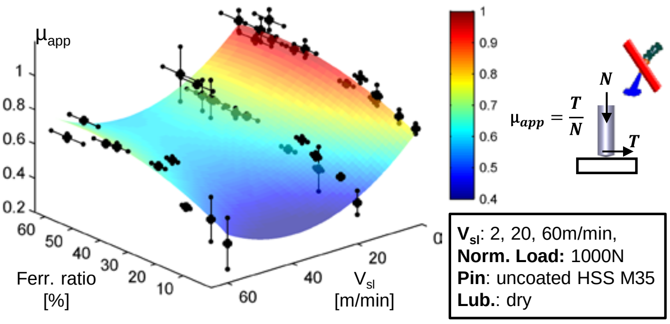

Figure 3. Influence of ferrite ratio on the apparent friction coefficient when using uncoated friction pins under dry conditions.

From a quantitative point of view, at 2m/min, μ_{app} increased by 20% when increasing the ferrite ratio from 5 to 70%. The results at 60m/min should be considered with caution as the pins exhibited a certain amount of wear which could explain the greater deviation noted in these tests. However, a reduction of 25% and 49% in terms of friction was identified at 2 and 60m/min respectively when the hardness was increased from 140 to 260HB. Decreasing F% enabled to limit the ploughing phenomenon but also to significantly reduce the adhesion tendency of the FP steels onto the friction pins.

The correlation between the trends identified in both the fundamental cutting and the tribological tests strongly suggests that when broaching a material with larger ferrite content, machining forces increase mainly due to a larger adhesion component, thus a tribological effect. Indeed, several studies showed that flow stress and then the machining forces increase when reducing the ferrite content [19][20]. This is contrary to what was observed in the present work tending to show that the friction contribution is predominant compared to the flow stress one. This is supported by the fact that the normal force *Fn*, component prone to be more sensitive to friction, was affected to a larger extent, a phenomenon also observed by [4].

4. Influence of a lubricant and TiN coating

To better highlight the influence of tribology, the contact conditions at the tool-material interface were modified by applying a lubricant and a TiN coating to both the tool and the friction pin. Ten variants from the 15 were selected and were cut at v_c = 2m/min and h = 40µm, cutting conditions, which exhibited the largest variations when changing the FP microstructure. The following results are presented only in terms of normal force *Fn*, as this was shown to be the most sensitive to friction.

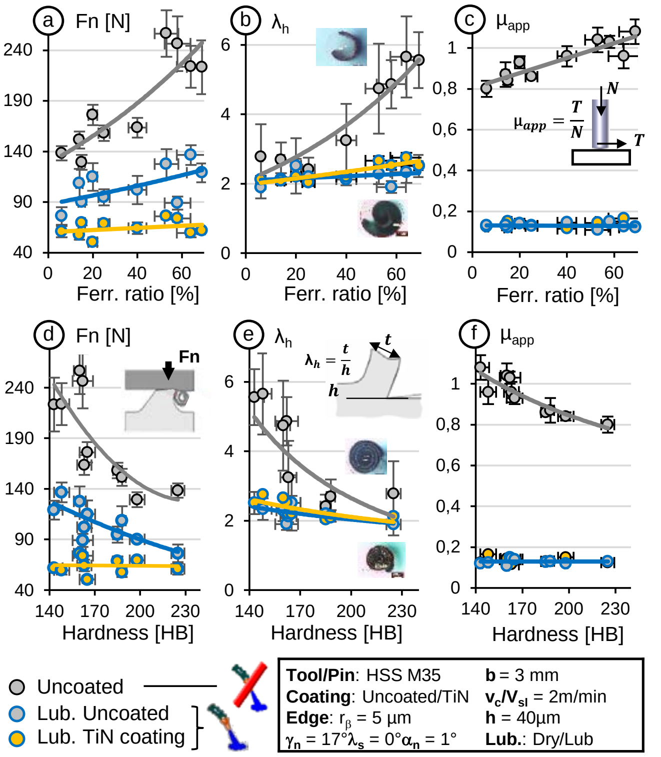

Figure 4. Influence of ferrite ratio and hardness on the normal force Fn (a,d), chip thickness ratio (b,e) and apparent friction coefficient (c,f) under dry and lubricated conditions.

Compared to the uncoated dry conditions, applying straight oil reduced the normal force by 35% at low ferrite ratio and up to around 60% for F% > 50% (Fig. 4a). This appears to confirm that tribological aspects are the main contributing factor to the cutting behaviour, as the oil is able to limit the higher adhesion tendency of the softer materials, thus leading to a stronger reduction of the machining forces.

During these tests, chips were also collected, embedded and polished to assess their average thickness *t*. The chip thickness ratio λ_h was then calculated as the ratio of *t* to *h*. Under dry conditions, λ_h was seen to drastically increase by a factor between 2 and 2.5 when increasing F% (Fig. 4b) or decreasing the hardness (Fig. 4e). Thicker chips are known to occur primarily when the friction along the tool-chip contact length is greater [18]. This trend is consistent with the increase generally observed in the normal force (Fig. 4a).

Similarly, λ_h was lowered by a factor close to 3 when using straight oil with steels with a large F%, attesting to its ability to lubricate the tool-material interface (Figs. 4b,e). The fact that the lubricant was straight oil and not a water-based emulsion excluded a potential thermal effect due to a beneficial cooling of the process. Nevertheless, although the lubricant significantly limited the effect of the FP microstructural parameters, it should be noted that the same trends as in dry broaching were found, but with a much lower amplitude.

Applying a TiN coating under lubricated conditions resulted in a further 35% reduction of *Fn* on average, and maintained the same trends as the uncoated conditions across the whole range of FP microstructures. However, Figures 4b,e show that no further modifications of λ_h were induced by this combination.

Figures 4c,f confirm a significant impact of straight oil on the tribological tests with an average reduction of μ_{app} of 85% compared to dry conditions. Combining lubrication and the TiN coating did not improve the friction behaviour with μ_{app} remaining at around 0.13 in average. This important reduction is in agreement with the decrease generally observed in the machining outputs and confirms the assumptions regarding the main contribution of friction in broaching.

5. Conclusions

This paper has presented a systematic study combining fundamental cutting tests and tribological experiments to identify the key parameters controlling the broaching performance of FP steels. It showed that the ferrite ratio F% had an important impact on the machining forces and chip formation with the main trends reported in Table 3. A strong correlation between the above and tribological testing was identified, and highly similar trends were observed regarding the apparent friction coefficient (Table 3), i.e. increasing F% led to increasing machining forces and apparent friction coefficient.

Table 3 Summary of the main influence of the investigated factors on the broaching and friction outputs.

Type	Factor	Fc	Fn	λh	μ_{app}
FP parameters	↑ F% (5-70%)	↑	↑	↑	↑
	↑ HB (140-260HB)	↓	↓	↓	↓
Cutting conditions	↑ V_c/ V_{sl} (2-60m·min^{-1})	↓	↓	↓	↓
	↑ h (10-40 μm)	↑	↑	↑	
Contact conditions	Lub/TiN+Lub	↓	↓	↓	↓

This shows that broaching is a friction-driven process, and that tribology plays a major role in machining performance. Moreover, the relationship between FP microstructural parameters and the friction coefficient was identified, which is of definite interest to the community focusing on tribological aspects. Finally, a secondary outcome of this study suggests that tribological tests performed under relevant conditions could be used as a simplified method to assess the machining performance of FP steels in broaching.

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