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Influence of Microstructure on Chip Formation when Broaching Ferritic-Pearlitic Steels

T. Mabrouki[a,**], C. Courbon[b], D. Fabre[b], I. Arrieta[b,c], P.-J. Arrazola[c], J. Rech[b]

[a] *Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis (ENIT), 1002 Tunis, Tunisie*
[b] *Université de Lyon, CNRS, Ecole Nationale d'Ingénieurs de Saint-Etienne, LTDS UMR5513, F-42023, France*
[c] *Mechanical and Industrial Production Department, Faculty of Engineering, Mondragon Unibertsitatea, Loramendi 4, Mondragon 20500 Gipuzkoa, Spain*

* Corresponding author. Tel.: +33(0)477437548; fax: +33(0)477437539. *E-mail address:* cedric.courbon@enise.fr

Abstract

Broaching is a specific process characterized by relatively low cutting speeds and uncut chip thicknesses. The latter is in the range of 0.1 to 0.25 mm in the roughing section of the tool but can decrease down to 0.0015 mm in the finishing one. This induces drastically different cutting behaviours compared to macroscale processes such as turning. The question of the scale effects in such conditions is thus clearly raising and especially the size and distribution of the microstructure. This paper proposes an investigation to assess the importance of the material heterogeneities on chip formation when broaching ferritic-pearlitic steels.

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Keywords: Broaching; microstructure; heterogeneous; simulation

1. Introduction

Despite of being a relatively old cutting process, broaching remains one of the most reliable one to manufacture complex and accurate components with a high productivity. Even if it has been commonly employed during more than a century in several leading-edge industries, few research groups focused their work on this specific process [1,2]. As wrote in [1], "broaching is a unique machining process. This is because the broach performs a sequence of roughing, semi-finishing and finishing operations in one stroke." Moreover, broaching reaches almost the limits of conventional cutting as (i) very low cutting speed, commonly between 1 and 5 m/min with High Speed Steel tools [3] and up to 60 m/min with carbide tools [4], as well as (ii) small uncut chip thickness from 0.1 to 0.25 mm in the roughing section of the tool or down to 0.0015 mm in the finishing one, are typically used. These values can take it somehow in the range of micro machining [5].

As emphasized by several authors [6,7], machining a material on the microscopic level can induce drastically different cutting mechanisms compared to those encountered at a macroscopic one. This is especially true as using a so small uncut chip thickness leads to two dominant phenomena. The contribution of the tool edge radius, fundamental parameter in metal cutting [8], is amplified and may significantly modify the effective rake angle or increase the ploughing tendency rather than cutting. Above all, the material removal occurs at the scale of the materials grain size. Hence, under a certain scale, the assumption of a homogeneous and isotropic material can be definitely questioned as well as the effect of the size and distribution of the microstructure [6,7]. These size effects can significantly affect the cutting performance compared to a macro cutting operation.

Ferritic-Pearlitic (hereinafter FP) steels are highly concerned as they can be seen as multiphase materials. It mainly consists of a ductile ferritic matrix with embedded islands of a hard second phase (pearlite) and changing the volume fraction directly governs the resulting mechanical or tribological properties. Even if steels with FP structure are among the most common materials, they are not at the very least the easiest materials to machine. More precisely, the machining performance appears to be highly dependent on the microstructural parameters. During machining, the low deformability and greater hardness of pearlite cause, on the one hand, significant abrasive wear and high resultant forces [9,10]. On the other hand, pearlite reduces the adhesion tendency and the formation of built-up edges of ferrite [11], promotes the formation of favourable chip forms, causes less burr formation on the workpiece and improves the surface quality [11,12].

**Corresponding Author.
Email address: tarek.mabrouki@enit.rnu.tn (T. Mabrouki)

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Going across the researches with reference to FP steels, few studies have yet investigated the contribution of ferrite/pearlite ratio or even grain size on the machining performance, especially in broaching, using a numerical approach [13,14]. The present study thus aims at investigating this point and assess the need of considering the material at the micro level when broaching carbon steels.

2. Materials and methods

2.1. Numerical model

A numerical model is a powerful tool to perform sensitivity studies and assess how variations of a cutting parameter or any input data can affect the outputs of the cutting process. In this work, it has been used to investigate the effect of different microstructure morphologies on the chip formation in broaching and compare them to an homogeneous material.

2.1.1. Modelling approach

A 2D orthogonal cutting model based on a Lagrangian approach has been employed in this analysis as it appears as the most relevant method to simulate cutting of heterogeneous materials. Built from the work of Mabrouki et al.[15], this Finite Element model is divided into three parts: the chip, the tool-tip passage zone and the workpiece (Fig. 1). Coupled thermo-mechanical simulations have been conducted in the commercial code Abaqus/Explicit©. The model consists of a deformable workpiece and a rigid cutting tool with both solids meshed using 4-node plane strain thermally coupled quadrilateral elements (CPE4RT).

The main drawback of this approach is that it requires a separation criteria such as a damage initiation and evolution for the elements deletion in the passage zone in order to form the chip. Data in this region are therefore lost and its size must be carefully selected in order to limit these effects.

2.1.2. Microstructural considerations

The microstructure has been taken into account only within the chip, as shown in Fig. 1. In order not to use a simple square or rectangular shape and insure a good mesh quality compared to spherical ones, grains have been assumed to be hexagonal as in [14] with the grain size corresponding to two times the side length. A Python script has been developed to automatically divide the chip geometry into grains and properly affect the properties of the ferrite or pearlite to model to different microstructure morphologies.

Three microstructural parameters have been investigated in this work: grain size, phase distribution and ferrite-pearlite ratio. Table 1 summarises the different simulated configurations. Examples of phase distribution are given in Fig. 1. A mesh sensitivity study has been performed to identify the proper mesh size in each part of the model. As an example, a mesh of 5 μm in the chip and 7 μm in the passage zone and workpiece has been selected when using a grain size of 20 μm.

	Ferrite/Pearlite ratio		
Grain size (μm)	75/25	50/50	25/75
16		V	
20		V	
36	R	V/H/R	R
50		V	

Table 1. Microstructural morphologies implemented within the chip: V = Vertical, H = Horizontal, R = Random.

Material properties		
	Steel	HSS M35
Density (kg/m3)	7850	8000
Young modulus (GPa)	207	238
Poisson's ratio	0.3	0.3
Specific heat (J/kg°C)	431	408
Thermal conductivity (W/m°C)	47	24
Thermal expansion (μm/m/°C)	10	10
Inelastic heat fraction	0.9	
Contact properties		
Heat partition	0.5	
Friction coefficient	0.1	

Table 2. Input data used in the numerical simulations.

2.1.3. Tool and work material specifications

The thermophysical properties of ferrite and pearlite have been assumed to be the same as those of a C45 carbon steel and are provided in [16]. Those of the HSS M35 cutting tool substrate can be found in Erasteel E M35 datasheet (PDS EM35 EN V0 2010) (Table 2).

In the three workmaterial parts, the material plastic behaviour has been implemented through the strain, strain rate and temperature dependent Johnson-Cook flow stress model (Eq. 1). C45 has been applied in the workpiece and passage zone with the parameters proposed by Jaspers and Dautzenberg[17]. In the chip, ferrite and pearlite Johnson-Cook parameters have been respectively selected based on the work of Abouridouane et al.[18] (Table 3). It can be noted that these constants are valid for a poly-crystal steels that can be considered as isotropic. This is an important assumption as, at the scale of a grain, the material certainly has an anisotropic behaviour. This would deserve a complementary study to highlight the consequence of an anisotropic grain behaviour.

$$\overline{\sigma_{eq}} = \left[A + B\left(\varepsilon_p\right)^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon_p}}{\dot{\varepsilon_0}}\right)\right]\left[1 - \left(\frac{T - T_0}{T_f - T_0}\right)^m\right] \quad (1)$$

In the passage zone, a Johnson-Cook damage initiation model (Eq. 2) with the parameters given by Duan et al.[19] had to be used. A fracture energy is implemented to control the damage evolution and more details are given in [20]. As chip formation is the main focus of the present work, plastic deformation and material flow ahead of the cutting edge radius has been assumed to be negligible with a low impact compared to the deformation process occurring within the primary shear zone and the intense frictional contribution at the secondary shear zone. The size of the passage zone has thus been min-

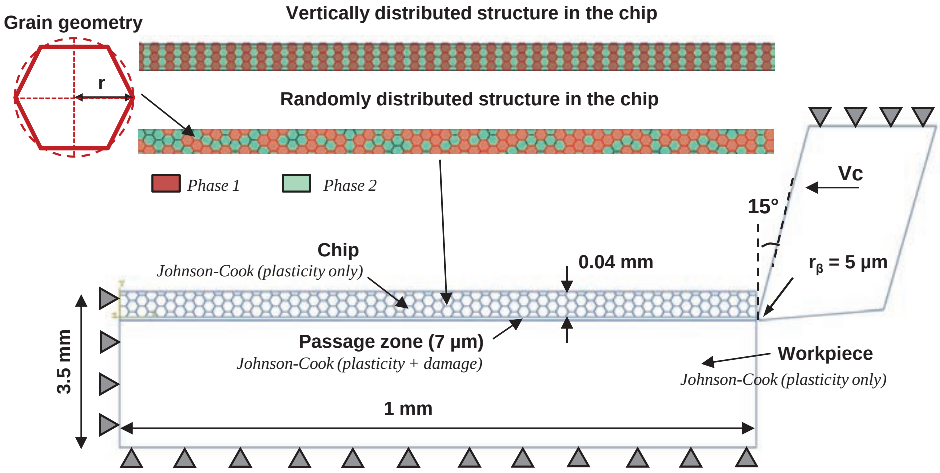

Fig. 1. Description of the numerical model employed.

imized to 7 μm, a bit larger than the size of the cutting edge radius of 5 μm, to limit its contribution and the lack of physics that could be induced to this single deleted element layer.

$$\overline{\varepsilon_{0i}} = \left[D_1 + D_2 exp\left(D_3 \frac{P}{\overline{\sigma_{eq}}}\right)\right] \times \left[1 + D_4 \ln\left(\frac{\dot{\varepsilon_p}}{\dot{\varepsilon_0}}\right)\right]\left[1 + D_5\left(\frac{T - T_0}{T_f - T_0}\right)\right] \quad (2)$$

2.1.4. Boundary and interface conditions

The Figure 1 shows a schematic representation of the boundary conditions. The nodes at the bottom of the workpiece are fixed vertically via a symmetry condition whereas the tool moves to the left with the prescribed cutting speed set at the nodes.

Performed under lubrication with straight oil, a constant Coulomb friction coefficient of 0.1 has been applied at the whole tool-chip-workpiece interface according to [21]. Heat partition is set to 0.5 considering the low cutting speeds involved. Losses due to convection as well as radiation have been neglected according to the short machining time and the lubrication conditions used for this cutting operation.

2.2. Experimental set-up

The experimental set-up is presented in Fig. 2. Experiments have been carried on a 4 axis machining center with a horizontal spindle. The latter was equipped with a specially designed workpiece holder, and a clamping system mounted on a 6 axis dynamometer maintains the broaching tool. In order to limit the perturbations induced by the entry/exit of the broaching tool teeth, tests were carried out with a single tooth cutting tool.

A HSS M35 tool TiN-coated on the flank face only (edge radius 5 μm) has been used with the following cutting conditions: a cutting speed of Vc 40 m/min and a rise per tooth (RPT) of 0.04 mm. Cutting tests have been carried out under straight oil lubricated conditions and replicated five times. Three ferritic

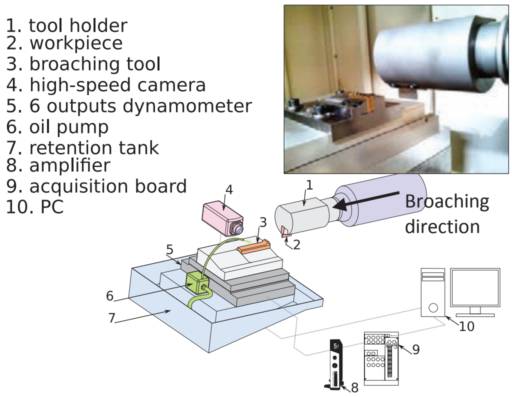

Fig. 2. Broaching experimental set-up.

pearlitic steels, i.e. 27MnCr5, C45 and C60, have been investigated to cover a large range of ferrite-pearlite ratio.

3. Results and discussion

3.1. Influence of the grain size

The first obvious phenomenon that can be observed when cutting heterogeneous materials is the stress distribution within the chip (Figs. 3b-c). Regions with the hard pearlite phase exhibit larger Mises stress whereas those with the ductile ferrite are highly deformed. Shear is more intense in the ferritic grains and lead to a pseudo serration with the extrusion of this soft phase to the surface of the chip. The pseudo-serration frequency thus directly depends on the phase distribution and spacing.

Simulated cutting forces were found to be 17 % lower than the experimentally measured ones (Fig. 3a). No major effect of the grain size can be seen on the main cutting force but variations are amplified when increasing the grain size from 16 μm to 50 μm. Oscillations observed on the cutting force versus time can be correlated to the spacing between the different phases in the microstructure. As shown in Figs. 3b-c, a small grain size

Steel	A [MPa]	B [MPa]	n	C	$\dot{\varepsilon}_0$ [/s]	m	T_m [°C]	T_0 [°C]
C45	553.1	600.8	0.234	0.0134	1	1	1460	25
Ferrite	175	571	0.35	0.034	0.002	1.86	1500	20
Pearlite	750	593	0.33	0.011	0.002	1.1	1500	20

Table 3. Johnson-Cook model parameters for the implemented materials ([17,18]).

implies a microstructure with a more frequent phase change between the soft one and the harder one. Cutting such a microstrucuture induces smoother variations when alternatively cutting ferrite and pearlite. On the other side, when large grains are simulated, a larger ferrite grain is first deformed before being followed by a pearlitic one leading to more sudden variations in terms of forces.

3.2. *Influence of the phase distribution*

Changing the morphology of the microstructure and organizing it in different ways did not again significantly affect the average cutting force (Fig. 4a). Considering the evolution versus time, an horizontal distribution is somehow leading to a more homogeneous behaviour as a stack of ferrite and pearlite layer will be continuously cut. Vertically organizing the different phases tends to introduce more variations in terms of forces as, being perpendicular to the cutting direction, they will be successively cut and deformed. Moreover, it can be seen in Figs. 4b-c that chip curvature and thickness can be affected.

3.3. *Influence of the Ferrite-Pearlite ratio*

The ferrite-pearlite ratio is an important parameter that describes the microstructure of a FP steel. Figures 5b-c show that a slight effect on chip curvature can be expected. Strains are concentrated in the regions where the soft ferritic phase is present. This is certainly limited by the low friction coefficient and the assumed lubricated conditions. Curvature discrepancies would be amplified when increasing friction, i.e. performing the broaching operation in dry conditions.

Simulating a material with a high pearlite content increases the main cutting force (Fig. 5a). The drop that can be seen after 0.7 ms is due to the fact that the cutting tool reached a region with predominant ferritic grains before progressively increasing again as the pearlitic ones start to enter the primary shear zone.

3.4. *Comparison with an homogeneous material*

The previous results using heterogeneous material properties within the chip have been then compared to an homogeneous material. Configurations representing a low pearlite content, a balance between ferrite and pearlite and a high pearlite content have been investigated. To this end, Johnson-Cook parameters were calculated based on the work of Abouridouane et al.[18] for three reference steels, 27MnCr5 C45 and C60, and uniformly applied on the whole chip. Numerical results, both with the homogeneous and heterogeneous approaches, have been compared to the experimental ones.

Figures 6a-b show that it is relatively difficult to clearly dissociate any effect on the average cutting force when comparing an homogeneous model to an heterogeneous one. The large difference that can be observed between the homogeneous C60 model and the heterogeneous 25%F/75%P up to 0.7 ms is due to the way the pearlitic grains have been distributed within the chip, as discussed before. Differences could be extracted over time but a frequency analysis (FFT) would be needed to clearly emphasise those aspects and connect them to the distribution of the microstructure. Compared to the experimental results, it is interesting to see that the trend is relatively consistent as cutting force decreases when changing from 27MnCr5 to C45 and then increases again when cutting C60. This phenomenon can be related to the balance between a ductile/highly workhardenable phase and a harder phase with a higher initial yield stress.

When focusing on the C45 configuration (Figs. 6c-d), chip curvature is slightly modified whereas the average cutting force is slightly higher when the heterogeneous approach is employed. As seen before, shear localisation occurs within the regions where ferrite is located and is able to form a pseudo-serration. On the other side, using an homogeneous material model leads to a perfectly continuous chip. Temperatures were found to be not drastically affected but a 10 % increase close to the tool tip has been observed.

4. Conclusions

This study investigated the effects of considering an heterogeneous material when modelling broaching of ferritic-pearlitic steels. Different grain size, phase distribution and ferrite-pearlite ratio have been simulated and compared in terms of main cutting force and chip formation.

Taking into account the microstructure on a more microscopic level is found to be of interest if the force signal over time and chip formation process are looked after. Grain size and phase distribution play a major role in the way the different phases are successively cut and therefore induce variations on the main cutting force. A pseudo-serration can be observed due to the shear localisation in the ferrite. The ferrite-pearlite ratio controls to a certain scale the mechanical response of cutting operation. Regions consisting of many pearlite grains will lead to a larger mechanical load on the tool which will decrease when the soft phase will be subsequently deformed.

When an homogeneous material is considered, this pseudo-serration can not be found and shear localisation within the chip does not appear at all. At last, implementing an heterogeneous material, especially via the phase distribution and ratio, seems to influence the chip curvature to a certain extent compared to an homogeneous approach. This is of interest as chip curvature and size is one of the main issue in broaching leading to cutting instabilities, surface defects and tool failures.

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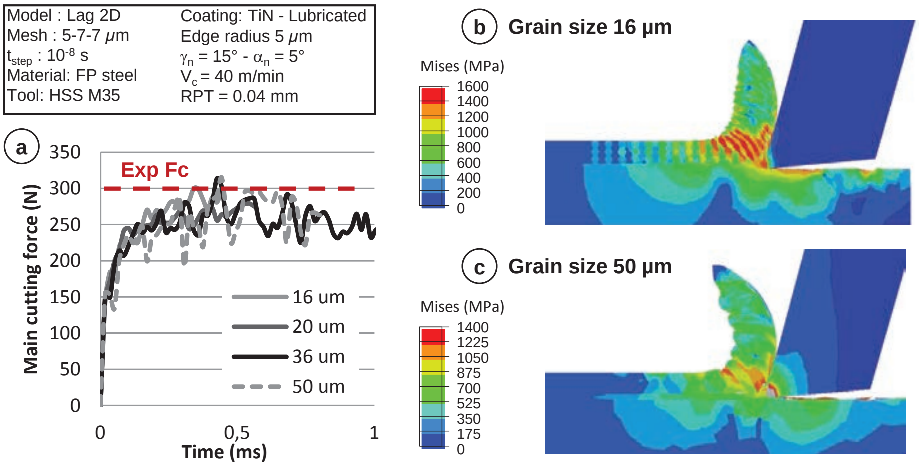

Fig. 3. Influence of the grain size on cutting forces (a) and Mises stresses (MPa) (b-c) within the chip (vertical distribution - 50 % FP ratio).

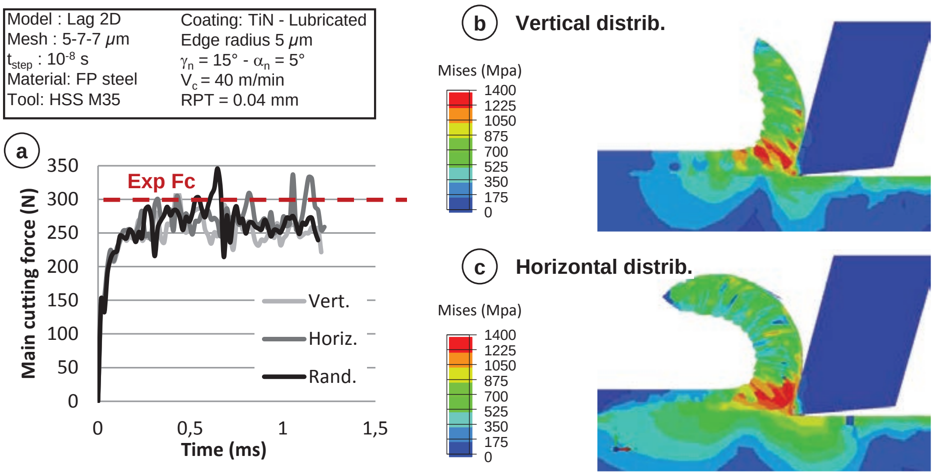

Fig. 4. Influence of the phase distribution on cutting forces (a) and Mises stresses (MPa) (b-c) within the chip (grain size 36 μm - 50 % FP ratio).

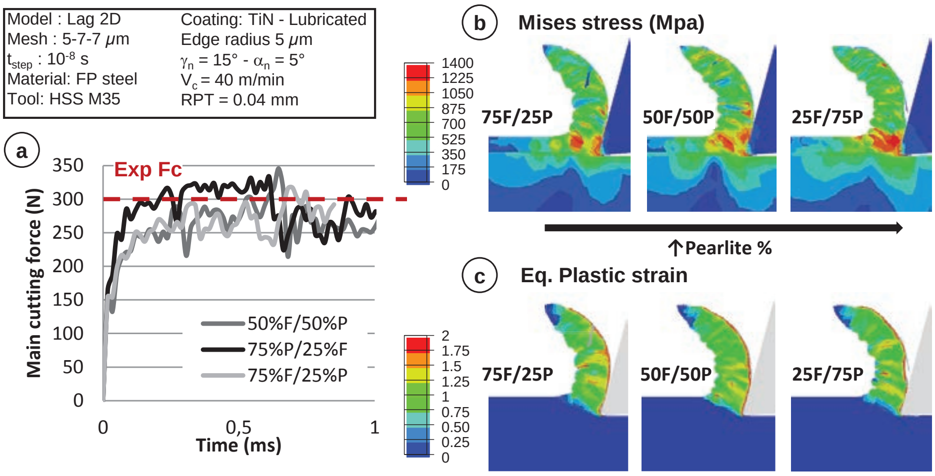

Fig. 5. Influence of the ferrite-pearlite ratio on cutting forces (a) and Mises stresses (MPa) (b) and equivalent plastic strains (c) within the chip (grain size 36 μm - random distribution).

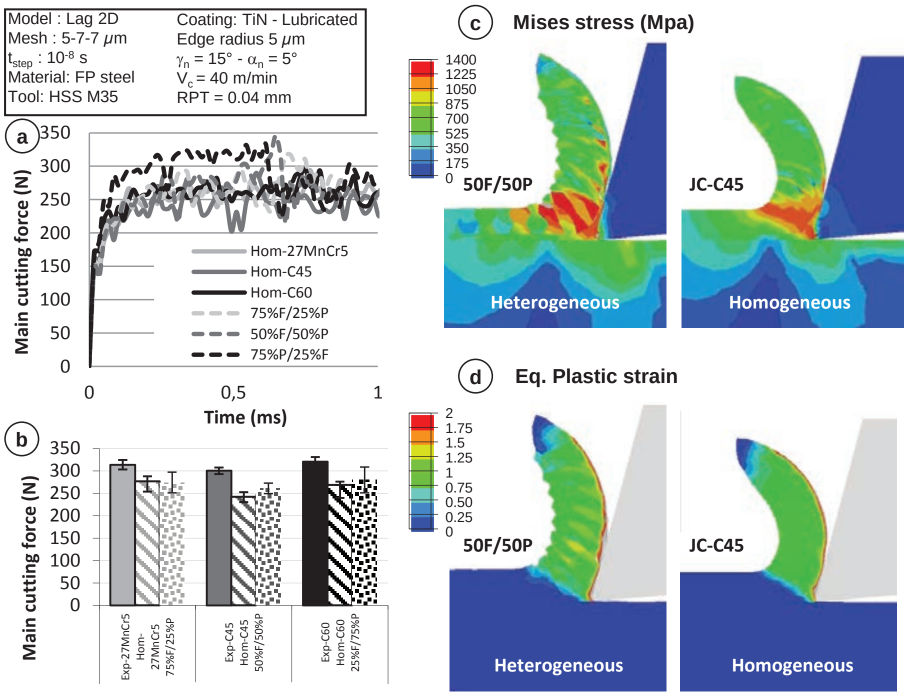

Fig. 6. Comparison between an homogeneous and heterogeneous material regarding (a-b) the main cutting force, (c) Mises stresses (MPa)and (d) equivalent plastic strains within the chip (grain size 36 μm - random distribution).

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