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Sensitivity analysis of the input parameters of a physical based ductile failure model of Ti-6Al-4V for the prediction of surface integrity

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Abstract

In machining of Ti-6Al-4V, it is commonly reported the appearance of segmented chip produced by adiabatic shearing (at high cutting speeds) and lack of ductility (at low cutting speeds). Moreover, machining is a manufacturing process that is based on applying external energy to the workpiece to produce a separation of a material layer. Thus, to analyze the physics involved in the new surface generation and in the chip segmentation process, it is necessary to apply ductile failure models. However, the characterization of fracture models in machining conditions (temperature, strain rate, stress triaxiality, Lode angle etc.) is an arduous task. Therefore, to define a ductile failure model applicable to machining it is almost inevitable to apply inverse simulations strategies to obtain reliable results in the not tested conditions. Nevertheless, there is few information about the influence of the input parameters of ductile failure model in fundamental outputs and even less in surface integrity aspects. The aim of this research was to conduct a sensitivity analysis of the influence of the input parameters of a physical based ductile failure model not only in fundamental variables (forces, temperatures and chip morphology) but also on surface integrity (surface drag). To this end, a subroutine was developed for the ductile failure model and it was implemented in the Finite Element Method (FEM) software AdvantEdge. Subsequently, using a statistical software and the Design of Experiments (DOE) technique the influence of the input parameters of the failure model on the outputs was analyzed.

Keywords: Ductile failure; FEM; Surface integrity; Machining; Ti-6Al-4V

1. Introduction

The interest in titanium alloys has increased in recent years due to its excellent thermo-mechanical properties that makes it an interesting material for aerospace, automotive, chemical and medical applications. The alloy Ti-6Al-4V (Ti64) is the most widely used one, since it presents high specific strength at high temperatures, as well as, high creep and corrosion resistance [1,2]. That makes this material prone to being used for manufacturing of components where very specific requirements of surface integrity are necessary.

However, it is considered a difficult-to-cut material due to the premature tool wear owing to its high chemical activity and short tool-chip contact length, which involves higher pressures and heat flux concentration. It also produces serrated chip at certain cutting conditions that may produce vibration during the machining operation [1,3].

The responsibility for chip segmentation is generally attributed to the low thermal conductivity of the material [4]. This property produces heat concentration in the primary shear zone that generates thermal softening and consequently adiabatic shearing. This phenomenon appears at high cutting speeds where high temperatures are reached [3]. Nevertheless,

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some researchers observed segmented chip at low cutting speeds (low temperatures) [3,5,6]. They argue this is due to the lack of ductility of the material that results in ductile failure and consequently chip segmentation. Low cutting speeds are commonly reported in different machining operations, such as, broaching or drilling (in the middle of the tool).

Those instabilities produced by the chip segmentation could worsen the surface integrity and consequently the fatigue performance of the part [7]. Hence, special attention has to be paid during the finishing operation of the pieces since it stablishes the final surface integrity of the component.

In this scenario, the Finite Element Method (FEM) could give an insight into the physics involved in chip segmentation process and help improving the surface integrity of the machined part. However, for the development of accurate FEM models it is necessary to select adequate input parameters in order to obtain robust results [8,9]. The flow stress model has always been considered the most critical input parameter. Nevertheless, it was recently observed that when a ductile failure model is applied in a FEM model, it seems that the flow stress model is less important than the failure model [10].

The adequate characterization of the input parameters is an arduous task due to the difficulty of reaching machining conditions in the characterization tests [8]. Therefore, it is necessary to apply additional strategies to get robust results, such as, the inverse simulation [11].

To develop a robust inverse simulation strategy it is necessary to know the influence of the input parameters in the outputs. There are many works that present sensitivity analysis of input parameters of flow stress model in fundamental variables [12]. Nevertheless, to the best of our knowledge the influence of the ductile failure model parameters in fundamental or surface integrity outputs have not been studied in spite of the high influence it has on the results [3].

Therefore, the aim of this paper is to make a sensitivity analysis of the input parameters of a physical based ductile failure model, for Ti-6Al-4V, to analyze their influence, not only on fundamental outputs (forces, temperatures and chip morphology) but also on surface integrity aspects, such as, plastic deformation of the grains in cutting direction, known as surface drag. For that, the FEM software AdvantEdge was used with a subroutine for the ductile failure model implementation. Finally, using the Design of Experiments (DOE) technique the influence of the input parameters on the outputs was analyzed.

2. Finite element model

The commercial machining finite element software AdvantEdge™-2D V7.4015 was employed. It has a coupled thermo-elasto-plastic Lagrangian code with continuous remeshing and adaptive meshing with triangular elements. The model is based on the previously published work [10]. The minimum element size in the simulation was set to 2 μm to obtain accurate results. It was also generated a fine mesh layer of 0.1 mm in the machined surface to extract more precisely the surface drag values. Consequently, the elapsed simulation time using 4-core parallel was of approximately 10 hours.

The flow stress laws coupled with the ductile failure model were implemented in the software by user-defined subroutines programmed in Fortran language. The phenomenological model chosen for the representation of the plastic behavior of the material was the Johnson and Cook model (JC), with the parameters previously characterized by compression tests and already published [10], since they used similar machining conditions. In that work it was demonstrated that JC model coupled with the proposed ductile failure model shows good agreement in the prediction of fundamental variables (forces, temperatures and chip morphology). The selection of the thermal exchange parameters, friction model and micro-geometry of the tool are in-depth explained in [10]. Table 1 shows a summary of the input parameters of the FEM model.

The machining conditions were chosen to observe the chip segmentation process in the lack of ductility regime, since it has barely been studied and it is interesting for low cutting speed machining applications.

Table 1. Input parameters of the FEM model.

Johnson-Cook model	A (MPa)	1130
	B (MPa)	530
	C	0.0165
	n	0.39
	$\dot{\varepsilon}_0$	1
	T_{melt} (ºC)	1650
	T_{room}(ºC)	20
	m	0.61
Young's modulus (GPa)	Ti-6Al-4V	115
	Carbide	500
Poisson's ratio	Ti-6Al-4V	0.3
	Carbide	0.3
Conductivity (W/mºC)	Ti-6Al-4V	6.7
	Carbide	100
Heat capacity (MJ/m^3)	Ti-6Al-4V	2.3
	Carbide	0.1
Friction coefficient	μ	1
Cutting speed (m/min)		7.5
Feed (mm)		0.1
Rake angle (º)		6
Clearance angle (º)		5
Cutting edge radius (μm)		25

2.1. Ductile failure model

The present work introduces a two-stage physical-based ductile failure model. Mohr-Coulomb failure law models the damage initiation stage (see equation 1). It expresses that damage (D) accumulates along an equivalent plastic strain path, depending on the variation of the failure plastic strain ($\bar{\varepsilon}_f$) along the path.

The failure strain depend on the failure strain in simple shear or torsion ($\varepsilon_{f,0}$)$_T$, the stress triaxiality (η) and the stress triaxiality sensitivity constant (c) (see equation 2). The stress triaxiality is the ratio between hydrostatic stress (σ_m) to the flow stress of the material ($\bar{\sigma}$) (see equation 3). The failure strain in simple shear/torsion is reported in literature depend on temperature. It is commonly represented as a linear increase, up to a critical temperature (T_{crit}) above which it increases rapidly (see equation 4 and 5). The temperature sensitivity is represented in the equation 4 by parameter a.

$$D = \int_0^{\bar{\varepsilon}_f} \frac{d\bar{\varepsilon}}{\bar{\varepsilon}_f} \quad (1)$$

$$\bar{\varepsilon}_f = \left(\varepsilon_{f,0}\right)_T \exp(c\eta) \quad (2)$$

$$\eta = \frac{\sigma_m}{\bar{\sigma}} \quad (3)$$

$$\left(\varepsilon_{f,0}\right)_T = \varepsilon_{f,0}(1 + aT), \qquad T < T_{crit} \quad (4)$$

$$\left(\varepsilon_{f,0}\right)_T = \infty, \qquad T > T_{crit} \quad (5)$$

Until the accumulated damage reaches the value of 1, the material plastic behavior is only governed by the undamaged flow stress model (JC). Once the damage value reaches 1, the damage evolution equations govern the flow stress reduction.

The damaged flow stress ($\bar{\sigma}_D$) depends on the reduction function of flow stress produced by the damage ($f(\eta, T)$) and the undamaged flow stress ($\bar{\sigma}$) (see equation 6). In equation 7 is represented the healing that is known to occur above a critical temperature (T_U), set in 700ºC [13]. Above that temperature, it is considered that the damage will not affect the flow stress of the material. Between T_L (600ºC) and T_U (700ºC) the influence of temperature and stress triaxiality are introduced in the equation 9. Below 600ºC the reduction function only depends on stress triaxiality (see equation 8). The sensitivity parameter of the stress triaxiality is μ_i.

$$\bar{\sigma}_D = f(\eta, T)\bar{\sigma} \quad (6)$$

$$f(\eta, T) = 1, \qquad T > T_U \quad (7)$$

$$f(\eta, T) = \tanh\left[-\sqrt{3}\mu_i\eta\right], \qquad T < T_L \quad (8)$$

$$f(\eta, T) = \tanh\left[-\sqrt{3}\mu_i\eta\right] + \left(1 - \tanh\left[-\sqrt{3}\mu_i\eta\right]\right)\left(\frac{T - T_L}{T_U - T_L}\right), \quad T_L < T < T_U \quad (9)$$

3. Design of Experiments (DOE) strategy

The aim of using the DOE technique is to obtain the influence of the input parameters in the outputs in a structured strategy. Hence, firstly the parameters to be analyzed need to be chosen. From the failure initiation equations the parameters $\varepsilon_{f,0}$ and a were chosen since they influence linearly the temperature sensitivity of the failure strain below the critical temperature (600ºC). The c parameter was also considered due to the fact that it represents the stress triaxiality dependency of the failure strain. To analyze the influence of stress triaxiality on the flow stress reduction process, the parameter μ_i was also analysed. Therefore, in the present work a factorial DOE was used composed by 2 levels and 4 variables ($\varepsilon_{f,0}$, a, c, μ_i). The factorial design used is presented in Table 2.

Table 2. Factorial design of the DOE.

Factor	Minimum value (-1)	Reference	Maximum value (+1)
$\varepsilon_{f,0}$	0.1	0.25	0.5
a	0	0.0012	0.024
c	-2	-1.5	-1
μ_i	0.5	1	1.5

The values were increased an reduced from the reference value which was taken from the works of Childs et al. [3] and Ortiz-de-Zarate et al. [10], which showed good agreement with experimental results. The selection of the values of the parameters was always made following a physical criterion, that is, the values were varied within the ranges observed in literature that were previously used for this material. Importantly, the selection of this range allows to obtain from continuous to segmented chip. In total 17 simulations where carried out, 16 of the DOE analysis and an additional simulation with the reference parameters [3,10].

Fig. 1 shows the influence of the analyzed parameters in the failure strain. In machining generally negative stress triaxiality is observed [3]. Fig.1a shows the influence of stress triaxiality at two temperatures (20ºC with full lines and 600ºC with dashed lines) and with the reference, highest and lowest values used in the DOE. As could be observed, there is not influence of temperature when the lower values are selected as also is presented in the 3D graph of Fig. 1c. Those values produce low critical strain which may produce premature segmentation of the chip. The higher values of the parameters seem to produce a significant increase in the critical strain, as well as, in the temperature sensitivity, as it could be also observed in Fig.1d. Therefore, with this strategy it could be analyzed clearly the influence of the different parameters with respect to the reference values of Fig. 1b.

Regarding the effect of μ_i in the flow stress reduction function, Fig. 2 shows how it varies with different temperature ranges. That is because as explained in the previous section there are three equations (7-9) to represent the flow stress reduction function depending on the temperature. Higher μ_i produces less flow stress reduction for the same triaxiality.

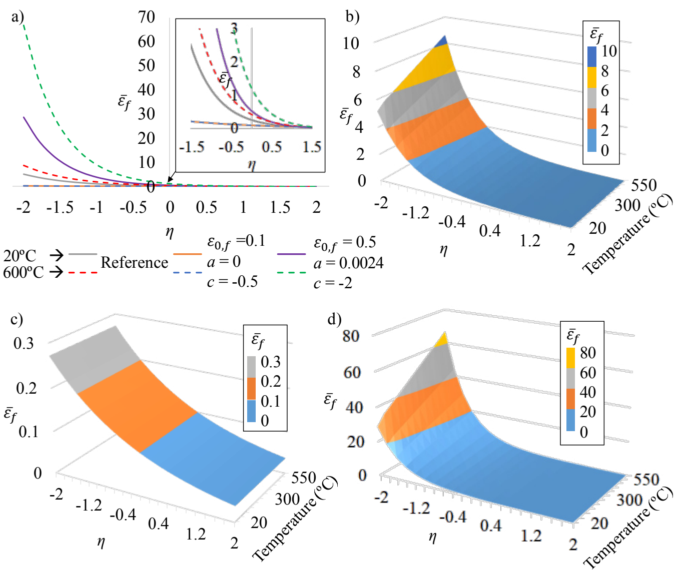

Fig. 1. a) Influence of the ductile failure parameters in the failure strain for 20ºC and 600ºC and ductile failure model for b) the parameters with the lowest values, c) reference values and d) highest values.

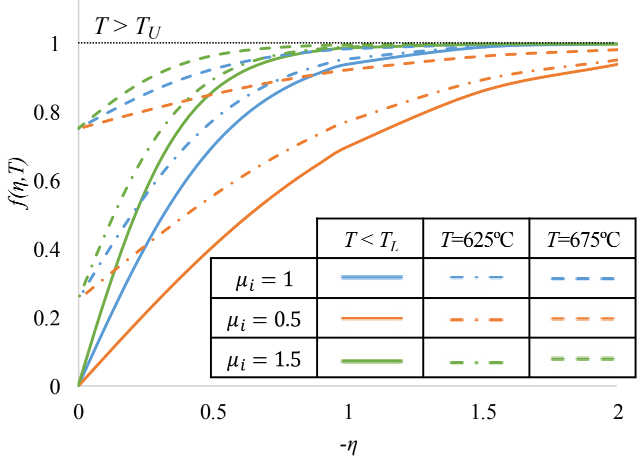

Fig. 2. Influence of the ductile failure model parameters on the flow stress reduction function.

4. Results and discussion

The DOE analysis was performed for the four variables and their interactions using the statistical software Minitab 18. However, it was only considered until second order interactions, since the influence of the interactions of higher order (3rd and 4th) are negligible. The interactions between factors is established by * symbol. All the results are presented in percentage of variation with regard to the average value.

4.1. Cutting and feed forces

The machining forces were extracted when the thermal-steady state was reached. Most of the results showed segmented chip. Therefore, for cutting and feed force analysis four variables where considered in each case: the maximum and minimum forces, as well as the ratio between them and the average. That allows analyzing the influence of the input parameters of the ductile failure model not only on the plastic behavior of the material (represented by the average forces) but also on the segmentation process, which produce force fluctuation that could consequently generate fatigue failure.

The results in both forces showed that the most influential parameters are μ_i and $\varepsilon_{f,0}$(see Fig. 3). The significant influence of μ_i is related to the flow stress model reduction produced by the damage, while $\varepsilon_{f,0}$ modifies drastically the chip segmentation process and consequently the forces.

Going more into detail with the results of cutting forces (F_c), μ_i is the most critical parameter when predicting the ratio between forces (see Fig. 3a). That parameter is also significant when predicting properly the average cutting force and the minimum force. Nevertheless, its influence on the maximum forces is similar to $\varepsilon_{f,0}$. This could be related to the fact that the increase of $\varepsilon_{f,0}$ produces the delay in the appearance of the segmentation which may influence more drastically the maximum forces than the other variables. Regarding the interactions, as expected, the most remarkable one is the $\varepsilon_{f,0}*\mu_i$, which principally influences the cutting force ratio, producing an additional increase.

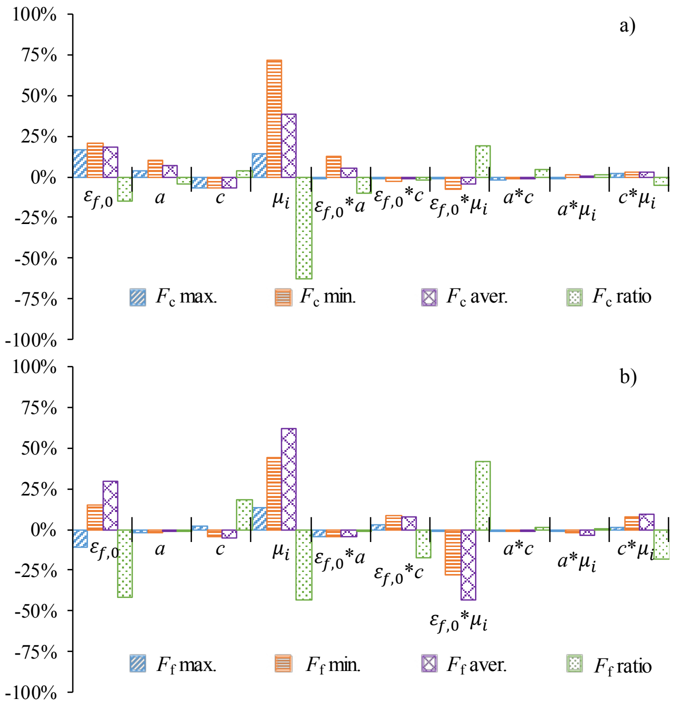

Fig. 3. Influence of the input parameters of the ductile failure model on a) cutting and b) feed forces.

The feed force (F_f) results showed similar trends (see Fig.3b). One of the main differences is that the influence of μ_i on the ratio of forces is similar to the one of $\varepsilon_{f,0}$. Moreover, the forces seems to decrease with the increase of $\varepsilon_{f,0}$ contrary to what observed in the cutting forces. The influence of the interaction $\varepsilon_{f,0} * \mu_i$ increased drastically on the feed force prediction for all the analyzed variables.

4.2. Tool temperatures

The temperatures were measured in the tool when the thermal steady state was reached. During the segmentation process fluctuation of temperatures occur, hence, the average value between fluctuations were selected. The influence of μ_i continues been the most important one, followed by $\varepsilon_{f,0}$ (see Fig. 4). It should be also highlighted the influence of the interaction between both parameters, which produces a reduction in temperature of about 15%.

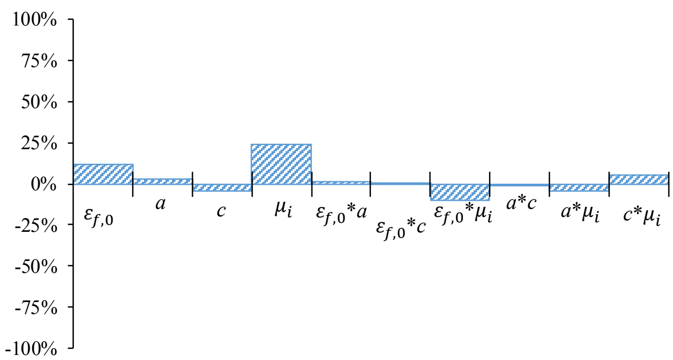

Fig. 4. Influence of the input parameters of the ductile failure model on tool temperature.

4.3. Chip morphology

Four variables where analyzed in each chip. The maximum and minimum chip thickness (t_2 max. and t_2 min.), the pitch and the degree of segmentation (*DS*), which is the ration between the maximum and the minimum chip thicknesses [7]. Fig. 5a shows an example of an experimental chip for the same machining condition. The input parameters of the ductile failure model chosen for the analysis allows producing different chips, from continuous to high segmentation conditions (see Fig. 5b-d).

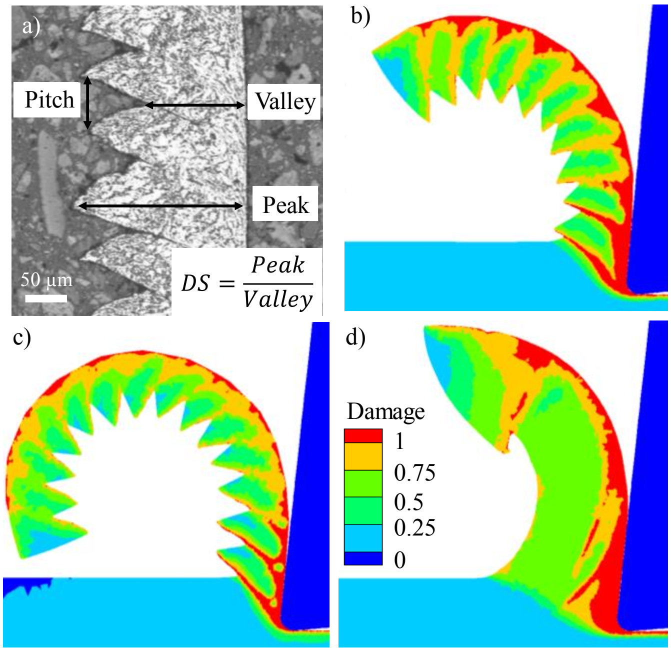

Fig. 5. a) Experimental chip [7] and predicted chips for b) reference values of the input parameters, c) lowest values and d) highest values.

As in the previous results, $\varepsilon_{f,0}$ and μ_i are the most critical parameters (see Fig. 6). However, in comparison to the other results the influence of a and c is significantly higher, due to their influence in the critical strain.

Since $\varepsilon_{f,0}$ directly influences the strain in which the segmentation starts, it clearly modifies the pitch. Due to the same reason, it also varies the maximum and minimum chip thicknesses, but its influence on the ratio between them is practically negligible.

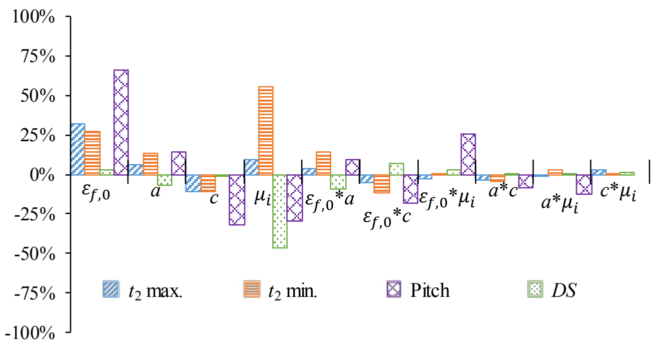

Fig. 6. Influence of the input parameters of the ductile failure model on chip morphology.

Regarding the influence of *a,* it produces a change of about 5-15% in the analysed variables. The *c* parameter also influences significantly the chip morphology (10-30%), in spite of the degree of segmentation.

The degree of segmentation is mainly only influenced by μ_i. This parameter also varies significantly the minimum chip thickness and the pitch. The influence on the maximum chip thickness is practically negligible in comparison to the rest of variables.

4.4. Surface drag

The high thermo-mechanical loads produced by the machining operation generally produce microstructural changes that may affect the fatigue performance of the part. The surface drag is one of the indicators commonly used to represent those microstructural alterations. Generally, the depth of the deformed layer expresses the surface drag. However, it is not clear from a materialistic point of view if it is more critical the depth of the deformed layer or the quantity of deformation. Therefore, in the present simulation two parameters were analyzed: a) the deformed depth, measured from the machined surface until strain lower than 0.1 were reached (it is considered that 0.1 is small enough to make a comparative study between simulations), and b) surface strain. Moreover, it was analyzed the surface layer in which the accumulated damage is greater than 1, since it could be related to a worsening of the thermo-mechanical properties of the workpiece.

All the results were obtained after 2 mm of cut, 1 mm far from the tool, once the workpiece was cooled until room temperature (20ºC).

Regarding the surface strain it was observed the high influence of mainly all the parameters, being the interaction $\varepsilon_{f,0}*\mu_i$ the most remarkable one (see Fig. 7). The deformed layer seems to be less sensitive to the input parameters of the ductile failure model. Finally, the damaged surface layer seems to be extremely sensitive to the variations of all the parameters and their interactions.

Therefore, to the adequate prediction of all the surface drag parameters, including damaged surface layer, precise adjustments need to be done in the inverse simulation strategy.

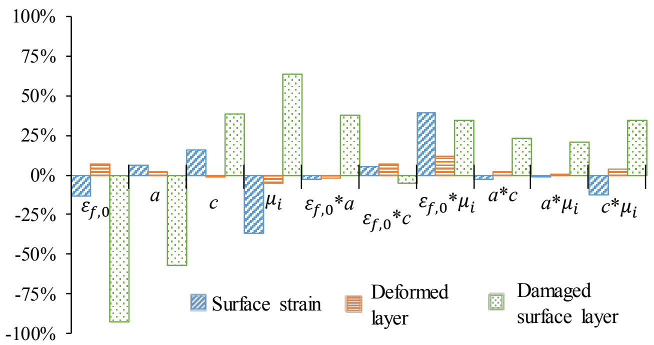

Fig. 7. Influence of the input parameters of the ductile failure model on surface drag.

5. Conclusions

In this paper, a sensitivity analysis of the input parameters of a physical-based ductile failure model in fundamental outputs and surface integrity aspects using FEM is presented. The main highlights of the study are the following:

- In general terms, $\varepsilon_{f,0}$ and μ_i seems to be the most critical parameters for all the analysed variables due to the high influence they have in the chip segmentation process and flow stress behaviour respectively. Therefore, in an inverse simulation strategy those should be the first terms to be correctly characterized and adjusted. However, it has to be considered that the variation in the input parameters of the ductile failure model was not the same for all of them. For instance, $\varepsilon_{f,0}$ was varied from 0.1 to 0.5, which mean a variation of 0.4, while c was only varied 0.0024.
- The parameters a and c need to be also correctly characterized if surface integrity want to be predicted due to the high influence they have in surface drag results, mainly in the damages surface layer and surface strain.
- It seems that the adequate selection of the input parameters of the ductile failure model is critical due to the severe influence they have in the results of the simulations. Since, using different parameters commonly applied for this material, significant differences were reported. For instance, the results showed from continuous chip to segmented chip.
- The surface drag, commonly reported by the deformed layer, seems to be not significantly influenced by the analysed parameters. Conversely, the surface strain and damages surface layers are drastically affected. Therefore, special attention should be paid in the adequate selection of the input parameters of the ductile failure model if all the surface drag parameters want to be correctly predicted.
- It has to be considered that even if the fundamental outputs are correctly predicted, slight variation in the parameters of the ductile failure model may produce the inadequate prediction of surface integrity. Therefore, the strategy proposed for the inverse simulation is composed of two stages. Firstly, a rough estimation of the input parameters need to be done, focusing most critical ones ($\varepsilon_{f,0}$ and μ_i) and in the adequate prediction of the fundamental variables. For that, the parameters chosen should cover a significant wide range of values, always maintaining their physical meaning. On the second stage, smaller variations of the parameters need to be done focusing on a and c. They may not produce significant differences in the prediction of fundamental variables but could adjust the surface integrity outputs.

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