To link to this article: DOI:10.4028/www.scientific.net/KEM.446.147
http://www.scientific.net/KEM.446.147

To cite this version:

Wagner, Vincent and Baili, Maher and Dessein, Gilles and Lallement, Daniel *Behaviour laws comparison for titanium alloys machining: Application to Ti5553*. (2010) Key Engineering Materials, vol. 446 . pp. 147-155. ISSN 1013-9826

Behaviour laws comparison for titanium alloys machining: Application to Ti5553

Vincent WAGNER[♮†], Maher BAILI[♮], Gilles DESSEIN[♮], Daniel LALLEMENT[†]

[♮]Université de Toulouse ; INP/ENIT ; LGP;
47 avenue d'Azereix, BP 1629, F-65013 Tarbes Cedex, France
[†] Messier Dowty Bidos ; rue Guynemer, BP 39, F-64401 Oloron Sainte Marie Cedex, France

Abstract

The aircraft industry uses materials more and more efficient. This trend affects the majority of parts such as structure parts. Titanium alloy (Ti-5AL-5Mo-5V-3CR) is now used for the production of landing gear. There are many goals in this paper. First, the physical and mechanical properties of the material will be presented. Secondly, we show the relationship between material properties and machinability. Third, the Ti5553 will be compared to Ti64. The Ti64 is $\alpha+\beta$ alloy group and Ti5553 is a metastable beta but we have chosen to compare these two materials. Ti64 is the most popular of titanium alloys and many of works were been made on its machining. After, we have cited the Ti5553 properties and detailed the behaviour laws. They are used in different ways, with or without thermal softening effect or without dynamic terms. We have to define the best model to use in cutting force model. Differents models are compared for two materials (steel and titanium alloy). To define the model, two methods exist that we have compared. The first is based on machining test however the second on Hopkinson bar test. These methods allow us to obtain different ranges of strain rate, strain and temperature. This comparison will show the importance of a good range of strain rate, strain and temperature for behaviour law, especially in titanium machining.

1 Introduction

The aircraft industry uses materials more and more efficient. This trend affects the majority of parts such as structure parts. Titanium alloy (Ti-5AL-5Mo-5V-3CR) is now used for the production of landing gear. The poor titanium alloys machinability is explained by ezugwu in [1]. The Ti5553 can be classified in hard to cut material and there is a low knowledge in Ti5553. Arrazola ([2]) compares the Ti5553 and the Ti64 alloys: the Ti5553 machinability is very poor compared to Ti64 one. No cutting force model has been defined in his work. However, some works have been made on the cutting model and especially on Ti64 machining ([3]). The machining is a processus where stress appears according to strain, srain rate and temperature. The temperature is the result of the high level of strain, strain rate and stress. The cutting model must have a law that defines this phenomenon. There is a lot of behaviour laws and they are never used in the same ways. Moreover, few researchers study the influence of the behaviour law in model of cutting force and cutting temperature. Espacially, in hard machining material where the cutting force is very sensitive to cutting conditions. Changeux ([4]) shows the influence of behaviour law in cutting force modelling. However, his work has been made for austenitic steel. In his work, Poulachon ([5]) explains that the identification methods of behaviour law can be classified by the strain rate range. He shows the difference beetween machining strain rate and identification methods strain rates. To allow a higher range of strain rate many works ([3, 6]) detail a method to identify the constants of behaviour law from machining.

There is many goals in this paper. First, the physical and mechanical properties will be presented. [7] shows the Ti5553 material properties but for a non treated Ti5553. We show the relationship between material properties and machinability. The Ti5553 will be compared to Ti64. The Ti64 is α+β alloy group and Ti5553 is a metastable beta but we have chosen to compare it with this material. Ti64 is the most popular of titanium alloys and many works were made on its machining. After, we have shown the Ti5553 properties and we have seen the behaviour laws. They are used in different ways, with or without thermal softening effect or without dynamics terms. The target is to define the best model to use in cutting force model. Different models are compared for two materials (steel and titanium alloy). An other important point is the model definition. There are different ways to define the constant model. We compared two methods. The first is defined from machining test and the second from Hopkinson bar test. This comparison will show the importance of a good range of strain rate, strain and temperature for behaviour law.

2 Physical properties

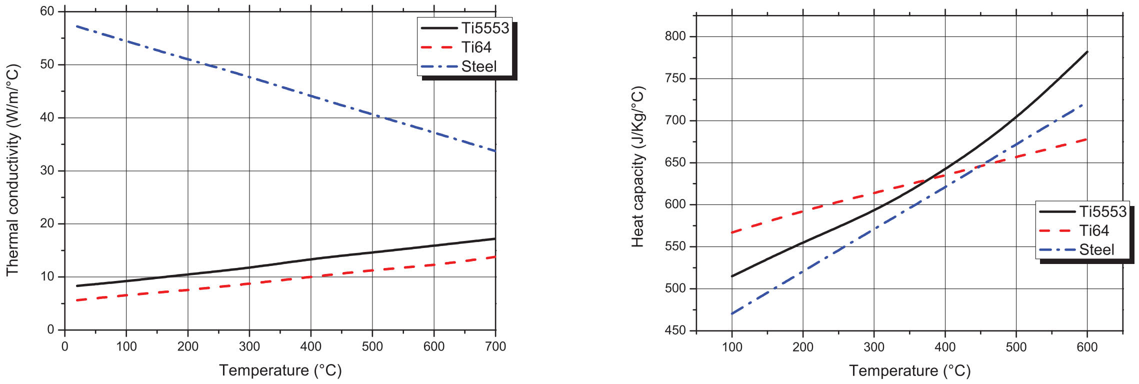
2.1 Phase diagram

The Ti5553 is a metastable beta with a low transus beta (occurs at 845°C). The titanium alloy Ti64 belongs to α+β alloys group, its transus beta occurs at about 990 °C . In machining, this difference between the two alloys can be important. In his paper, Ozel ([3]) uses the Oxley model ([8]) to estimate the cutting temperatures. He shows in [3] that the cutting temperatures of Ti64 machining are range from 750°C to 940°C. Consequently, they are always less than the transus beta temperature. So, the titanium structure α+β and its concentration do not change.

The mechanical properties of Ti5553 compared to the Ti64 alloy are higher and the physical properties are almost the same (table 1). The cutting temperatures will be also higher when machining Ti5553 alloy. In addition to that, they are superior than the transus beta temperature, as a result, the alloy structure will be changed. The beta phase concentration becames more important. For Arrazola ([2]), the differences of structures with a variable quantity of the alpha phase and the morphology of the transfromed α+β phase can explain the poor Ti5553 machinability. This modification of phase will be important, especially in machining of structure part.

2.2 Thermal conductivity

The Ti5553 alloy have a poor thermal conductivity and can be classified like heat resistant material. The figure 1 (a) shows the thermal conductivity of Ti5553 and Ti64 alloys. Indeed, according to temperature, we can see that whatever the steel thermal conductivity is the highest. It decreases when temperature increases whereas the titanium thermal conductivity increases. If we compare the titanium values, the Ti5553 thermal conductivity is always higher than the Ti64 one. This can be a problem in machining. This poor thermal conductivity limits the heat evacuation in chip. In his paper [1], Ezugwu depicts the distribution of thermal load when machining titanium and steel. In titanium machining, a large proportion (80%) of the heat generated is conducted in tool. However, in steel machining only 50% of heat generated is conducted in tool. This difference can be explained by the higher thermal conductivity of tool (60 $W/m/°C$) compared to titanium alloy thermal conductivity (8 $W/m/°C$). Whereas, for the used machining tool, the thermal conductivity compared to steel one are quite the same. The heat is being quickly conducted in tool, so the thermal softening can be easily obtained.



(a) (b)

Figure 1: Thermal conductivity and heat capacity comparison [9]

In their models, [10] and [8] demonstrate that temperatures in shear plan and at the tool-chip interface are function of thermal conductivity (equations 1 and 2).

$$T_{AB} = \frac{(1-\beta)F_s cos\alpha}{\rho S t_u w cos(\phi - \alpha)} \tag{1}$$

$$\beta = 0.5 - 0.35 log(\frac{\rho S V t_u}{K} tan\phi) \tag{2}$$

Where: T_{AB} = Average temperature in shear plan; ρ = Density; S = Heat capacity; V = Cutting velocity; t_u = Undeformed chip thickness; K = Thermal conductivity; ϕ = Shear angle; α = Rake angle; w = width of cut; F_s = Shear force.

Equation 2 defines the heat rate conducted into the part. However, equation 1 represents the average temperature in primary shear plan. When K increases, the proportion of heat conducted into the part (β) is higher and leads to a reduction of temperature in primary shear plan (T_{AB}).

2.3 Heat capacity

The figure 1 (b) shows a comparison between heat capacity of steel and titanium alloys. To the contrary of thermal conductivity, the heat capacity of the three materials increases according to temperature. The steel heat capacity is higher for low temperatures (575 $J/kg/°C$) whereas the Ti64 is the lowest (460 $J/kg/°C$). When the temperature increases, the Ti5553 heat capacity becomes highest

(775 $J/kg/^{\circ}C$ at 600°C). This value is 20% upper than Ti64 one. For Ti5553, the increasing heat capacity between low and high temperatures is more than 35%, whereas it is only about 15% for Ti64.

In [10, 8] models, the cutting temperature is inversely proportional to the heat capacity (equation 1). We can see that increasing heat capacity leads to reduction of the cutting temperature. Like thermal capacity, with a high heat capacity it is difficult to obtain the thermal softening. The cutting temperature can be limited by these high values and can be less than beta transus.

3 Mechanical properties

3.1 Tensile test

Figure 2 shows the true stress according to true strain. This value was obtained with ambient temperature and with constant deformation speed. The Young modulus, strain, tensile yield stress (TYS) and ultimate tensile stress (UTS) were identified from the tensile test. The values are noted in table 2. First, we can say that the Ti5553 material properties values are higher compared to Ti64. The ultimate tensile stress and tensile yield stress are 20% higher. The second point is the low ductility: 0.01%. In comparison with Ti64, this value is very low and show that the Ti5553 is a brittle material.

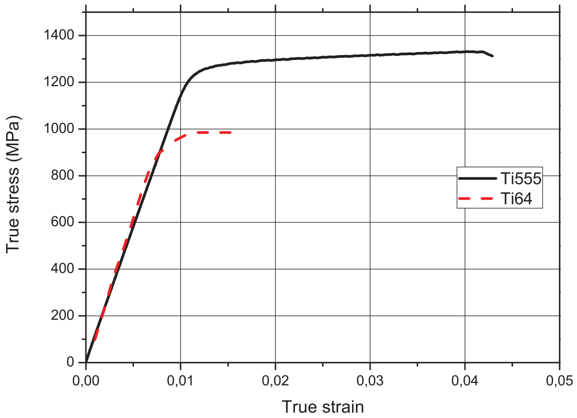


Figure 2: Tensile test Ti64 and Ti5553

Table 1: Material properties of Ti5553 and Ti64

Material	TYS (MPa)	UTS (MPa)	Modulus (GPa)	Elongation (%)	Hard. HB±5	TYS 400°C (MPa)
Ti5553	1250	1320	110	0.01	370	860
Ti64	1050	1200	105	18	241	550

The material properties influence the machining responses and can explain the high cutting force values. The Ti5553 ultimate tensile stress is also higher even at 400°C in machining and the cutting forces are also higher. Another consquence oh high mechanical properties and poor ductility, it will be difficult to get a segmented chip.

3.2 Behaviour law

There are two goals in this section. First, we will determine the best model defining the cutting forces and temperature in machining. Secondly, we will propose the best solution to define the behaviour law.

The behaviour laws are used to determine the stress according to strain, strain rate and temperature. Some different laws are used in modeling of cutting forces and cutting temperatures. [8] uses the Hollomon model and neglects the temperature and strain rate effects. [11], [12] and [3] use the Johnson-Cook law. Other models can be considered. Lindholm model defines stress according to strain and strain rate. However, it does not take into account the temperature. The Norton-Hoff law can also be considered. Johnson-Cook model seems to be the best to model the cutting forces.

$$\overline{\sigma} = \left[A + B(\overline{\varepsilon})^n\right]\left[1 + Cln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \tag{3}$$

However the Johnson-Cook model (equation 3) is used in different ways. In their works, [11] and [12] consider an adiabatic process and neglect the heat influence in primary shear plane. They determine the shear flow stress along primary plan from the restricted Johnson-Cook law. The thermal softening effect is not inserted in restricted Johnson-Cook model. In [3], Ozel used also this model but in its complete definition with thermal softening effect. The target is to verify these assumptions and to see if it is always true in high mechanical and poor thermal properties materials. The titanium alloys have a poor thermal conductivity and a high heat capacity. The heat is rapidly conducted in tool ([1]). The Johnson-Cook model must have the thermal softening effect to define the cutting shear flow stress. The tensile test depicts that the titanium alloy are brittle. The strain rate constant (C) must be integrated in the model.

In this first part, we set the parameters to insert into the model. To define the best model, we have compared two materials: AISI1045 steel and Ti64 titanium alloy. For each material, the Johnson-Cook model have been used in three different ways and we have compared the theoretical results ($\overline{\sigma}_{JC}, \overline{\sigma}_{JC1}, \overline{\sigma}_{JC2}$) and the experimental results (σ_{AB}), where σ_{AB} is effective flow stress in primary shear plan defined in Oxley model from machining ([8]). σ_{JC} represents the stress obtained with the Johnson-Cook model. $\sigma_{JC1}$and σ_{JC2} are the stress obtained without the thermal softening effect and without the strain effect (equations 4 and 5). In [3], the Johnson Cook model used is defined by Hopkinson bar test.

$$\overline{\sigma}_{JC2} = \left[A + B(\overline{\varepsilon})^n\right] \tag{4}$$

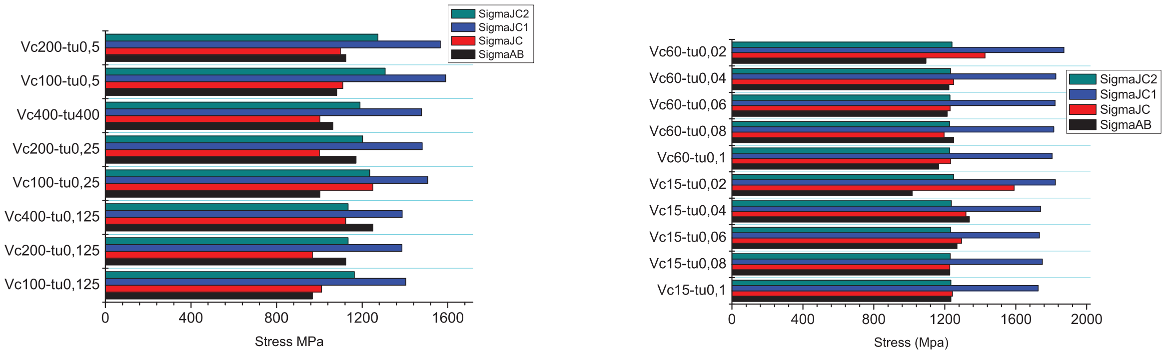
$$\overline{\sigma}_{JC1} = \left[A + B(\overline{\varepsilon})^n\right]\left[1 + Cln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right] \tag{5}$$

$$\overline{\sigma}_{JC} = \left[A + B(\overline{\varepsilon})^n\right]\left[1 + Cln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \tag{6}$$

The results for the two materials and the three models are presented in figure 3. Figure 3(b) shows the comparison between theoretical results and the experimental results (σ_{AB}) for Ti64. However, figure 3(a) depicts the same comparison for AISI1045. For steel, the best model seems to be the complete Johnson-Cook model. The errors between the values defined in machining and with the Johnson-Cook models are $\sigma_{JC} = 7\%$; $\sigma_{JC1} = 15\%$ and $\sigma_{JC2} = 9\%$. For steel, the second model (σ_{JC1}) is the worst one. The best values obtained for Ti64 are also obtained with the complete model (equation 6). The errors between the values defined in machining and with the Johnson-Cook models are $\sigma_{JC} = 5\%$; $\sigma_{JC1} = 30\%$ and $\sigma_{JC2} = 5\%$. Like for steel, the worst model is the model without thermal effect.

First, this analysis shows the importance of thermal softening effects in shear plan model. Without thermal effect, the effective flow stress values is higher. It seems to be important to use the complete Johnson-Cook model in steel and in titanium alloy. Moreover, the mechanical properties of titanium remains high even at high temperature.

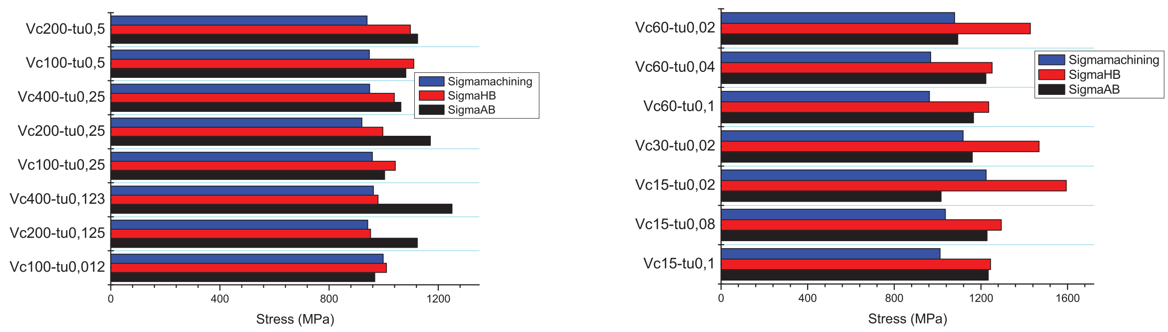
The figure 3(a) depicts that the titanium model seems to be more sensitive to the behavior law. The good fit for steel is due to the good range of strain rate, strain and temperature of Johnson-Cook model. The used model is defined at test strain up to $10^4 s^{-1}$ and a temperature up to $600°C$. The strain rate and the temperature defined in cutting modeling are often in this range ($3399 < \overline{\varepsilon}_{AB} < 12653$ and $428 < T_{AB} < 494$). For Ti64, the material law is defined for a strain rate of $2000 s^{-1}$ and a temperature up to $1100°C$. Our calculations show some strain rate values up to the strain rate model ($1780 < \overline{\varepsilon}_{AB} < 84993$) and a temperature between $531°C$ and $671°C$. The difference between model strain rate range and machining strain rate range is the error explanation. It seems to be very important to define correctly the range of strain rate and temperature. Especially, when the machining generates high strain rate.



(a) (b)

Figure 3: Behaviour law comparison

The constant of Johnson-Cook model can be defined by different methods. Poulachon ([5]) explains that the method must be chosen according to the strain rate (figure 6). The split Hopkinson bar test is the most commonly used method for determining stress according to high rates of strain. The Taylor test may be also considered. It allows to obtain higher strain rate ($5 \times 10^3 s^{-1} < \overline{\varepsilon} < 5 \times 10^6 s^{-1}$) ([13]). An other method can be considered. Indeed, Ozel ([3]) and Tounsi ([6]) have developed a method to define the Johnson-Cook material model from machining test. There are different advantages with these



(a) (b)

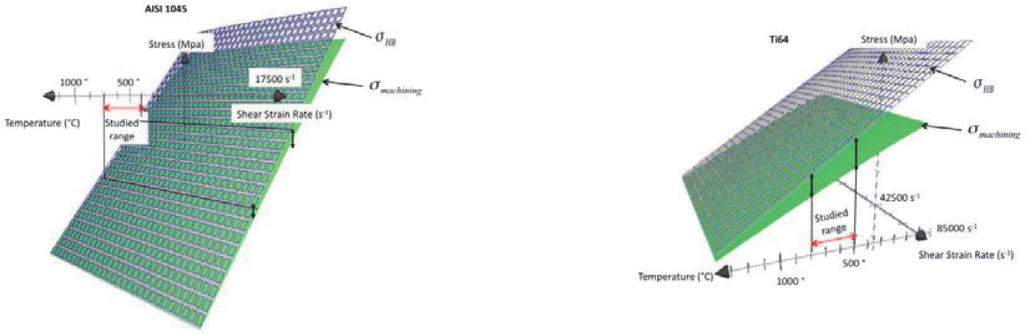
Figure 4: Comparison between two identification methods

methods. First, the strain rate and temperature are always those obtained in machining. Secondly, the impact test is not always feasible for brittle material. The increasing of temperature can rise the ductility of the material. Thus, impact test becomes possible.

We have compared two material models. The first model has been defined with Hopkinson bar test and the second from machining tests. We have chosen to use the model defined in [3]. This test has been made on titanium alloy (Ti64). σ_{AB} is the effective flow stress at primary shear zone and has been determined from Oxley model. σ_{HB} is the stress defined from Johnson-Cook model and $\sigma_{machining}$, the stress obtained with behaviour law identified from machining.

Figure 4 shows the stress obtained from the two models. The tests have been made in different cutting speed (Vc) and different undeformed chip thickness (tu). For steel, $\sigma_{machining}$ and σ_{HB} are quite equal. The identification method does not seem to influence the results. For, Ti64, it can be observed that sometimes $\sigma_{machining}$ is better and sometimes σ_{HB} is the best. A analysis shows that the results are function of strain rate values. For low strain rate values (Vc15-tu0.1, Vc15-tu0.08), the best model is the model obtained with Hopkinson bar test. Whereas, for high strain rate (Vc15-tu0.02; Vc60-tu0.02) the best model is one that is defined from machining test. This analysis show the importance of the good definition of model range. The Hopkinson bar test allows a maximum strain rate of $2000s^{-1}$while strain rate machining is $85000s^{-1}$. Moreover in analysing, the behaviour law obtained from machining test limits the influence of strain rate constant ($C_{HB} = 0.028$ and $C_{machining} = 0.000002125$). In high strain rate, the stress is also reduced with increasing of strain rate. This observation seems to be coherent with machining tests and explains the stress decreasing.

The other point is the temperature effect. To explain the difference between the two materials some response surfaces have been plotted. The figures 5 (a) and (b) show the stress plotted according to strain rate and temperature. In machining, $\sigma_{machining}$ is always lower at σ_{HB}. The two surfaces show the difference between two identifications methods. In studied range temperature and strain rate, the difference between the stress is different for the material. The figure 5 (a) shows that the two surfaces obtained are close and almost parallel. They are closer to high temperatures. In machining test, $\sigma_{machining}$ and σ_{HB} are the same, the results seems to be coherent. For Ti64, the two surfaces are more remote and the slope is different. Increasing of temperature reduces the gap between the two surfaces. However, in comparison with steel, the gap is higher. This analysis shows the importance of thermal softening above all in titanium alloy machining and the importance of a good beahaviour law.



(a) (b)

Figure 5: Response surfaces

The modeling of cutting force in titanium alloy machining is more sensitive to behaviour law. The complete model must be used to define the shear flow stress along primary zone. The behaviour law must be defined with Hopkinson bar if strain rate values are good (figure 6). However, another point to consider is the temperature. It is very important above all in machining of titanium alloy where the strain rate seems to be higher.

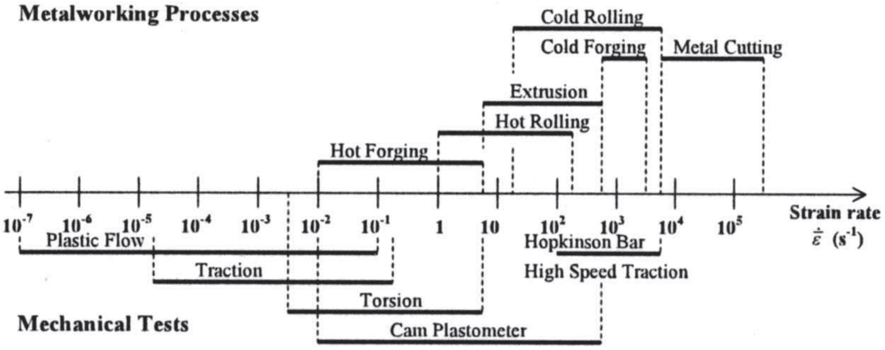


Figure 6: Strain-rate range reached in metalworking and limitations of the standard mechanical tests [5]

For Ti5553, the first terms of Johnson-Cook has been made. A is the yield stress when B and n represent the effects of strain hardening. These values show the high properties of Ti5553. If compared with Ti64 yield stress, the Ti5553 one is higher. The table 2 illustrates that the effect of strain hardening in Ti5553 is higher compared to Ti64. These values show the poor ductility of Ti5553. Moreover, the effect of strain hardening is higher for Ti5553.

Table 2: Johnson Cook Law [3]

Material	A (MPa)	B (MPa)	n
Ti5553	1250	403	0.47
Ti64	783	498	0.28

In using those results and works established in [14], we have defined the strain obtained in Ti5553 machining. The test has been made with constant undeformed chip thickness ($t_u = 0.2mm$), constant rake angle ($\alpha = 13°$) and a low edge preparation. We can denote that Ti5553 machining creates a very high strain rate (table 3). Those results show the importance of the behavior law definition. In this case, Hopkinson bar test do not allows the good strain rate. To get the good strain rate, two methods are possible, the Taylor test which permits us to get very high strain rate ($5 \times 10^3 s^{-1} < \overline{\varepsilon} < 5 \times 10^6 s^{-1}$) [13] or to define model with machining tests. We have chosen to use test machining to define behavior law. These methods allow us to define the behavior law in good range (strain rate and temperature) but especially to increase material ductility with the increasing of temperature.

Table 3: Strain rate for Ti5553

Test	Co	$\dot{\overline{\varepsilon}}_{AB}(s^{-1})$	Fc (N)	Ft (N)
$Vc = 25m/min$	36	34104	1899	1238
$Vc = 35m/min$	47	62029	1905	1358
$Vc = 40m/min$	37	55492	1898	1245
$Vc = 45m/min$	38	65201	1903	1268
$Vc = 50m/min$	42	77808	1906	1302
$Vc = 55m/min$	46	94438	1886	1321
$Vc = 60m/min$	36	79871	1873	1210
$Vc = 65m/min$	38	92228	1875	1240
$Vc = 75m/min$	35	98571	1882	1210
$Vc = 85m/min$	41	129057	1841	1247
$Vc = 95m/min$	49	175614	1829	1321

4 Conclusion

This paper shows the influence of behaviour law in cutting force model. We have compared different models of shear stress along primary plan. These tests have shown that the model must have the thermal effect especially in titanium alloys machining. Moreover, the model strain rate range must be the same as machining. To limit error, we have shown that the best method to define the behaviour law is the definition from machining. This method allows the good stain rate and the good temperatures. We have shown that observations are very important in Ti5553 machining. Indeed, the strain rate seems to be very high compared to Ti64. So, we have chosen to define a complete Johnson-Cook model based on machining tests. Other tests must be made to define the Johnson-Cook law constract. They make us to define the influence of cutting conditions on cutting forces ant cutting temperature. The

Johnson-Cook law will be defined from these tests where cutting temperature has been recorded with thermocouples. The strain rate and strain will be defined from Oxley model ([8]).

References

[1] E.O. Ezugwu and Z.M. Wang, Titanium alloys and their machinability - a review, Journal of Material Processing Technology No. 68 (1997) 262-274.

[2] P.J. Arrazola, A. Garay, L.M. Iriarte, M. Armendia, S. Marya, F. Le Maître, Machinability of titanium alloys (Ti6Al4V and Ti555.3), Journal of Materials Processing Technology, 2008.

[3] T. Özel, E. Zeren, A methodology to Determine Work Material Flow Stress and Tool-Chip Interfacial Friction Properties by Using Analysis of Machining, Journal of Manufacturing Science and Engineering, Vol. 128, (2006), 119.

[4] B. Changeux, Loi de comportement pour l'usinage. Localisation de la déformation et aspects microstructuraux, PhD Thesis, ENSAM Paris, 2001.

[5] G. Poulachon, A. L. Moisan, M. Dessoly, Contribution à l'Etude des Mécanismes de Coupe en Tournage Dur, Mécanique et Industries, (2002) Vol.3, 291-299.

[6] N. Tounsi, J. Vincenti, A. Otho, M.A. Elbestawi, From the Basic Mechanics of Orthogonal Metal Cutting Toward the Identification of the Constitutive Equation, International Journal of Machine Tools & Manufacture, Vol. 42, (2002) 1373-1383.

[7] J.C. Fanning, Properties of TIMETAL 555 (Ti-5Al-5Mo-5V-3Cr), ASM International, Vol.14, pp788-791.

[8] P.L.B. Oxley, Mechanics of Machining an Analytical Approach to Assessing Machinability, Ellis Horwood Limited, 1989.

[9] R. Tricot, Thermo-mechanical Treatments of Titanium Alloys, Proc. 6th World Conf. on Titanium, 1988.

[10] G. Boothroyd, Temperatures in Orthogonal Metal Cutting, Pro. Inst, Mech. Eng, (1963) 189-802.

[11] L. Puigsegur, Caractérisation Thermique d'un Procédé d'Usinage par Tournage Approche Analytique et par Identification de Système non Entiers, PhD Thesis, 2002.

[12] P. Joyot, Modélisation Numérique et Expérimentale de l'Enlévement de Matière, PhD Thesis, 1994.

[13] I. Nistor, Identification Expérimentale et Simulation Numérique de l'Endommagement en Dynamique Rapide : Application aux Structures Aéronautiques, PhD Thesis, 2005.

[14] G. R. Johnson, W.H. Cook, A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures.