ANALYSIS OF CONSTITUTIVE EQUATIONS AND THEIR RELATIONSHIP WITH THE METAL CUTTING PROCESS

Patrícia Alves Barbosa, barbosa_patricia@hotmail.com
Izabel Fernanda Machado, machadoi@usp.br
Engineering School of the University of São Paulo, Department of Mechatronics Engineering and Mechanical System, São Paulo, Brazil, Zip Code: 05508-900

Abstract. *Machining is one of the oldest processes for shaping components in the manufacturing industry, and over the last hundred years an extensive study has been carried out on the machining of metals. Unfortunately , a much smaller volume of research, however, has been guided towards discovering the fundamental mechanisms underlying metal cutting processes in general. The greatest barrier for developing a more basic, efficient approach is that the material behavior under unique deformation conditions of cutting is not fully understood. Accordingly, this work is based on the concept of machinability, which is defined as the way in which a material behaves during cutting. The analysis of some constitutive equations that consider high strain, high strain rates, and elevated temperature, and their relationship with machining can contribute to prepare and formulate predictive metal cutting models. These models can be powerful tools used for the development and improvement of FEA programs and machining process simulations, which is important because it contains information that can be applied to the improvement of machining techniques related to process optimizing , and to material and tool innovations.*

Keywords*: machining, mechanical behavior, constitutive equations, predictive metal cutting models.*

1. INTRODUCTION

Machining is one of the oldest processes for shaping components in the manufacturing industry, and an extensive study has been carried out on the machining of metals in the past hundred years. Most of this focused on the down-to-earth reduction of machining costs and in the manufacture of parts of acceptable dimensional accuracy and surface quality. Unfortunately, a much smaller volume of research has been devoted to discovering the fundamental mechanisms underlying metal cutting processes in general. The greatest obstacle to develop a more basic, efficient approach is the lack of understanding of the material behavior under unique deformation conditions of cutting. (Astakov, 1999a; Astakov, 1999b).

In spite of the continuous efforts of metal cutting researchers, however, tool engineers are obliged to solve their problems with the aid of their experience. Nowadays, the industry relies completely on empirical data as those presented by tool and machine tool manufacturers, as well as by professional engineering associations, through handbooks, which provide only a good starting point thus leaving the users to determine the optimal values of cutting parameters for each particular case. Solutions by costly trial-and-error methods of yesterday can be obtained today by making use of the scientific approach (Astakhov and Shevets, 2001). Thus, empirical prediction is replaced by studies of process mechanics and of plasticity theories in an attempt to predict metal cutting by the development the mathematical techniques for prediction of plastic deformation of workpieces in a broad range of strain, strain rate, temperature, and complex loading histories (Guo *et al*., 2005; Mayers, 1994).

A fundamental knowledge of the metal cutting process is essential to the optimization of operations related to cutting conditions, the development of new equipment, and predicts variables of interest for increasing process efficiency and part quality (Guo, 2003). Since the surface integrity is a major concern because it significantly affects the performance of machined components subjected to dynamic loading aggressive environments (Anurag and Guo, 2007), the material mechanical behavior has shown to be a powerful tool in machine design and in the development of new materials for improving process efficiency.

However, machining is considered a complex process, due to the large number of variables involved, and according to Shaw (2005), it is virtually impossible to predict the metals mechanical behavior, but every point thoroughly studied and properly interpreted contributes to the understanding of the process, thereby leading closer to this predicting ability. Numerous attempts have been made, but instead of establishing a predictive theory, the research focuses in the development of theories of descriptive nature that only explain post-process phenomena, and after many years of study, theory is still lagging behind practice (Astakhov, 1999a).

In the sense, this study is based on the concept of machinability - defined as the way the material behaves during cutting - and on the analysis of some constitutive equations considering high strain, high strain rates, and elevated temperature, besides their relationship with machining, which can contribute to the preparation and the formulation of predictive metal cutting models, as well as to the development and improvement of FEA programs and machining process simulations.

2. MACHINABILITY

Ferraresi (2003) defines the material machinability as a technological quantity, which expresses, through a comparative index, a set of machining metal properties in relation to others taken as standard, i.e., it indicates the degree of difficulty in metal cutting. The machinability depends on mechanical properties such as hardness, chemical composition, previous operations performed on the material (cold or hot), and the possible degree of hardening, but it is a function of the process conditions employed. Therefore, Trent and Wright (2000) suggest that machinability is not a material property, but the "way" the material behaves during cutting.

Among the machinability criteria evaluated, a knowledge of the magnitude and direction of the resultant cutting force or of its components forms the basis for designing machine tools, establishing the cutting parameters, predicting the attainable accuracy of the part, and especially interpreting the phenomena which occur at the contact point (Klocke, 2008). As a rule, the cutting of harder-to-machine materials entails higher forces. The cutting force is directly related to the stresses and strains imposed on the chip-tool interface during machining, and therefore it can bring valuable information about the material mechanical behavior, which can be employed in the constitutive equations for the predictability of cutting metals.

3. CONSTITUTIVE EQUATION

Constitutive equations, which depend of the material behavior, they are those that relate stress and strain, in other words, they are equations describing the state of stress or strain in a body (Dieter, 1988).

Machining processes occurs in a broad range of strains, strain rates and temperatures, and the deformation state can be very complex. The material flow stress is known to depend on many factors. These factors can be divided into factors dependent and independent of the cutting process. The main dependent factors on cutting process are strain ($\bar{\varepsilon}$), strain rate ($\dot{\bar{\varepsilon}}$) and temperature (T). They can be cited as independent factors the initial crystal orientation, initial crystal size, hardening state, microstructure, etc (Jaspers and Dautzenberg, 2002). Therefore, high strain rate plastic deformation of materials is often described by constitutive equations, which stress is linked with strain, strain rate, and temperature (Meyers, 1994).

The material behavior in cutting narrows down three problems:

- Determination of conditions under which material is deformed in cutting (strain (path), strain rate and temperature);
- Development of material and cutting tests can be used to measure the flow stress under conditions similar to those in cutting;
- Development of an effective method to construct the constitutive equation of a work material in machining.

Table 1 gives an overview of typical strain, strain rates and temperature found in machining compared with metal forming processes.

Table 1. Typical strains, strain rates, and homologous temperatures (T_h=T/T_{melt}) of metal forming and machining processes (Kalpakjian, 1997; Alexander, 1985).

Process	**Strain**	**Strain rate (s^{-1})**	**$T_{homologous}$**
Extrusion	2 - 5	10^{-1} - 10^{2}	0.16 - 0.7
Forging/rolling	0.1 - 0.5	10^{0} - 10^{3}	0.16 - 0.7
Sheet-metal forming	0.1 - 0.5	10^{0} - 10^{2}	0.16 - 0.7
Machining	1 - 10[a]	10^{3} - 10^{6}	0.16 - 0.9

[a] : The strain could be larger in the secondary shear zone.

Different methods have been developed to estimate the material behavior in large deformation processes, including low strain rate tension, torsion, and compression tests, in which the strain, strain rates, and temperatures that workpiece experiences in manufacturing processes are much higher than those encountered in conventional static material tests, as can be seen in Tab. 1 that shows the strain rates in machining of the order of 10^3 – 10^6 s^{-1} whereas in traditional material tests are in the order of 10^{-3} – 10^{-1} s^{-1}. Another test fairly used is split Hopkinson pressure or torsion bar (SHPB) to measurements material behavior in moderate and high strain rate. However, there is an intense discussion about the machining process can be evaluated or not by conventional tests of materials (Merchant, 1945; Zorev, 1966; Usui, 1988; Oxley, 1989; Stevenson, 1997; Astakhov, 1999a; Shaw, 2005). These different viewpoints can be due to the cutting conditions investigated, which may suggest that the cutting process is considered a cold or hot working process (Astakhov, 1999a; Shaw, 2005; Longbottom and Lanham, 2006; Barbosa and Machado, 2011).

A number of empirical and semi-empirical plasticity constitutive models have been proposed to predict flow stress in machining. The success of a particular model depends on how effectively it duplicates the actual machining conditions as well as on its ability to capture all relevant strain parameters in constitutive equation (Anurag and Guo, 2007).

4. CONSTITUTIVE MODELS

The commonly used plasticity constitutive models will be reviewed in relation to their possible applicability for predicting the material behavior in machining.

4.1. Power law equation

The power law equation Eq. (1), well known as curve stress (σ) - strain (ε) equation (Dieter, 1988), is the constitutive simplest and most popular model used to describe simple deformation processes. This equation has been generally good for low strain rate processes.

$$\sigma = k\varepsilon^n \qquad (1)$$

The two material constants, strength (k) and strain hardening (n) coefficients are estimated by curve fitting the experimental data.

This simple constitutive model does not account for any strain rate or temperature effects, and it may not be applied to machining due to the complex deformation state involving large strain rates and temperature.

4.2. Johnson Cook model

At present, the Johnson Cook (JC) model (Johnson and Cook, 1985; Meyers, 1994) is a widely popular and successful constitutive model, because it analyzes stress in deformations involving strain, strain rate, and temperature and has proved to be better than the power law equation for estimating flow stress. And thus, the JC model, Eq. (2), has become an important and much used tool in finite element simulating of machining, forming, and other deformation processes (Guo *et al*., 2005; Anurag and Guo, 2007).

$$\sigma = (\sigma_0 + B\varepsilon^n)\left(1 + C\,ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)(1 - T_h^m) \qquad (2)$$

This equation has five experimentally determined parameters (σ_0, B, C, n, m) by a non-linear curve fitting. $\dot{\varepsilon_0}$ is a reference strain rate that can, for convenience, be equal to 1 (Meyers, 1994).

One of the problems with the JC model is that all parameters are coupled by being multiplied by each other, that is, the terms of strain, strain rate, and temperature in the constitutive equation contribute with their independent effect only, and the coupling effect has not been included.

The Johnson-Cook equation has been most widely used, and the parameters are known for a large number of materials; it was modified to incorporate dynamic recrystallization at higher temperatures through a reducer function *H(T)*, to overcome certain problems due to the recrystallization temperature that affects the flow stress by phase transformations in the material (Meyers, 1994; Anurag and Guo, 2007). Equation (3) presents the modified JC model.

$$\sigma = (\sigma_0 + B\varepsilon^n)\left(1 + C\,ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)(1 - T_h^m)H(T) \qquad (3)$$

Where

$$H(T) = \frac{1}{1 - \left[1 - \frac{(\sigma_f)_{rec}}{(\sigma_f)_{def}}\right]u(T)}$$

u(T) is a step function of temperature defined as:

$$u(T) = \begin{cases} 0\ to\ T < T_c \\ 1\ to\ T > T_c \end{cases}$$

$(\sigma_f)_{rec}$ and $(\sigma_f)_{def}$ are the flow stresses of material just after and prior to recrystallization, respectively.

Figures 1 and 2 present some comparisons obtained from compression tests and orthogonal cutting in 6061-T6 aluminum, respectively. A good accuracy of the JC model for the quasi-static tests, and a small deviation of the machining tests can be observed. These error sources may be due to the strain path, deformation state, and cutting conditions, which do not predict material deformation and cutting modes, which are not predicted by the constitutive equation. Therefore, this model has its limitations to predict the complex machining deformation pattern.

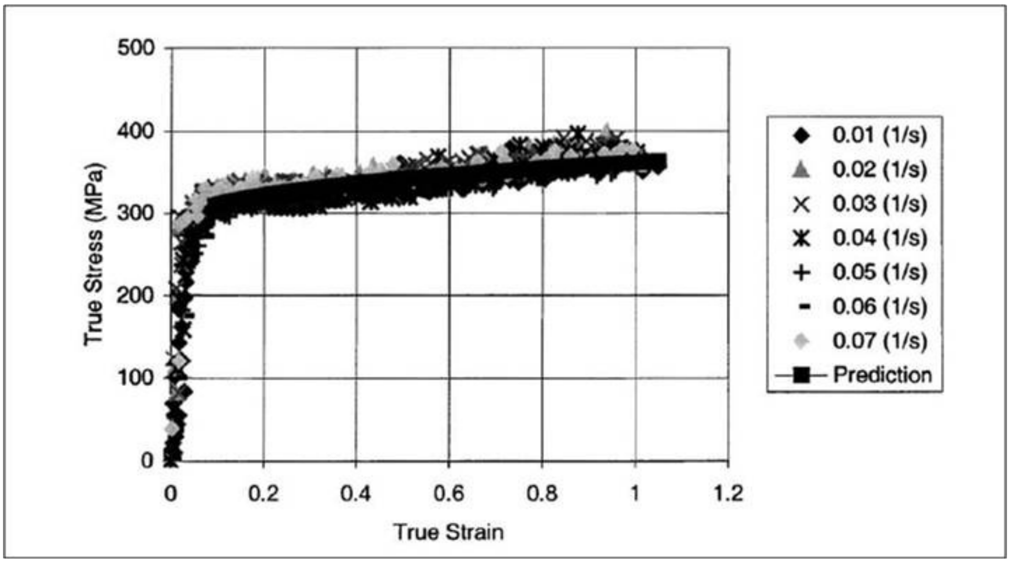

Figure 1. 6061-T6 aluminum comparison of predicted flow stresses to compression data at low strain rates and room temperature (Guo, 2003)

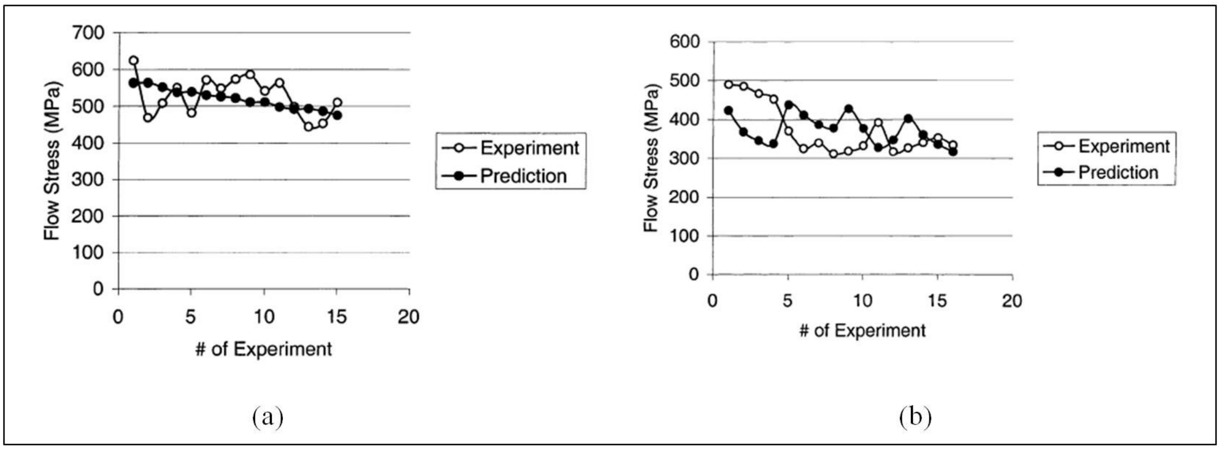

Figure 2. 6061-T6 aluminum comparison of predicted flow stresses to the test data in the cutting condition, (a) strain, moderate strain rate, and low temperature, (b) strain, high strain rate, and moderate temperature (Guo, 2003)

4.3. Usui model

In 1983, a constitutive model was proposed based on split Hopkinson bar hot compression testing, which can be applied to the analysis of material behavior in the machining plastic zone (Shirakashi *et al*., 1983; Maekawa *et al*., 1983). Maekawa *et al*. (1996), and Dirikolu *et al*. (2001) used this model to obtain flow stress characteristics in studies of steel machining simulations. The model is unique in that it considers the coupling effect of strain rate and temperature as well as the history effects of strain rate and temperature.

The full expression for flow stress, including strain path effects, is given by Eq. (4).

$$\sigma = A\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{M} e^{kT}\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{-m}\left\{\int_{T,\dot{\bar{\varepsilon}}\equiv h(\bar{\varepsilon})} e^{-kT/N}\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{-m/N} d\bar{\varepsilon}\right\}^{N} \quad (4)$$

Where coefficients *A*, *M* and *N* reflect the flow stress at a strain rate of 1000 s^{-1} and a strain of 1, the strain-rate sensitivity, and strain hardening index, respectively, are functions of temperature *T*. *k* and *m* are constants associated with strain path dependence (Dirikolu *et al*., 2001). Two different methods for evaluating the history effects are derived from Lagrangian and Eulerian points of view, respectively. However, both analytical methods are proved to yield the same empirical expression of the flow stress.

The Usui model is capable of predicting the mechanical behavior over a number of strain rate and temperatures, but it is a semi-empirical model and does not provide physical interpretation of deformation, does not include anneal softening and age hardening effects, and it has no predictive power on the microstructural effect (Maekawa *et al*., 1983; Guo *et al*., 2005; Anurag and Guo, 2007).

4.4. Micromechanical physics based model

Assuming that the response of materials at high strain rate is intimately connected with the evolution of the microstructure, and that defects, cracks, phase transformations, and their mutual interplay establish the mechanical performance, there are qualitative different mechanisms as the scale of deformation is changed from the micro to the macro level (Meyer, 1994). Therefore, the plastic flow is assumed to basically occur due to the motion of dislocations.

From the concept based on dislocations kinetics, a constitutive equation of micromechanical physics based as given in Eq. (5) was proposed (Meyers, 1994; Nemat-Nasser and Guo, 2000; Cheng *et al*., 2001).

$$\sigma = \sigma_a + \sigma^* \tag{5}$$

In this model, the flow stress is divided into athermal stress (σ_a) and thermal stress (σ^*).

The athermal stress (Eq. (6)) represents the resistance to the motion dislocation by long-range barriers such as dislocations forests, grain boundaries, precipitates. This flow stress part is strain rate and temperature independent, and represents the material microstructure.

$$\sigma_a = a_0 + a_1 \varepsilon^n + \cdots \tag{6}$$

Where a_0, a_1, and *n* are material constants estimated experimentally by curve fitting.

The thermal stress (Eq. (7)), on the other hand, represents the resistance to the motion of dislocations by short barriers like points defects such as vacancies, alloying elements and other dislocations. This component is a major function of temperature and strain rate considering the coupling effect.

$$\sigma^* = \hat{\sigma}^* \left[1 - \left(-\frac{kT}{G_0}\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)^{1/q}\right]^{1/p} \tag{7}$$

Where G_0 is the free energy required for a dislocation to overcome the barrier solely by its thermal activation; $\hat{\sigma}^*$, the flow stress above which the barrier is crossed by dislocation without any assistance from thermal activation; *k*, the Boltzmann's constant; *p* and *q* define the profile of short-range barrier. $\dot{\varepsilon}_0$ is the pre-exponential factor given by Eq. (8).

$$\dot{\varepsilon}_0 = \rho_m b \bar{v} \tag{8}$$

Where ρ_m is the average density of mobility dislocations; *b*, the magnitude of Burger's vector; and $\bar{v}$, the average velocity of mobile dislocations.

Another part, a remaining viscous-drag component (σ_d), can be introduced in this constitutive model, which is usually important at high temperatures and high rates (Guo and Nemat-Nasser, 2006). The viscous-drag stress may be related to the dislocation motion by assuming Eq. (9).

$$\sigma_d = \frac{MBv}{b} \tag{9}$$

Where *M* is the Taylor factor; *B* is the drag coefficient; and v is the average dislocation velocity.

Nevertheless, for temperatures above critical temperature (T_c), the micromechanical physics based (PB) model simply gives a constant value for all temperatures. In the particular case of machining, temperature rise above T_c is common, and therefore the PB model cannot satisfactorily be applied in larger deformation processes such as machining (Anurag and Guo, 2007).

Anurag and Guo (2007) explored the PB model in an attempt to determine flow stress in manufacture processes through extending the original micromechanical model to predict flow stress above the critical temperature by introducing the coefficient approach. The modified model is capable of predicting flow stress in the entire temperature range, but the function coefficient must be fit to each material and specific deformation condition.

Zerilli and Armstrong proposed two microstructurally constitutive equations based on the framework of thermally active dislocation motion from the PB model concept, which incorporates the effects of strain hardening, strain-rate hardening, and thermal softening, showing an excellent match with experimental results (Meyers, 1994; Guo *et al.*, 2005; Voyiadjis and Abed, 2005; Abed and Voyiadjis, 2005).

Zerilli-Armstrong model provides two different relations for the face cubic centered (FCC) and the body cubic centered (BCC) metals, as shown in Eqs. (10) and (11) according to Voyiadjis and Abed (2005).

$$\sigma = \hat{Y}\left(1-(\beta_1 T - \beta_2 T \ln \dot{\varepsilon})^{1/q}\right)^{1/p} + B\varepsilon^n + Y_a, \text{ to BCC structure} \quad (10)$$

$$\sigma = B\varepsilon^n\left(1-(\beta_1 T - \beta_2 T \ln \dot{\varepsilon})^{1/q}\right)^{1/p} + Y_a, \text{ to FCC structure} \quad (11)$$

Where $\hat{Y}$ is the threshold yield stress of Peierls barrier to the initial dislocation motion. B and n are the plastic hardening constants; Y_a represents the athermal yield stress; β_1 and β_2 are related to the microstructure physical components.

The deformation mechanism of BCC metals is generally attributed to the resistance of the dislocation motion by short-range barriers showing a strong behavior dependence on the thermal yield stress on the strain rate and temperature, whereas the plastic hardening was hardly influenced by either the strain rate or temperature and, therefore, it contributes to the athermal part of the flow stress, i.e., the dependence of flow stress is not affected by temperature or strain rate. In contrast, in FCC metals, a heterogeneous microstructure of dislocations and the long-range intersections between dislocations dominates and controls the thermal activation mechanisms; thus, these materials consider that the strain dependence is strongly affected by the strain rate and temperature.

5. CONCLUSIONS

This paper presented some phenomenological plasticity constitutive models including the power law, Johnson-Cook, Usui, micromechanical and Zerilli-Armstrong models. These models have been developed to relate flow stress to plastic strain, strain rate, and/or temperature, and usually have been used in an attempt to predict materials behavior in a wide range of temperatures and strain rates generally imposed on manufacturing processes.

Various materials testing methods to obtain material properties in large deformation have been proposed and discussed to approach manufacturing processes to help in the mechanical behavior analysis through constitutive equations based on test data. The conventional material tests such as tension, torsion or compression yield stress–strain responses in low strain rates. Split Hopkinson pressure or torsion bar test (SHPB) is used for moderate or high strain-rate material measurements, which is widely used to approximate the deformation states in manufacturing processes.

Each constitutive model has its particularity, with advantages and limitations. The power law model does not account for any strain rate or temperature effects. The Johnson-Cook model is a popular and successful constitutive widely used model; however, the terms of strain, strain rate, and temperature in the constitutive equation contribute with their independent effect only, and the coupling effect has not been included. The Usui model is unique in that it considers the coupling effect of strain rate and temperature as well as the history effects of strain rate and temperature, but it is a semi-empirical model and does not provide physical interpretation of deformation, besides having no predictive power on microstructural effect. Finally, the micromechanical and Zerilli-Armstrong models account for the microstructure effect, but cannot satisfactorily be applied in larger deformation processes such as machining since the constitutive equation is only valid below critical temperature despite the function fitting coefficient.

Therefore, in accordance with the above, there is still a need to develop a unique model that includes all the variables involved in the process, i.e., the flow stress as a function of microstructure, strain rate, strain, temperature, and stress state, beside fracture mechanisms; capable to predict the machinability of materials. And these constitutive models are shown as the starting point for this challenge.

6. ACKNOWLEDGEMENTS

The authors thank CNPq (Brazilian National Council of Technological and Scientific Development) and Fapesp (the State of São Paulo Research Foundation) for the financial support given to the development of this research trough processes number CNPq:141559/2010-1, CNPq:301577/2009-9, Fapesp: 2010/01073-3.

7. REFERENCES

Abed, F.H., Voyiadjis, G.Z., 2005, "Plastic deformation modeling of Al-6XN stainless steel at low and high strain rates and temperatures using a combination of bcc and fcc mechanisms of metals", International Journal of Plasticity, Vol.21, pp.1618-1639.

Alexander, J.M., 1985, “On problems of plasticity flow of materials”, Plasticity Today, Elsevier/Applied Science Publishers, London.
Anurag, S., Guo, Y.B., 2007, “A modified micromechanical approach to determine flow stress of work materials experiencing complex deformation histories in manufacturing processes”, International Journal of Mechanical Sciences, Vol. 49, pp. 909-918.
Astakhov, V.P., 1999a, “A treatise on material characterization in the metal cutting process. Part 1: cutting as the fracture of workpiece material”, Journal of Materials Processing Technology, Vol.96, pp.22-33.
Astakhov, V.P., 1999b, “A treatise on material characterization in the metal cutting process. Part 2: A novel approach and experimental verification”, Journal of Materials Processing Technology, Vol.96, pp.34-41.
Astakhov, V., Shvets, S.V., 2001, “ A novel approach to operating force evaluation in high strain rate metal-deforming technological processes”, Journal of Material Processing Technology, Vol.117, pp.226-237.
Barbosa, P.A., Machado, I.F., 2011, “Strain Rate Effect on the Mechanical Behavior of Austenitic Stainless Steel during Machining”, Proceedings of the13th CIRP-Conference on Modeling of Machining Operations.In press.
Cheng, J. Nemat-Nasser, S., Guo, W., 2001, “A unified constitutive model for strain-rate and temperature dependent behavior of molybdenum”, Mechanics of Materials, Vol.33, pp. 603-616.
Dieter, G.E., 1988, Mechanical Metallurgy”, SI Metric ed., Ed. McGraw-Hill, London, 751p.
Dirikolu, M.H., Childs, T.H.C., Maekawa, K., 2001, “Finite element simulation of chip flow in metal machining”, International Journal of Mechanical Sciences, Vol.43, pp. 2699–2713.
Ferraresi, D., 2003, “Fundamentos da Usinagem dos Metais”, Vol. 1, Ed. Edgard Blücher, São Paulo, Brazil, 751p.
Guo, W., Nemat-Nasser, S., 2006, “Flow stress of Nitronic-50 stainless steel over a wide range of strain rates and temperatures”, Mechanics of Materials, Vol.38, pp 1090-1103.
Guo, Y.B., 2003, “An integral method to determine the mechanical behavior of materials in metal cutting”, Journal of Materials Processing Technology, Vol.142, pp. 72–81.
Guo, Y.B., Wena, Q., Horstemeyerb, M.F., 2005, “An internal state variable plasticity-based approach to determine dynamic loading history effects on material property in manufacturing processes”, International Journal of Mechanical Sciences, Vol.47, pp. 1423–1441.
Jaspers, S.P.F.C., Dautzenberg, J.H., 2002, “ Material behaviour in metal cutting: strains, strains rates and temperature in chip formation”, Journal of Materials Processing Technology, Vol.121, pp.123-135.
Kalpakjian, S., 1997, “ Manufacturing Process for Engineering Materials”, 3rd ed., Addison Wesley/Longman, Menlo Park.
Klocke, F., 2008, “Machining and Machinability”, Encyclopedia of Materials: Science and Technology, pp. 4683-4688.
Longbottom, J.M., Lanham, J.D., 2006, “ A review of research related to Solomon’s hypothesis on cutting speeds and temperatures”, International Journal of Machine Tools & Manufacture, Vol.46, pp 1740-1747.
Maekawa, K., Ohhata, H., Kitagawa, T., Childs, T. H. C., 1996, “Simulation analysis of machinability of leaded Cr-Mo and Mn-B structural steels”, Journal of Materials Processing Technology, Vol.62, pp. 363-369.
Maekawa, K., Shirakashi, T., Usui, E., 1983, “Flow stress of low carbon steel at high temperature and strain rate (Part2) – Flow stress under variable temperature and variable strain rate”, Bull. Japan Soc. of Prec. Eng., Vol.17, n.3, pp. 167-172.
Merchant, M.E., 1945, “Mechanics of metal cutting process”, Journal Applied Physics, Vol.16, pp.267-275.
Meyers, M.A., 1994, “Dynamic Behavior of Materials” , John Wiley & Sons, New York, 668p.
Nemat-Nasser, S., Guo, W., 2000, “Flow stress of commercially pure niobium over a broad range of temperatures and strain rates”, Materials Science and Engineering A, Vol.284, pp. 202–210.
Oxley, P.L.B., 1989, “Mechanics of Macnining: An Analytical Approach to Assessing Machinability”, Ellis Horwood, Chichester, England.
Shaw, M., 2005, “Metal Cutting Principles”, 2nd Edition, Oxford University Press, 651 p.
Shirakashi, T., Maekawa, K., Usui, E., 1983, “Flow stress of low carbon steel at high temperature and strain rate (Part1) – Propriety of incremental strain method in impact compression test with rapid heating and cooling systems”, Bull. Japan Soc. of Prec. Eng., Vol.17, n.3, pp. 161-166.
Stevenson, R., 1997, “ Study on the correlation of workpiece machanical properties from compression and cutting tests”, Journal Machining Science and Technology, Vol.1, pp. 67-79.
Trent, E.M., Wright, P.K., 2000, “Metal Cutting”, 4.ed., Butterworth, England, 466p.
Usui, E., 1988, “Progess of predictive theories in metal cutting”, JSME International Journal, Serie III, Vol.31, pp. 363-369.
Voyiadjis, G.Z., Abed, F.H., 2005, “ Microstructural based models for bcc and fcc metals with temperature and strain rate dependency”, Mechanics of Materials, Vol.37, pp. 355-378.
Zorev, N.N., 1966, “ Metal Cutting Mechanics”, Pregamon Press, Oxford.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.