Proceedings of COBEM 2005
18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG

Determination of the Mechanical Behavior of AISI 304 austenitic stainless steel in Machining Processes

João Paulo Pereira Marcicano.
Departamento de Eng. Mecatrônica e Sistemas Mecânicos – EPUSP. Av. Prof. Melo Moraes, 2231; 05508-900
marcican@usp.br

Luanna Oliveira de Almeida.
Departamento de Eng. Mecatrônica e Sistemas Mecânicos – EPUSP. Av. Prof. Melo Moraes, 2231; 05508-900
lumath_oli@hotmail.com

Izabel Fernanda Machado.
Departamento de Eng. Mecatrônica e Sistemas Mecânicos – EPUSP. Av. Prof. Melo Moraes, 2231; 05508-900
machadoi@usp.br

Amauri Hassui
Departamento de Eng. Mecatrônica e Sistemas Mecânicos – EPUSP. Av. Prof. Melo Moraes, 2231; 05508-900
ahassui@usp.br

***Abstract**. The mechanical behavior of AISI 304 stainless steel within the practical range of stress, strain, strain rate, and temperature encountered in metal cutting is characterized by Johnson-Cook constitutive equation. The coefficients of constitutive equation are determinated by fitting the data from both quasi-static compression and machining tests. An analytical model based on the plasticity theory and orthogonal cutting is utilized to estimate the effective stress, strain, strain rate, and temperature on the main shear plane. This approach is valid for machining with continuous chips. It was verified good agreement between experimental and estimated values.*
***Keywords**: machining, AISI304, Johnson-Cook model*

1.Introduction

The machining processes have great economic importance in the mechanical industry due mainly to the dimensional precision that can be achieved. The knowledge of the metal cutting processes is essential to development of new tools and machines. Numerical and analytical models have been used with relative success in the modeling of these processes. Information on the mechanical behavior of metals within machining process is of utmost importance in both the analytical and numerical models.

However the physical phenomena taking part in metal cutting are numerous and complex. Chip formation is the result of plastic deformation caused by relative motion between the tool and the work piece. Deformations are large and the strain rate reaches 10^6 s^{-1}. These intense circumstances result in mechanical behavior far from that encountered in conventional material tests. Moreover the sliding at the tool/chip interface happens under very hard conditions of pressure, strain rate and temperature. (Tounsi et al., 2002).

According to Altintas (2000) there are basically two types of assumptions in the analysis of the primary shear zone. Merchant (1945) developed an orthogonal cutting model by assuming the shear zone to be a thin plane. Others, such as Lee ,Shaffer and Oxley (1977), based their analysis on a thick shear deformation zone for continuous ship and Okushima (1961) for discontinuous chip formation.

Recently Tounsi et all (2002) re-evaluated the mechanics of primary shear zone for continuous chip formation deriving the expressions of the effective stress, strain, strain rate and temperature on the main shear plane. These expressions are deduced from an estimated velocity field derived from strain rate fields observed in experimental work and finite element method results.

Guo (2003) presented a method to characterize the mechanical behavior of materials in metal cutting based on Johnson-Cook model. The author deduced the coefficients of equation of Johnson-Cook fitting the data from quasi-static compression and machining tests. The primary shear zone was modeled with Oxley method and the temperatures were estimated with Loewen-Shaw model.

In this paper, a methodology to identify the material constants of the Johnson-Cook constitutive equation is presented. It is based on analytical modeling of the primary shear zone, quasi-static compression test, machining tests and numerical minimization. The experimental and model results are compared and discussed.

2.Theory

Tounsi (2002) developed the model adopted to analyze the primary shear zone. This model considers that the shear zone is a shear band of constant thickness and the effective strain rate is maximum on the main shear plane and vanishes at the boundaries of the primary shear zone.

The model is valid under the following assumptions:

- quasi-static conditions; plane strain conditions;
- continuous chip formation;
- sharp cutting edge;
- deformed material is homogeneous and isotropic;
- shear stress, strain, strain rate, and temperature fields depend only on the one coordinate; and ;
- constant thickness of the primary shear zone.

The effective strain rate on the shear plane is expressed as follows:

$$\dot{\varepsilon}_{AB} = \frac{2}{\sqrt{3}} \frac{V_c \cos(\gamma_n)}{h \cos(\phi_n - \gamma_n)} \tag{1}$$

Where V_c is the cutting velocity, γ_n the rake angle, ϕ_n the shear angle and h the primary shear zone thickness. The shear angle is calculated from the value of the measurement of the chip thickness (t_1) and the uncut chip thickness (t_0).The primary shear zone thickness was estimated by one-half of the uncut chip thickness, i.e. $h=0.5\ t_0$.

The effective strain on the main shear plane is expressed:

$$\bar{\varepsilon}_{AB} = \frac{1}{\sqrt{3}} \frac{\alpha \cos(\gamma_n)}{\cos(\phi_n - \gamma_n) sin(\phi_n)} \tag{2}$$

The proportion of the main shear zone before the main shear plane α is calculated as follows:

$$\alpha = \frac{1}{2} + \frac{\cos(2\phi_n - \gamma_n)}{2\cos(\gamma_n)} \tag{3}$$

The expression of the effective stress on the shear plane is:

$$\bar{\sigma}_{AB} = \sqrt{3} \frac{sin(\phi_n)}{t_0 a_p} (F_c \cos(\phi_n) - F_a sin(\phi_n)) \tag{4}$$

Where a_p is depth of cut, F_c is the cutting force and F_a is the thrust force.

The temperature on the main shear plane can be expressed as:

$$T_{AB} = T_0 - \left(\frac{\alpha \cos(\gamma_n)}{\rho C_p sin(\phi_n) \cos(\phi_n - \gamma_n)} \right) \left(\frac{2\tau_{AB} + \tau_0}{3} \right) \tag{5}$$

Where T_0 is the room temperature, ρ is the mass density of the material, C_p is the specific heat, τ_{AB} is the shear stress on the main shear plane and τ_0 is the shear stress at main shear zone inlet. τ_{AB} is calculated by $\sigma_{AB}/\sqrt{3}$, and τ_0 is estimated from the elastic yield strength divided by $\sqrt{3}$.

In equation 5 the primary shear zone was considered under adiabatic conditions and the friction also was neglected. Moreover the heat flux was considered unidirectional.

There are many material constitutive equation, Altan (1983) presents several of those. In this work the Johnson-Cook model will be used. It can be expressed as:

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n) \left(1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_0}{T_m - T_0} \right)^m \right) \tag{6}$$

The material constants (A,B,n,C and m) are determinated by numerical non-linear minimization. The constants A,B and n are determined by a least-square approximation applied to the experimental results of compression test executed at temperature T_0 and strain-rate $\dot{\varepsilon}_0$. T_m is material melting temperature. The remained constants C and m are determinated by the minimization of the summation of square of differences between the flow stress estimated by equation 6 and the experimental flow stress from the cutting tests.

3.Experimental Results

Two types of experiment were executed: quasi-static compression and cutting tests. The material tested was the AISI 304 stainless steel annealed.

3.1.Compression tests

The compression test is used for determining flow-stress data, true stress/true strain relationships for metals at different temperatures and strain-rates. The test consists in deform by compression the test specimen under flat dies. During the test the load and displacement are measured. From this measurement the flow stress and the strain are calculated.

The samples have cylindrical form and they were prepared with a diameter of 5.25 mm and height of 5.2 mm. The press utilized in the test is a Instron model 5569 and the tests were conducted at room temperature of 25°C and very low average strain-rate of 0,004 1/s. Figure 1 presents the calculated true stress-strain curve.

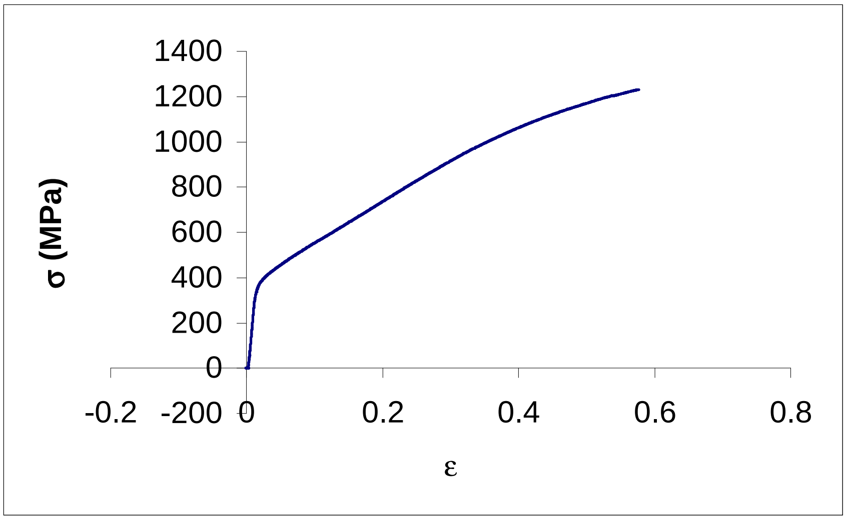

Figure 1. True flow stress-strain curve for annealed AISI 304.

As shown in equation 6, the parameter A corresponds to the elastic yield strength at the reference strain rate and temperature. The parameter B and n are calculated with a least-squares fit of the compression test data to a power law equation. Table 1 shows the values of Parameters A,B and n calculated from the values shown in Figure 1.

Table 1.Calculated Johnson-Cook Parameters

Parameter	Value
A	360 MPa
B	1244 MPa
n	0.72

3.2.Cutting tests

Orthogonal cutting tests were performed on machined tubes of annealed AISI 304. The tests were executed in a ROMI model S-30 lathe equipped with a load cell type dynamometer. The dynamometer was hooked to a personal computer with acquisition software. It was utilized two inserts with same geometry but from different fabricants. The inserts ISO code were TPGN 160308, M type carbide, uncoated, without chip breaker and with a rake angle of 5° .

During the tests, chip samples were collected in each cutting condition. The thickness of the collected chips was measured with a digital caliper in seven different locations and the average was used for the chip thickness. The resulting average chip thickness (t_1), measured cutting (F_c) and thrust forces (F_a) for each cutting condition are presented in Tab. 3 and 4. The utilized feed rate in each test corresponds to the uncut chip thickness (t_0) and the depths of cut were 1mm for tool A and 1,5 mm for tool B.

Tables 3 and 4 also present the values of the effective strain, strain rate, stress and temperature on the main shear plane calculated with equations 1-5 from the cutting test data and physical characteristics of the material. The physical characteristics used are presented in Tab. 2.

The Johnson-Cook parameters C and m of Eq. (6) were calculated to the different tools by numerical minimization performed in MathLab. The results are presented in Tab. 5.

Figures 2 and 3 shows the graphs of the experimental flow stress and the Johnson-Cook predicted flow stress calculated with parameters presented in Tab. 5 for the points presented in Tab.3 and Tab.4.

In order to verify the differences of the predict flow stress values from the determinated Johnson-Cook equations (Tool A and B). It was calculated for the values of strain, strain rate and temperature shown in Table 6 the flow stress with C and m parameters determinated for tool A, the flow stress with C and m parameters determinated for tool B and the related error. The selected conditions of Tab. 6 were chosen to cover the cutting conditions verified on executed cutting tests. Figure 4 also shows these results.

Table 2. Physical characteristics of the AISI 304

ρ	8000 Kg/m^3
T_m	1400 ^oC
C_p	500 $J/(Kg\ ^oC)$
T_0	25 ^oC
τ_0	$360/\sqrt{3}$ MPa

Table 3. Cutting Test Data for insert of fabricant A

t_0(mm)	t_1(mm)	ϕ_n (^{o})	Fa(N)	Fc(N)	Vc(m/min)	$\bar{\varepsilon}$	$\dot{\bar{\varepsilon}}$ (1/s)	$\bar{\sigma}$ (MPa)	T (^{o}C)
0.097	0.388	18.2	341	360	38	2.27	15188	1165	534
0.428	0.963	14.3	548	983	38	1.25	3609	1124	298
0.428	1.120	24.7	633	957	60	1.47	5589	977	308
0.097	0.330	21.5	455	401	60	1.92	24150	1302	500
0.060	0.256	16.7	335	281	60	2.42	38642	1311	627
0.060	0.193	13.4	136	190	24	1.82	15740	1225	451
0.097	0.235	17.6	185	274	24	1.35	9995	1259	350
0.428	1.347	23.1	755	1114	24	1.77	2210	1035	384
0.205	0.623	18.0	447	612	24	1.71	4626	1181	413
0.205	0.597	18.6	466	582	38	1.64	7324	1108	376
0.205	0.513	19.4	461	549	60	1.40	11725	1070	317

Table 4. Cutting Test Data for insert of fabricant B.

t_0(mm)	t_1(mm)	ϕ_n (^{o})	Fa(N)	Fc(N)	Vc(m/min)	$\bar{\varepsilon}$	$\dot{\bar{\varepsilon}}$ (1/s)	$\bar{\sigma}$ (MPa)	T (^{o}C)
0.060	0.196	17.4	165	265	17	1.84	10937	1170	439
0.097	0.243	22.4	227	378	17	1.40	6924	1191	345
0.205	0.464	24.6	375	665	17	1.26	3318	1051	284
0.428	0.799	29.3	743	1394	17	1.03	1642	1125	249
0.428	0.810	28.9	639	1322	13	1.05	1310	1107	249
0.060	0.194	17.5	156	260	13	1.83	8754	1164	434
0.097	0.237	22.9	210	369	13	1.37	5555	1195	338
0.205	0.419	27.0	349	650	13	1.13	2698	1076	262
0.205	0.379	29.5	338	652	13	1.02	2749	1111	244
0.205	0.546	21.2	340	627	17	1.49	3255	940	304
0.205	0.453	25.1	482	733	27	1.23	5352	1099	287
0.205	0.494	23.2	349	639	42	1.35	8345	999	290
0.205	0.469	24.4	306	622	67	1.27	13256	1024	281

Table 5.Calculated Johnson-Cook parameters C and m

Tool Fabricant	C	m
A	-0.0321	3.525
B	-0.0230	1.201

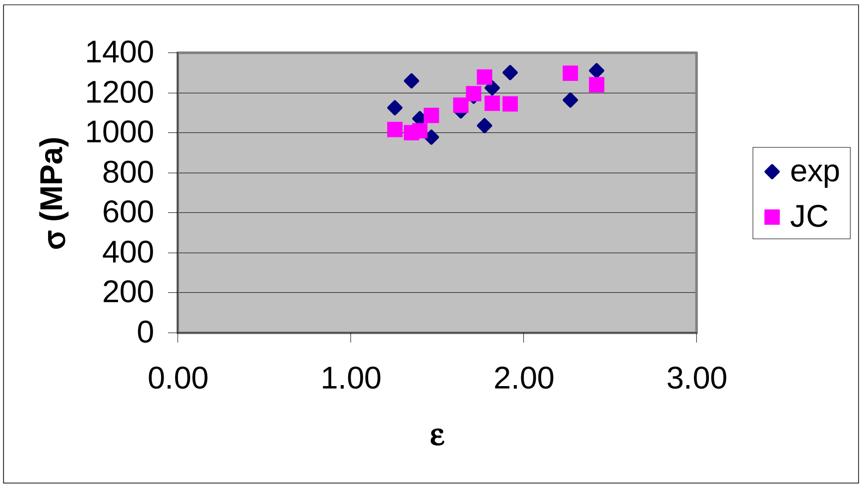

Figure 2. Comparison of Johnson-Cook predicted and experimental flow stress for the tool of fabricant A.

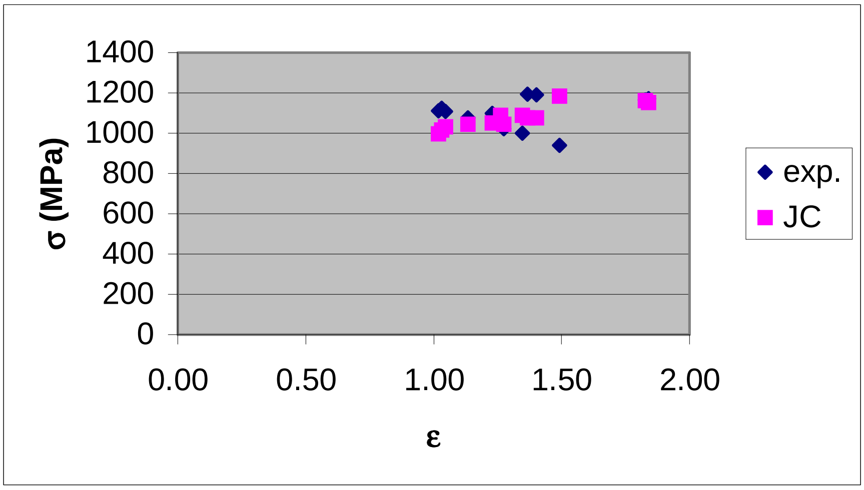

Figure 3. Comparison of Johnson-Cook predicted and experimental flow stress for the tool of fabricant B.

Table 6. Predict Johnson-Cook flow stress for different conditions

Condition	$\bar{\varepsilon}$	$\dot{\bar{\varepsilon}}$ (1/s)	T (^{o}C)	$\bar{\sigma}$ (MPa) tool A	$\bar{\sigma}$ (MPa) tool B	error (%)
1	1.5	5000	300	1109	1173	5.8
2	1.5	5000	500	1085	983	9.4
3	1.5	10000	300	1064	1146	7.6
4	1.5	10000	500	1041	960	7.8
5	1.5	20000	300	1019	1118	9.7
6	1.5	20000	500	997	937	6.1
7	2	5000	300	1319	1395	5.8
8	2	5000	500	1291	1169	9.4
9	2	10000	300	1265	1362	7.6
10	2	10000	500	1238	1141	7.8
11	2	20000	300	1212	1329	9.7
12	2	20000	500	1186	1114	6.1
13	2.5	5000	300	1514	1602	5.8
14	2.5	5000	500	1482	1342	9.4
15	2.5	10000	300	1453	1564	7.6
16	2.5	10000	500	1422	1311	7.8
17	2.5	20000	300	1392	1527	9.7
18	2.5	20000	500	1362	1279	6.1

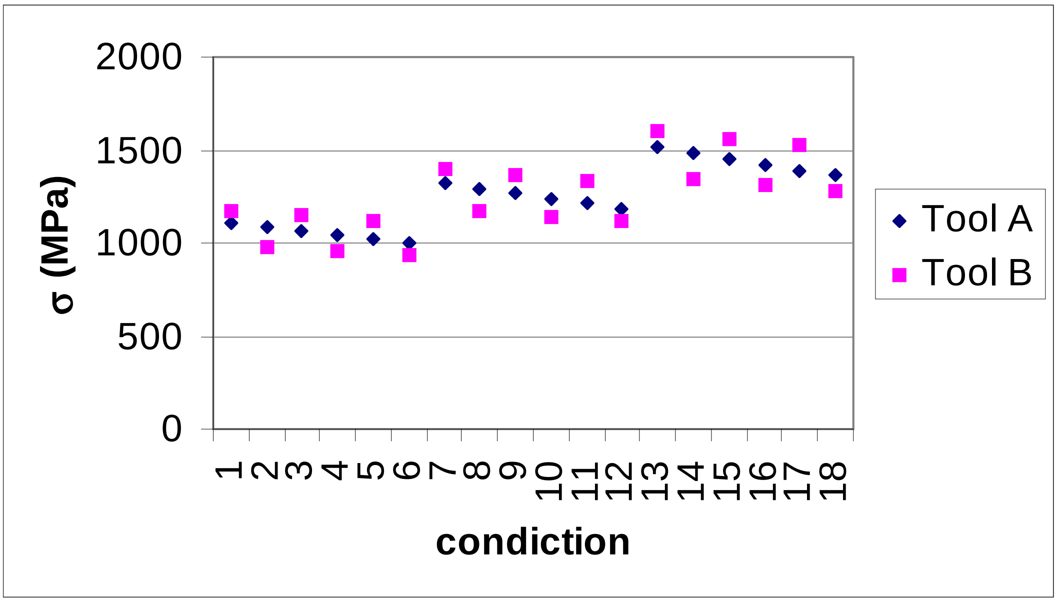

Figure 4. Predicted flow stress with Johnson-Cook parameters from tool A and B.

4. Discussions and Conclusions

It was expected the coincidence of estimated C and m Johnson-Cook parameters of the different tools because the method utilized is not affected by the secondary shear zone as well as by the friction along the tool/chip interface (Tounsi et al., 2002). However the estimated flow stress values for tools A and B are relatively close as can be observed in Tab.6 and Fig. 4. For the conditions presented in Tab. 6 the highest difference is 9.7% and the average difference is 7.7 %.

A factor to be considerated is the edge radius of the tools that was not measured and it might influence the results. It will be measured in the future works. The accuracy of the cutting models is limited by some oversimplifications as the errors of strain path, deformation modes, cutting models and Johnson-Cook model are difficult to evaluate. As a result, the proposed method should be regarded to give a first approximation of the actual mechanical behavior. On the other hand, the method can be valuable for FEA of plastic flow at high stain rates, where a simple analytic relationship is desirable.

A method based on the Johnson-Cook model has been presented to characterize the flow stress of work material in machining. The model parameters are determinated by fitting the data from compression and machining tests. Case study of compression test and machining of AISI 304 were realized. It shows that the model predicted flow stresses agree with the test data with reasonable accuracy.

The utilized method provided the evaluation of mechanical behavior of the tested material in a range of strain rate from 1000 to 40000 1/s, easily obtained in the cutting tests with the adjust of the feed rate and the cutting speed.

5.References

Tounsi N.,Vicenti J., Otho A. and Elbestawi M.A., 2002, "From the basic mechanics of orthogonal metal cutting toward the identification of the constitutive equation", Int.J. of Mach.T. Manuf, 42, pp.1373-1383.

Altintas Y., 2000, "Manufacturing Automation", Cambridge University Press, Cambridge, UK, pp. 4-13.

Okushima K. and Hitomi K., 1961, "An Analysis of the Mechanism of Orthogonal Cutting and Its Application to Discontinuous Chip Formation", J.Eng.for Industry, nov., pp. 545-556.

Oxley P.L.B. and Hastings W.F., 1977,"Predicting the strain rate in the zone of intense shear in which the chip is formed in machining from the dynamic flow stress properties of the work material and the cutting conditions", Proc.R.Soc.London, A 356, pp. 395-410.

Guo Y.B., 2003, "An integral method to determine the mechanical behavior of materials in metal cutting", J.Mat.Proc.Tech., 142, pp. 72-81.

Merchant M.E., 1945, "Mechanics of the Metal Cutting Process.II.Plasticity Conditions in Orthogonal Cutting", J. Applied Physics, vol. 16, pp. 318-324.

6.Responsibility notice

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