FLOW STRESS BEHAVIOR OF MILD STEELS AND ITS INFLUENCE ON MACHINABILITY

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ABSTRACT

Flow stress characteristics of metallic materials are essential in the prediction of machinability. A Finite Element Simulation modeling of machining of steels is presented in this paper. Predictions of tool forces are compared with experiments. The material flow properties required for the simulations have been obtained from two sources; for a 708M40 low alloy steel, existing experimental data on the strain, strain rate and temperature dependence of the flow stress, carried out at temperatures of up to approximately 700°C and strain rates of up to 2000 per sec., on high speed compression tests using Split Hopkinson bar apparatus, has been used. The sensitivity of the simulations to changes in dynamic strain aging and high temperature softening of the steel was tested and the results used, together with other published data, mainly from Hot-compression and machining tests, and results from simple plane strain compression tests, to create flow stress data for a range of other carbon steels, with carbon contents ranging from 0.11 to 0.56%C. The simulations are in good agreement with experiments at high feeds (0.254mm/rev.) but show poor correlation at low feeds (0.125mm/rev.). The simulation method presented here can be used to predict machinability of other alloys as well.

1. INTRODUCTION

1.1 Historical Perspective

The earliest work in machining research can be traced back to 1851 from the work of Coquilant as reported by Boothroyd and Knight (1989). Various studies have been done on the chip formation process, and the mechanics of metal cutting. Notable contributions have been from the works of Tresca in 1878 and Taylor in 1906 (ibid). Analytical work done by Ernst and Merchant (1941) and Lee and Shatter (1951) mostly based on a shear plane model, contributed to the present theories that form the basic principles of the mechanics of metal cutting. As the simple shear plane model does not account for the influence of temperature and material properties on the machining process, (Shaw and Finnie, 1955), more analytical techniques were subsequently developed to account for these complexities. These include the slip-line field analysis (Hill, 1954; Dewhurst, 1978) in which the work material was modeled as isotropic, homogeneous and rigidly perfectly plastic (constant flow stress and no work-hardening). Oxley and co-workers

(Oxley, 1989) later modified the slip-line field model to include work hardening and temperature effects. Their work demonstrated the dependency of the chip formation process on strain, strain rate and temperatures developed at the cutting zone; and that work hardening occurred during the plastic deformation process.

The limitations of the slip-line field theory and unrealistic friction characteristics rendered it inadequate in predicting accurate chip flow. As a result, a more recent approach in the studies of metal cutting has been the use of the finite element method (FEM). The FEM is more accurate due to the ability to incorporate more realistic assumptions of material behavior, and the influence of friction (Usui and Shirakashi 1982; Wang *et al.* 1988).

1.2 Finite Element Analysis of Machining.

Childs *et al* (2000) describes the details of the finite element analysis of machining and compares the different models and approaches. Because of the various material behaviors one can either incorporate a rigid-plastic or elasto-plastic model. In the rigid plastic model, the material is assumed to be fairly brittle and exhibits little or no elastic behavior in the whole deformation field. On the other hand, an elasto-plastic model assumes some elastic deformation, followed by plastic deformation prior to fracture. The analysis can also be modeled using a Lagrangian or Eulerian approach. In the Lagrangian approach the material is assumed to consist of single particles that retain their identity and nature as they move through space. Position is given by coordinates in some reference system, and are functions of time – thus time is the only independent variable. The Eulerian approach on the other hand assumes that all processes are characterized by field quantities that are defined at every point in space. The computational grid is fixed as the material passes through it. Available literature on mild steels (Usui *et al.*, 1981) suggests an inherent elasto-plastic behavior. For this reason, this work was based on that model, with an updated Lagrangian approach.

Machining is characterized by large strains, strain rates and temperatures at the shear zone during deformation, presenting real challenges in the analyses. In addition, the influence of friction at the shear zone has to be accounted for. Many researchers have addressed this issue and a lot of success has been reported in literature. In this work, a friction model that is dependent upon shear stress (Childs, 1990) was adopted and used.

1.3 Flow Stress Characteristics of Material

The accurate prediction of chip flow and cutting forces depend on reliable material property data (Oxley, 1989; Usui and Shirakashi, 1982). There have been many attempts by several researchers to predict flow stress properties of metals. The main difficulty in determining the flow stress for machining applications lies in the fact that with the high deformation rates, and temperature gradients, it is not easy to develop experimental validations for flow stresses under these circumstances. Additionally, for steels, thermally activated processes such as dynamic strain aging introduce more complications (Cottrell and Bilby, 1949; Baid, 1990).

A number of flow stress relations, developed from empirical and experimental data, have been suggested and used for a wide range of problems. Previous researchers believed that flow stress depended simply on strain, by a power law equation, of the form;

$$\sigma = k\varepsilon^{n} \tag{1}$$

k is a material constant and n is the strain hardening exponent. Because stress depends on other factors as well, various forms of this equation were then developed; a comprehensive list is presented by Otieno (1990).

Among the early pioneers to incorporate the stress dependency on temperature, strain and strain rate for steels was Oxley and co-workers (see Oxley, 1989 for detailed work). A summary of his final flow stress equation is presented in the same reference. Oxley's flow stress properties have been derived from a mixture of hot compression and machining tests. Although good results were reported, there was still a need for independent material property tests to improve and validate the accuracy of the analyses. A few attempts to obtain flow stress for steels were made by other pioneers such as Vinh and co-workers (Vinh *et al*, 1979) and Eleiche (1980) but temperatures used were still too low compared to those obtained in machining. Existing literature suggest that there is a further dependency of flow stress on the history of deformation and this may have been the reason why these equations were not very accurate.

To alleviate this problem, Usui and coworkers (Shirakashi *et al*; 1983; Maekawa *et al*, 1983) used a split Hopkinson bar apparatus to simulate the deformation process in machining, with rapid heating of samples using an induction coil to reach temperatures of up to 700° C. Strains of up to 2.0 were achieved from repeated impacts of 0.05 strain increments, at strain rates of between 200 and 2000 per second. They obtained empirical formulae for flow stress, $\bar{\sigma}$, of steels in the general form;

$$\bar{\sigma} = B\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{M} e^{k\theta}\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{-m}\left\{\int_{\theta,\dot{\bar{\varepsilon}}=h\left(\bar{\varepsilon}\right)} e^{\frac{-k\theta}{N}}\, d\bar{\varepsilon}\right\}^{N} \tag{2}$$

where B, M, N and K are functions of temperature. The integral takes care of history effects. Because of its extensive treatment of temperature dependency this equation was adopted for this study.

Flow stress data obtained by this method have been used extensively in machining studies on various steels with good results reported (see Otieno, 1990 for a comprehensive list of literature). However it is not quite clear whether the fact that the tests were carried out at temperatures of up to 700°C, and results extrapolated to hold for higher temperatures, represent the true deformation process in steels during machining. It is therefore essential to perform more investigation into the validity of this form of equation. This paper thus presents the flow stress behavior of steels under high strain rate deformation and its influence on the prediction of chip formation in steels.

2. MODELING OF FLOW STRESS PROPERTIES

Equation 2 suggests that flow stress increases with increase in strain and strain rate. At low strain rates, steels exhibit a distinct yield drop. Strain rate effects are more pronounced at low strains and at high strain rates the work hardening rate is lower. In addition, it has been shown that strain rate effects are more pronounced than those of strain. At low cutting speeds, increase in flow stress is largely due to increase in strain and strain rate. At higher cutting speeds, the temperature of the material increases and thermal softening occurs causing the flow stress to reduce. However, for steels, at a sufficiently high temperature (about 200° C), a thermally induced aging process known as dynamic strain aging causes the flow stress to start increasing. Figure 1 represents a plot of flow stress vs temperature for equation 2 at various values of strain and strain rate, indicating the dynamic strain aging effect.

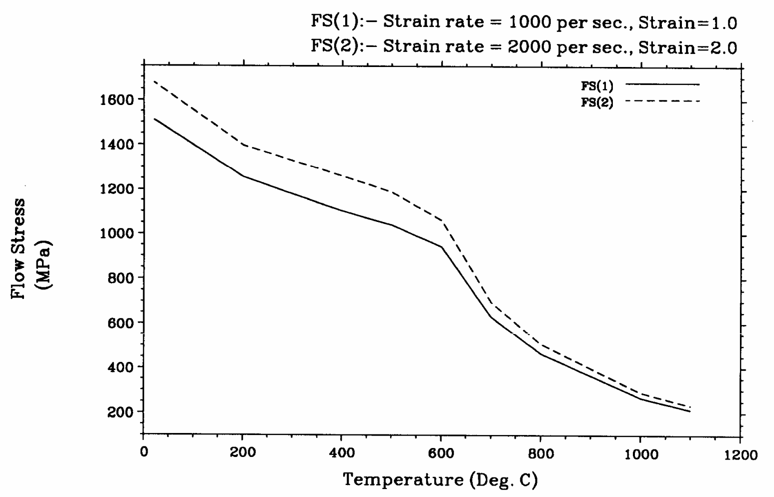


Figure 1: Flow stress plot for 708M40 British grade steel.

According to the theory of Cottrel and Bilby (1949), the peak should occur at a temperature of approximately 1000°C for carbon steels. However in practice, this peak seems to occur at a lower temperature of about 600°C. There is a mixed effect of temperature and strain-rate on the flow stress of steels. To investigate the effect of the phenomena, a model was introduced where the amount of aging could be varied at different strains and strain rates. Thus, equation 2 was simplified to exclude the history effects. The modified flow stress, $\bar{\sigma}$, is given by:

$$\bar{\sigma} = B\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{M}\left(\bar{\varepsilon}\right)^{N} \tag{3}$$

The term B consists of two terms; the first is responsible for thermal softening and the second for dynamic strain aging, as shown below;

$$\mathrm{B} = \mathrm{A} + \mathrm{C} \tag{4}$$

Taking an example of 708M40 steels, the experimental results are as follows (Shirakashi *et al*, 1983);

$$A = 1490e^{(-0.0018\theta)} + 330e^{\left(-0.0001(\theta-450)^2\right)} \tag{5}$$

and

$$C = 160e^{\left(-0.0002(\theta-570)^2\right)} \tag{6}$$

The temperature θ is in degrees Celcius.

Figure 2 below shows the components of the flow stress equation.

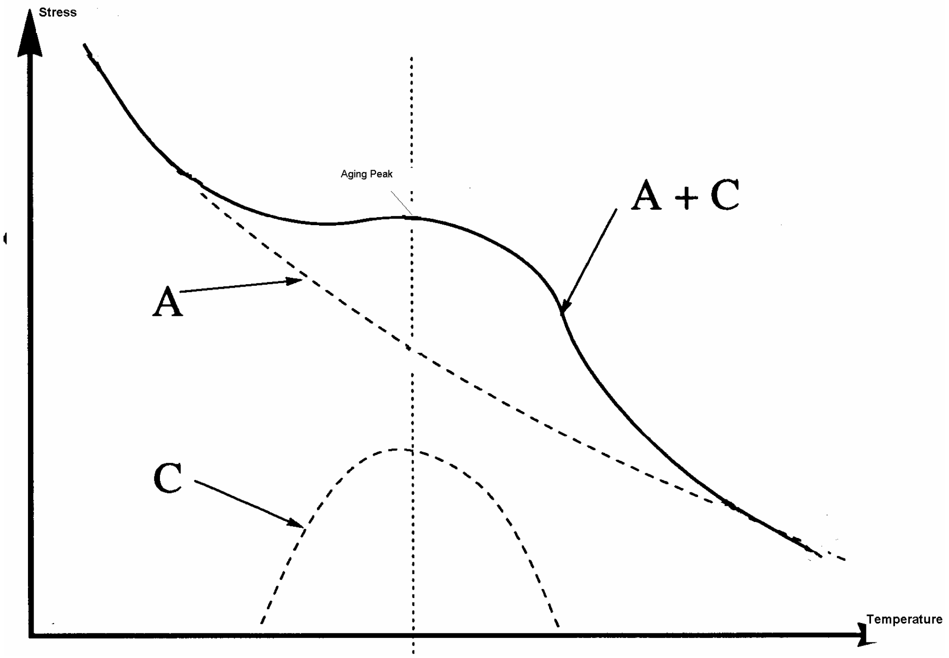


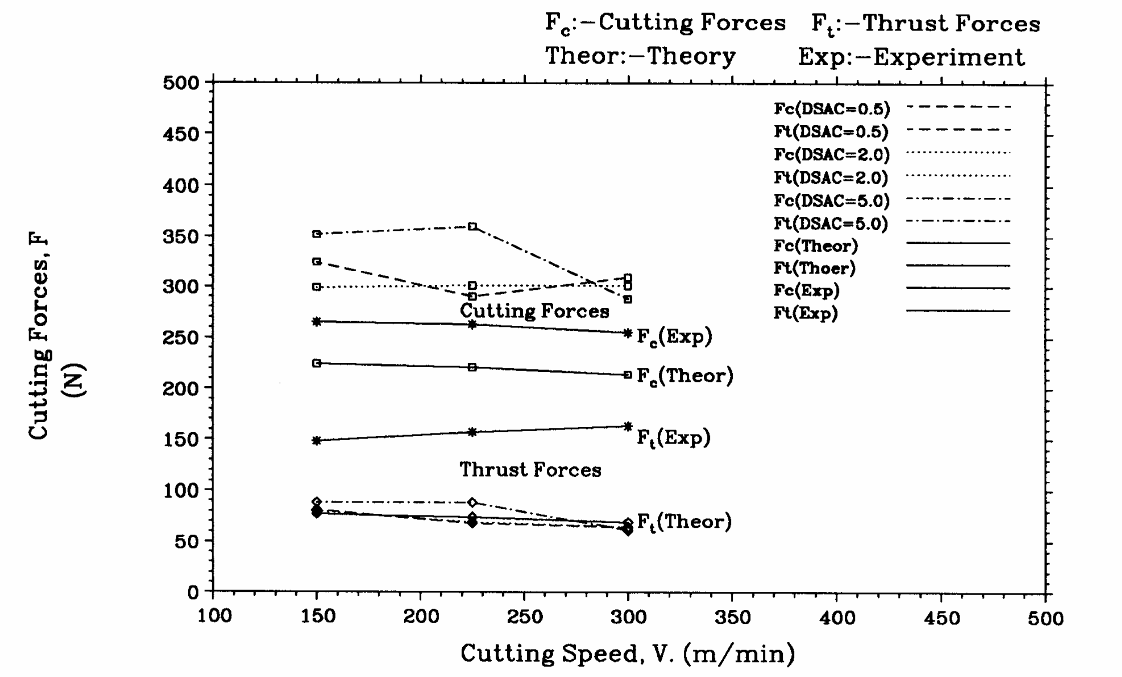
Figure 2: Components of flow stress equation.

In the proposed model the level of dynamic strain aging was varied arbitrarily. Equation 3 (below) was modified by introducing a factor, DSAC, to vary the aging peak;

$$\bar{\sigma} = \left(A + (DSAC)C\right)\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^{M}\left(\bar{\varepsilon}\right)^{N} \tag{4}$$

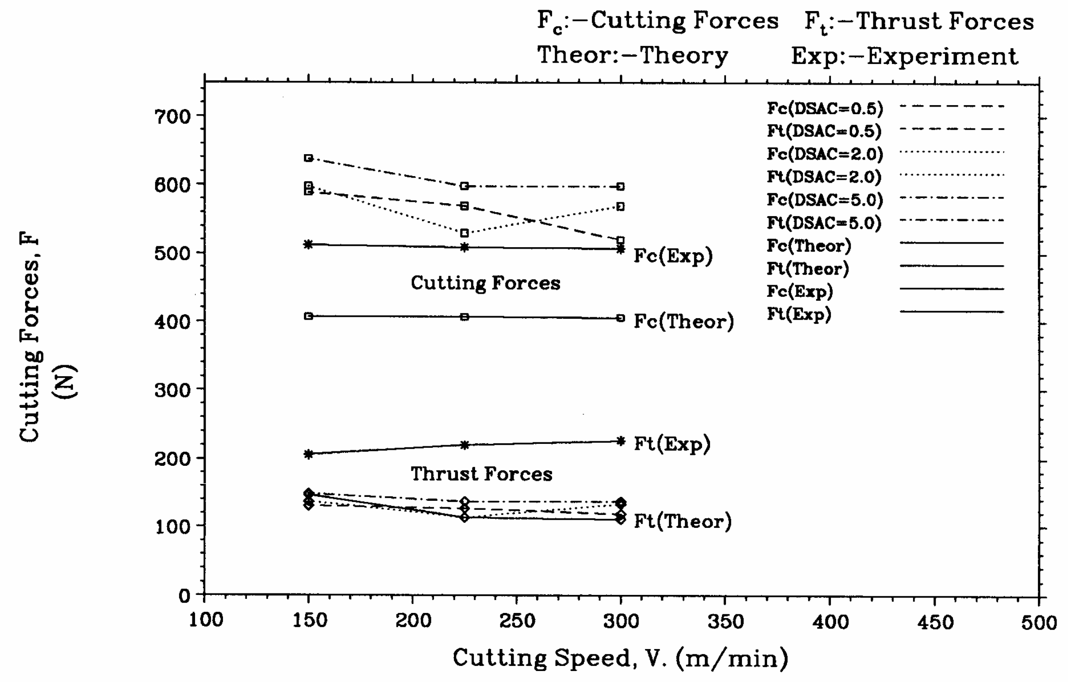
3. RESULTS, DISCUSSIONS, AND CONCLUSIONS

The above equation (4) was introduced into the finite element model and analyzed at values of DSAC ranging from 0.5 to 5.0 for 708M40 BS standard steel. The resulting predicted cutting and thrust forces were compared with experimental values at feeds of 0.125 and 0.254 mm/rev. The plots are shown below in figure 3.



(a) feed=0.125mm/rev

a)



(b) feed=0.254mm/rev

b)

Figure 3: Comparison of theoretical and experimental results for 708M40 steel.

From the results it is seen that at low feed rates there is a general higher discrepancy between experiment and theory. This suggests that at higher deformations the model is more accurate, confirming the importance of including strain and strain rate terms in the flow properties. There is better agreement between theory and experiment at higher feeds, and at higher cutting speeds. The results also show that by introducing a dynamic strain aging model there is a considerable increase in the cutting forces; but there is little or no effect on the thrust forces. In orthogonal cutting, fracture occurs ahead of the tool in the cutting direction of cutting and therefore the contribution of the thrust forces to the fracture is considerably less than the cutting forces.

Although this work is still under development a number of important conclusions can be drawn. First, material flow properties affect the chip formation process. In steels, the thermally activated reactions such as dynamic strain aging affect the prediction of the chip formation and should therefore be incorporated into the material flow stress equation. There is a need for researchers continuing work in this area to determine a more accurate deformation behavior of steels that can be incorporated into machining analyses.

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