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REPORT

Flow Stress Measurements for Machining Modelling

Literature Review

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ABSTRACT

This report is a review of literature concerned with measurement methods to obtain flow stress data at high temperatures and high rates of strain relevant to models of the machining process. Data relevant to the hyperbolic sine expression relating strain rate to stress and temperature are highlighted together with an uncertainty analysis of the hyperbolic sine expression.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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CONTENTS

	Page
REVIEW SUMMARY	1
1 BACKGROUND	1
2 LITERATURE PRECIS .	3
3 ACKNOWLEDGEMENTS	8
4 REFERENCES .	8

REVIEW SUMMARY

Finite element analyses indicate that strain rates of between 10^2 - 10^4 s^{-1} are present in the shear zone of workpieces in the metal cutting process. Only one test method has been reported for obtaining data at these very high strain rates - the split Hopkinson bar (Kolsky) technique. This technique is not widely available. It is limited also in the maximum strains that can be imparted and the difficulty of doing the tests at high temperatures. It is used generally for studying projectile deformations, usually at temperatures much lower than that experienced in the metal cutting processes. Methods are clearly needed for measuring properties at high strain rates >50 s^{-1} . Information from tests at these high strain rates would also be relevant to forging and rolling as well as metal cutting processes. New methods for flow stress measurement at high rates of strain would also benefit from experimental measurements of positional-dependent temperature rises in the tests. FE modelling of testpiece deformation would assist in the interpretation of measurement uncertainties. The hyperbolic sine expression that relates stress to strain rate and temperature can be analysed to give an indication of fractional uncertainties in flow stress due to fractional uncertainties in strain rate and temperature.

1 BACKGROUND

Project MMP4 (Thermomechanical Measurements) in the DTI Materials Measurements for Processability Programme contains a task on mechanical measurement methods for data for machining models. The objective is to assess the industrial requirement for test methods and data for such models. This task includes an assessment of literature in this field, focusing in particular on the measurement methods that are used to generate flow stress data at the very high rates of strain ($>10^2$ s^{-1}) that occur in machined workpieces. The mechanics of machining have been reviewed in a recent book [1] which uses plane strain slip line field analyses to assess flow stress data from machining tests. However, it was acknowledged that independent tests to determine strength as a function of strain rate and temperature would be more suitable for machining modelling.

The literature search used the following key words in various combinations

Machining	High Rate Deformation	Tool/Chip interface
Plastic deformation	Flow stress	Impact material tests

A list of the references examined are given in Section 4 (References). Inevitably the search also yielded papers on high rate deformation tests which border on the strain rate regime relevant to machining. These have been briefly summarised as well, particularly where they include information on the constants in the hyperbolic sine empirical expressions below, relating flow stress to strain rate and temperature, since these are helpful in evaluating flow stress uncertainties.

$$A[\sinh(\alpha\sigma)]^n = \dot{\epsilon} \exp [Q/RT] = Z \text{ (Zener-Hollomon parameter)} \quad (1)$$

This note, therefore, provides a précis of the contents of the various papers with an emphasis on the test methods used, together with a summary. Some of the papers examined were in Japanese. These have been retained in the list as they appear to contain useful flow stress data.

Evaluation of the hyperbolic sine expression for the dependence of flow stress on strain rate and temperature requires values for four constants α , Q , n and A for a wide range of materials. Where possible, values for these constants have been extracted from published work for evaluation of the differential forms of the hyperbolic sine expression, i.e.

$$\frac{d\sigma}{\sigma} \text{ as } f\left(\frac{dT}{T}, \sigma, \frac{d\dot{\epsilon}}{\dot{\epsilon}}\right)$$

since from expression (1)

$$\frac{d\sigma}{dT} = \frac{-Q}{nRT} \tanh(\alpha\sigma) \quad \text{and} \quad \frac{d\sigma}{d\dot{\epsilon}} = \frac{1}{\alpha n \dot{\epsilon}} \tanh(\alpha\sigma) \quad (2)$$

Fractional changes in flow stress ($d\sigma/\sigma$) can thus be evaluated as a function of the fractional change in temperature or strain rate (dT/T) or ($d\dot{\epsilon}/\dot{\epsilon}$). If values for the constants in the hyperbolic sine relation between σ , $\dot{\epsilon}$ and T [expression (1)] are known then uncertainties in flow stress can be estimated from uncertainties in temperature and strain rate.

$$\frac{d\sigma}{\sigma} = \frac{dT}{T} \frac{-Q}{nRT} \frac{\tanh(\alpha\sigma)}{\sigma} \quad \text{and} \quad \frac{d\sigma}{\sigma} = \frac{d\dot{\epsilon}}{\dot{\epsilon}} \frac{1}{n} \frac{\tanh(\alpha\sigma)}{\sigma}$$

Some typical results for an aluminium and a ferrous alloy are given in Fig 1.

$(ds/s)/(dsr/sr)$ and $(ds/s)/(dT/T)$

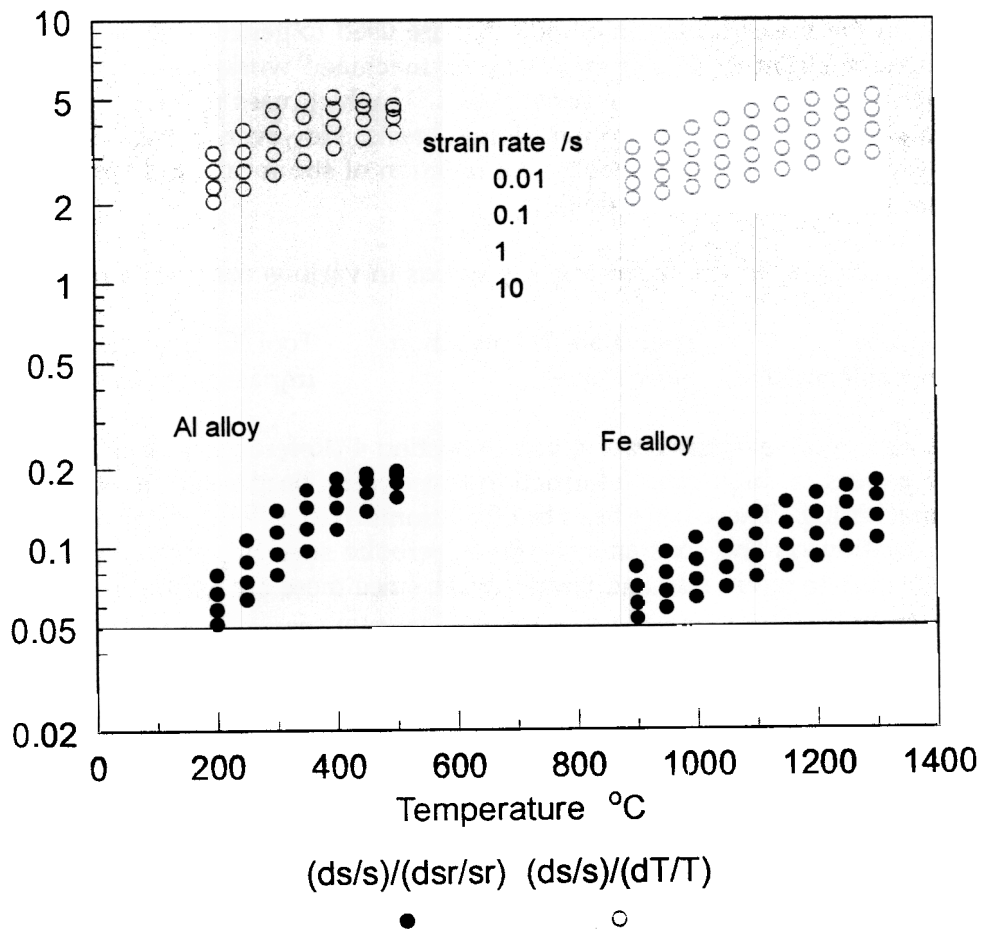


Fig 1 Temperature dependence of the fractional change in stress (ds/s) normalised by fractional change in strain rate (dsr/sr) or temperature (dT/T) for typical Al and Fe alloys for four strain rates (0.01-10 s⁻¹).

2 LITERATURE PRECIS

Each paper or group of papers is preceded by a box in which, if the information is given in the paper, the most relevant test parameters are shown as follows:

Test Characteristics

Machine	Strain Rate	Material
Other Details	Geometry	Temperature

Yada et al [4] - 1981

Test Characteristics

Thermomechanical simulator servohydraulic	up to 250 s ⁻¹	Various steels
Induction heating	Plane strain compression 10 mm thick x 15 mm wide testpiece. Tool width - 5 mm	900 - 1100 °C

An in-house thermomechanical simulator with a quenching facility was developed to measure the flow stress of a variety of steels and the dependence of stress on temperature and strain rate. A plane strain compression testpiece was used for the tests. The equipment was developed to investigate behaviour relevant to wire rod and hot strip rolling mills and could perform multiple bit compression strains with subsecond intervals. It was concluded that sequential small deformations could be simulated by a single deformation with a large final strain. The results were modelled using

$$Z = M \sigma^p \qquad \text{where } M \text{ and } p \text{ are constants}$$

rather than the hyperbolic sine expression.

An activation energy of 267 kJ mole⁻¹ was used and values of 6-11 were found for p for a range of steels. The stress, σ , could be taken to be either the maximum or the steady state value in the σ/ϵ curve.

Maekawa et al [5-7] - 1983

Test Characteristics

Hopkinson Bar (incremental)	up to 1200 s ⁻¹	Low C steels
	6 mm diameter by 10 mm height	RT-750 °C

A split Hopkinson bar test method was used to obtain stress/strain data on low C steels at strain rates up to 1200 s⁻¹. The method was used in incremental fashion to achieve the high strains necessary to model metal working processes, because standard one shot Hopkinson bar tests only provide data at relatively low strains. A torsion version of the equipment was also investigated.

The work also drew attention to the importance of history effects, ie flow stress can be dependent on prior deformation conditions and retained internal structure.

Harding (8) - 1988

Presents a review of material behaviour at high rates of strain (defined as $>10^3 \text{ s}^{-1}$) particularly in terms of internal structure and strain history dependence. Test method used-split Hopkinson bar (compression or torsion). Primarily discusses behaviour of nominally pure materials, Cu and Al.

Corran (9) - 1989

Reviews numerical modelling techniques for high strain rate phenomena. Classifies responses in relation to transient time of elastic waves in testpieces.

Laasraoui and Jonas (10) - 1991

<i>Test Characteristics</i>		
Cam plastometer Axisymmetric compression	up to 50 s^{-1}	Various steels
Induction heating for high $\dot{\epsilon}$	Cylindrical ht/diameter ratio = 1.5	800-1100 °C

Discusses microstructural evolution laws, particularly for dislocation densities, and mechanical constitutive behaviour in high rate deformation tests at high homologous temperatures. Includes discussion of temperature rises due to deformation, which can cause 10% errors in flow stresses in some cases. Gives values for hyperbolic sine behaviour for various steels (expression (1)) of:-

α

= 0.012 to 0.016 MPa⁻¹ (similar to that of other steels)

n

= 4 to 5

Q

= 312 to 382 kJ/mole (cf 508 for stainless steel and 435 for HSLA steel)

A

= 9×10^{10} to $2 \times 10^{13} \text{ s}^{-1}$

Kumar et al (11) - 1992

<i>Test Characteristics</i>		
Servohydraulic Axisymmetric compression	up to 10 s^{-1}	IS: 2062 CMnSi steel
He gas quenching	10 mm diameter by 12 mm height	900-1100 °C

FE modelling of deformation of axisymmetric testpiece coupled with microstructural modelling of grain size and recrystallisation. A friction coefficient of 0.5 was assumed. Model includes temperature rises due to plastic work.

Lin et al (12,17) - 1993,5

FE study of orthogonal cutting of mild steel. Flow stress data obtained from other sources (G Barrow et al, Int J Mach. Tool Des. 22 (1), 1982, 5-85). Discusses importance of friction, heat generation and heat transfer. Strain rates of 10^2 - 10^3 calculated in workpiece.

Takuda et al (13) - 1983

Test Characteristics

Cam Plastometer	up to 34 s^{-1}	Al Alloys 300-500 °C
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An investigation of the effects of $\dot{\epsilon}$ and T on the deformation of Al alloys. Attention was drawn to three types of deformation curve:

Work hardening Work softening Work stable

The problem of choosing a representative stress for obtaining the Zener Hollomon parameter was discussed with a recommendation of measuring the stress at a true strain of 0.2.

Childs et al (14) - 1994

Reviews the influence of flow stress data on machining simulations. For modelling the authors define two key requirements:

Flow stress data at appropriate temperatures and strain rates.

Friction data.

Refers to data sources using the split Hopkinson bar test method (Japanese data - reference 14 and 16). A different expression is used to calculate the temperature and strain rate dependence of stress to the $\sinh(\alpha\sigma)$ /Zener-Hollomon equation, ie

$$\sigma = A\dot{\epsilon}^B \epsilon^C \tag{2}$$

where A, B and C are temperature dependent constants. Split tool dynamometers are generally used to obtain friction data.

Lee and Tarng (15) - 1994

Predicts cutting forces in machining steels. Predictions require compression data. Uses Japanese results from 1967 (M Oyane et al. Proc 10th Japan Congress on Materials Testing, 1967, 72-76).

Jin et al (16) - 1995

Modelling the hot rolling of steel. Hyperbolic sine law (expression (2) above), stress parameters of $\alpha = 0.013 \text{ MPa}^{-1}$, $Q = 293 \text{ kJ/mole}$, $n = 0.47$ and $\ln A = 25.6$. Gleeble 1500 used to obtain test data. Maximum effective strain rates of 115 s^{-1} were predicted.

J Y Sheikh-Amad and J A Bailey (18) - 1995

Test Characteristics

Torsion (tubular testpiece)	up to 120 s ⁻¹	CP Titanium
Split furnace	1.42 mm thick tube (OD = 9.9 mm)	150-750 °C

Emphasises importance of calculating temperature rises during deformation to correct for decrease in flow stress caused by deformational heating. Gives plots of calculated temperature rise versus strain for different strain rates at different deformation temperatures. This can be 75 °C for $\dot{\epsilon} = 120 \text{ s}^{-1}$ at 450 °C. Evaluates a thermal softening function used to adjust flow stress for temperature rise effects.

Shih (19) - 1996

Assesses FE methods for the simulation of the metal cutting of a carbon steel. Emphasises the importance of friction. Typical strain rates of $2\text{-}6 \times 10^3 \text{ s}^{-1}$ were estimated, together with effective stresses of up to 2000 MPa and strains between 0.5-5. Temperatures of 300-800 °C were calculated.

Anderson and Evans (20) - 1996

Test Characteristics

Servohydraulic Axisymmetric compression	up to 40 s ⁻¹	Low C steels
glass lubricant + BN coating	6 mm diameter by 8 mm height	up to 1100 °C

A study of hot axisymmetric compression tests on two low C steels to provide data and values for parameters in constitutive deformation laws, in particular a hyperbolic sine behaviour.

Typical values were found for one steel of 0.020 MPa⁻¹ for α , 360 kJ/mole for Q, 28.5 for lnA and 3.3 for n. For another steel they were 0.1 MPa⁻¹, 395 kJ/mole, 35 and 5.75 respectively. These parameters were claimed to be within the same range as those obtained in similar ferrous materials, ie typically 0.012 MPa⁻¹, 310-370 kJ/mole, 20-40 and 5.

Nemat-Nasser and Isaacs (21) - 1997

Split Hopkinson Bar (Incremental)	up to 6000 s ⁻¹	Tantalum and Ta-W alloys
	?	-200 to 1000 °C

Gives original references for Hopkinson Bar method.

B-J Lee et al (22) - 1997*Test Characteristics*

Split Hopkinson bar	up to 10^4 s^{-1}	Ta
Tube furnace	5 mm diameter by 5 mm height	up to 500 °C

Deduces thermal softening effects by comparing multi-hit low strain results with a one hit high strain test.

Sheppard and Jackson (23) - 1997

Compares results from compression and torsion testing, especially with respect to the calculation of temperature rises.

Test Characteristics

Servohydraulic Axisymmetric compression	up to 80 s^{-1}	7075 Al alloy
Graphite lubrication	8 mm diameter by 10 mm height	260-420 °C

* Compression tests performed at IRC/Swansea

Provides values for the constants in the hyperbolic sine expression (compression testing)

$$\alpha = 0.011 \text{ MPa}^{-1}$$

$$n = 6.5$$

$$Q = 156 \text{ kJ/mole}$$

$$A = 1.58 \times 10^{12} \text{ s}^{-1}$$

Test Characteristics

Torsion (solid)	up to 50 s^{-1}	Various Al alloys
	10 mm diameter by 10 mm gauge height	250-500 °C

Temperature rises were calculated to be higher in torsion testing. Data were corrected for temperature rise to generate values for the constants in the hyperbolic sine expression.

Tabulates these constants for a wide range of Al alloys. Some of which are given below:

Alloys	α MPa ⁻¹	n	Q kJ/mole	lnA s ⁻¹
1100	0.045	5.65	158	29.7
2024	0.016	4.25	149	19.6
3005	0.032	4.95	183	29.9
5052	0.016	5.25	155	29.5
6061	0.045	3.55	145	19.3

Shi et al (24) - 1997

Test Characteristics

Plane Strain Compression	up to 25 s ⁻¹	Al and experimental Al-Mn and Al-Mg alloys
Lubricated tests	10 mm thick by 50 (or 30) mm wide by 60 mm long	300-500 °C

Evaluates a power law expression for flow stress dependence on strain and uses hyperbolic sine expression for flow stress dependence on strain rate and temperature. Temperature rises of up to 30 °C were noted in low temperature high $\dot{\epsilon}$ tests. Hyperbolic sine constants were determined at the saturation stress:

Material	α MPa ⁻¹	n	Q kJ/mole	A s ⁻¹
Al	0.036	5	156	1.96 x 10 ¹¹
Al-1% Mn	0.039	5	156	1.21 x 10 ¹⁰
Al-1% Mg	0.012	6	156	1.96 x 10 ¹¹

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