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Tools and Lubricants for High Temperature Metalworking Laboratory-Scale Tests

This Measurement Note presents a summary of some of the key tool materials and lubricants currently used in high temperature metalworking. The note contains recommended tool/lubricant combinations for a variety of materials and practical advice about carrying out laboratory-scale tests to measure flow stress.

The note is in two parts. The first part includes background information on the range of tool materials and lubricants used in warm and hot metalworking. The second part addresses some of the specific issues related to laboratory-scale testing, specifically the hot axisymmetric compression and plane strain compression tests.

Summary tables are provided, where appropriate, covering the combination of tools and lubricants used by participants in the current project.

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Introduction

A number of laboratory-scale tests have been developed to generate workpiece flow stress data, and the most commonly used of these include the hot tensile, torsion, plane strain compression and axisymmetric compression tests. The latter two probably offer the best solution for accurate measurement of the data because they involve large-scale plastic deformation. To ensure the relevance of the laboratory approach, it is vital that a realistic simulation of the metalworking conditions are achieved in these tests and this includes the interactions at the tool/workpiece interface. These interactions are very complex and are strongly affected by the temperature, heat transfer, contact and process times, and by the lubrication and the choice of the tool materials. Two *Good Practice Guides* have been developed as part of the current work - for the Hot Axisymmetric Compression Test [1] and Plane Strain Compression Test [2]. This *Measurement Note* summarises some of the issues relevant to the selection and application of tools and lubrication in these tests.

In the next section, some information is presented on the common tool materials and lubricants used in warm and hot metalworking. In a separate section some of the specific issues related to the laboratory-scale tests are addressed.

Tool And Die Materials

Requirements

The demands placed on a tool or die vary considerably depending on the application, but for hot metalworking in general there are a number of requirements, including:

- Low basic cost.
- Good machinability.
- Simple heat treatment cycle.
- High strength.
- Good wear resistance.
- Toughness and ductility.
- Resistance to mechanical and thermal fatigue.

Tool material suppliers are in the best position to give advice regarding the suitability of a particular material, and can provide detailed mechanical property data, heat treatment, processing and machining information. Although a particular tool material may offer a range of attractive properties, in many cases a compromise must be made between the properties, cost, and the ease of manufacture. It has been reported [3] that tooling costs can account for up to 15% of the total production cost in hot forging. New materials are often difficult to introduce because of the knowledge and experience gained over the years with one particular material.

Conventional Die Steels

The most common group of hot working tool steels are the medium or high alloy steels, which have relatively low carbon contents (< 0.6% C). There are three classes within this group - designated the AISI H series - in which the principal elements responsible for the high temperature properties are chromium, either tungsten or molybdenum, and both tungsten and chromium in equal proportions. Of these only the chromium-based steels H1l, H12 and H13 are used in any quantity, and within this group the 5% chromium hot work steel, H13, is by far the most popular and versatile.

A material unique to the British forging industry is a low alloy 1.5 Ni-Cr-Mo steel, designated BS 4659 (1989) No.5 die steel [4]. It is one of the most widely used material for die blocks in drop forging in the UK, where high strength and good shock resistance are important. To ensure the desired combination of properties and adequate resistance to softening and heat checking, tempering is carried out at temperatures slightly above those encountered in service. Dies are usually preheated to 150-200°C before use to reduce the risk of damage from thermal shock, but surface temperatures during forging may be appreciably higher.

Increased demands on the strength of materials led to the development of the maraging steels in the 1960's. They were originally developed for structural parts in aircraft and spacecraft, but they have found applications in hot working as forging dies, heading dies, extrusion dies and punches. Maraging steels contain virtually no carbon and are high Ni-Co-Mo steels capable of developing high strength and toughness. The main advantage offered by the maraging steels is not strength, since higher strengths are readily attainable in many conventional steels. The maraging steels do, however, offer a combination of high strength and toughness, and this can be achieved by a simple heat treatment cycle. Also, hardening does not depend on the cooling rate, and full hardness can be developed uniformly in thick sections with no distortion or size change.

A number of maraging steels have been developed, containing 25, 18 and 10 - 15 per cent nickel. The grades containing 18% nickel have received the greatest attention because of their excellent fracture toughness, and the simple, single-step ageing process. The applications of maraging steels in hot working should be restricted to temperatures below ~ 480°C, because above this limit austenite reversion leads to a dramatic loss of strength and hardness.

Ceramics

Ceramic tools are now being increasingly considered for die inserts [5] in metalworking where their wear resistance, tensile strength and resistance to thermal shock are superior to conventional metallic tool materials.

Because ceramics are brittle materials there has been a cautious approach to the use of these materials in heavily stressed applications. Brittleness should not be confused with weakness however, and a full appreciation of the properties and design procedures for these materials should reduce problems and eliminate undesirable stress conditions. The lack of ductility means that locally, stresses are not relieved by plastic deformation. This is particularly important in the dense engineering ceramics where there are no internal defects or porosity to inhibit crack propagation. Furthermore the size of the ceramic tool is limited by the increasing probability of fracture.

Partially Stabilized Zirconia (PSZ) has hot hardness and the resistance to deformation normally associated with ceramics, and it also has a high resistance to thermal shock. PSZ is an unusual and particularly tough ceramic. The high toughness is developed in dense ZrO_2 by mixing stable and unstable powders prior to sintering. During the application of load and temperature the unstable material undergoes a phase transformation, accompanied by a change in volume, which causes internal stresses to build up in the matrix which suppress crack propagation and lead to improved fracture properties.

Silicon nitride components may be produced in dense forms from powder by conventional ceramic processing. Fully dense hot pressed silicon nitride (HPSN) is very strong and most of the present applications rely on its hardness, strength and high temperature properties. HPSN is now well established, but a further development has seen the production of dense sintered silicon nitride-based materials - *Sialons* - which can be produced without the application of external pressure, using liquid phase sintering aids such as MgO and Y_2O_3 singly, or together with Al_2O_3. The advantages of sialon over silicon nitride arise from its improved mechanical properties and the ease of fabrication.

Surface Treatments

Many surface treatments are available that provide superficial hardening of the tool surface. Carburising increases the resistance to wear by the diffusion of carbon into the surface layers, and nitriding has been applied successfully to certain hot working die steels. The compound surface layers enhance the high temperature abrasive wear resistance because the hot hardness is superior to that of the untreated material. Both carburising and nitriding are treatments which change the composition of the surface layers of the tool, but surface coatings deposited via electroplating, spraying, ion plating and chemical vapour deposition are also used. In general, the choice of coating is dictated by the bulk metal and the necessity for a good bond between the coating and the substrate, the absence of residual stresses and matched thermal expansion coefficients. By modifying the surface of a tool it is possible to increase wear resistance at relatively low cost.

Table 1 provides some details of the tool materials and lubricants used for processing of different materials. The details were collated from a questionnaire of companies and a literature search carried out in the current project. Although the list is not exhaustive it provides useful information regarding current practice and the most popular workpiece/tool/lubricant combinations.

Lubricants

Lubrication is an important variable in metalworking. It is often stated that the primary purpose of lubrication is to reduce friction but this is frequently over-emphasised and a more extensive list of the functions of a metalworking lubricant includes the ability to:

- Provide lubrication at high pressures and high temperature.
- Reduce wear and increase die life.
- Control the flow of metal by controlling friction.
- Reduce chilling.
- Facilitate die release
- Dissipate heat from the die surface.
- Control surface finish.

The mechanism of lubrication is best defined by the thickness of the lubricant film which separates the die and workpiece. Boundary lubrication exists where high loads and low speeds are used, and this is the case in many metalworking operations where there is extensive plastic deformation of the workpiece metal and the surfaces are separated by very thin lubricant films.

It is important that the integrity of the lubricant layer is maintained throughout the process as even a local breakdown can have serious consequences for the processing.

Lubricant Types

Lubricant suppliers are in the best position to advice on the compatibility of specific lubricants for particular applications and materials. Further information can be found at the following web sites:

www.achesoncolloids.com

www.amlube.com

www.lubeserv.co.uk

www.renite.com

www.fuchs.com

Please note that this list is not exhaustive and any reference to the suppliers or proprietary tradenames in this document does not represent an endorsement by NPL.

Table 2 gives a summary of the major lubricant types. The choice of lubricant depends on the processing conditions, the characteristics of the die and workpiece, and the temperature at the interface. The most commonly-used lubricants in the hot forging of steel are graphite-based, usually in the form of a dispersion of colloidal graphite in water or oil. Lubricant is normally applied to the die by swabs, or sprayed onto the die surface between forgings. The frequency of application of the lubricant depends directly on the temperature, size and complexity of the die and the frequency of the forging operation. Spraying has the advantage over other methods of application because the lubricant dries quickly and leads to a thinner, uniform coating. Additional advantages of water-based graphite lubricants are the absence of fumes and the relative cleanliness of the forge and the surrounding area. The properties of the graphite lubricant can be characterised by the particle size, volume fraction, crystal structure, microhardness, texture and purity of the graphite, and the characteristics of the carrier medium. Results have shown that large particles of high purity and low hardness, reduce wear. Lubricant concentration normally varies between 5 and 40%, the average being about 20%. Molybdenum disulphide is sometimes used as a substitute for graphite in some cases, but it is more expensive. Synthetic lubricants have also been developed, but they have not replaced conventional lubricants because they are unable to withstand the high pressures encountered in metalworking.

The operating temperature probably has the greatest influence on the lubricant selection. At low temperatures Teflon and graphite based lubricants are adequate for most purposes, but at higher temperatures glass-based lubricants are often used. There is some overlap in the operating temperature ranges for the different lubricant types and often a number of different lubricants can be applied to a particular situation.

Specific Testing Issues

The hot axisymmetric compression and plane strain compression tests are used to make measurements of flow stress under controlled laboratory conditions without disruption to the production run. The specific details of the test methods are covered in the *Good Practice Guides* [1,2], which were developed as part of the current project. The tests themselves can be carried out on a variety of different test machines. Whilst it is highly unlikely that the different laboratory systems are alike, there are a number of issues related to the tools and application of load that should be addressed. Some of these are discussed below. They can have an important effect on the success of the test and the reliability of the data.

Alignment

Misalignment of the load train and platens should be avoided as it will result in non-uniform deformation of the testpiece. It is recommended therefore that the alignment of the platens should be checked at intervals not exceeding 100 tests using a suitably strain gauged compression cylinder or dial gauge indicator. For the plane strain compression tests the platens should be parallel to within 0.1% (ie 0.01mm across a 100mm wide testpiece). In both the hot axisymmetric compression and plane strain compression tests specific criteria on barrelling and non-uniform deformation must be satisfied to obtain a valid test.

The potential for misalignment and bending is reduced if the load train and push rods are kept short, but this depends on the individual test configuration and heating setup.

Alignment and positioning of the testpiece at the centre of the loading axis is also important. A special rig should be used to ensure accurate and repeatable location of the testpiece on the platens.

Platens & Inserts

Platens must be strong enough to sustain the loads required for hot deformation and must not react with the testpiece and lubricant at the test temperature. Special care should be taken with ceramic inserts which are generally brittle if loaded in tension. It is particularly important to ensure that the supporting platen surface is clean and free from scale or debris.

For some applications, ceramic platens are joined to other components - usually metals. Again, special care is needed to avoid tensile stresses and unfavourable stress concentrations in the ceramic, which may arise because of the differences in the coefficients of thermal expansion. Partially stabilised zirconia (PSZ) has been used for dies for the hot extrusion of steel rod and copper tubes. The joining problem was overcome by using an interference fit of the ceramic die in a steel casing. It was possible to build in large compressive stresses in the die which, combined with the strength of the PSZ itself, provided sufficient strength to withstand the stresses during extrusion. Other recommendations for the joining of ceramics to metals are presented by Morrell [6]

Surface Finish and Regrinding

Generally, a fine ground surface finish is adequate. Edges of platens should be chamfered to avoid stress concentrations and edge damage**.** If possible, the platens or inserts should be removed and cleaned after every test to remove lubricant, metal and oxide scale**,** but this is not always practical. Depending on the test conditions the operator must make a judgement on the replacement and remachining of the tools.

Temperature Measurements and Gradients

Recommended methods for measuring the temperature of the workpiece and platens are being developed by NPL and the industrial partners, but some practical issues relating to the hot axisymmetric and plane strain compression tests are covered here.

If the workpiece is removed from a furnace prior to testing the drop in temperature should be measured and noted. Transfer times should be minimized and tests should be carried out as soon as possible to reduce the level of die chilling. This may occur preferentially on the lower platen and lead to further inhomogeneities in the testpiece deformation. Some overheating of the testpiece may be necessary therefore to ensure that deformation takes place at the appropriate working temperature.

Die preheat is important and should be monitored throughout the test with a suitable thermocouple mounted close to the tool surface. To ensure a quick response it is important that the thermocouple is in intimate contact with the die.

Summary

The following points deal with specific issues in the laboratory-scale tests.

- The selection of tool material and lubricant should be consistent with the metalworking process. Often this is based on user experience. Tool material and lubricant suppliers are probably in the best position to give advise regarding the suitability of a product for a particular application.
- Unless specified all tests should be carried out with lubrication.
- Where possible the platens should be cleaned or replaced after each test, and remachined when there is any sign of wear or damage.
- Tools and platens should be preheated if appropriate prior to testing.
- Edges of platens should be chamfered to avoid stress concentrations and edge damage.
- The temperature of the platens should be monitored using a thermocouple just below the surface.
- The push rods and load train should be kept as short as practicable to reduce the possibility of misalignment and bending.
- It is recommended that the alignment of the platens and loading train should be checked at intervals not exceeding 100 tests using a suitably strain gauged compression cylinder or dial gauge indicator.
- The platens should be parallel to within 0.1% (ie 0.01mm across a 100mm wide testpiece).
- Allow for the expansion of the push rods and load train during heating.
- Ceramic inserts should be designed carefully to avoid tensile stresses.
- Alignment and positioning of the testpiece at the centre of the loading axis is important. A special rig should be designed to ensure accurate and repeatable location of the testpiece on the platens.

Table 1: Summary of suggested workpiece/tool/lubricant combinations used by organisations involved in the current project

Workpiece	**Temperature Range (°C)**	**Lubrication**	**Platens**
	RT - Liquidus	Glass	Al_2O_3, glass, Mo plates

ALUMINIUM ALLOYS	200-450	Graphite	H13 steel
	300-400	Graphite	Quartz
	< 350	Teflon	Tool steel
	350-600	Water-based Graphite	Tool steel
	400-450	Tallow Grease	H13 tool steel
	400-450	Synthetic oil	H13 tool steel
	< 400	PTFE dry lubricant spray	INCO 718
	450-550	Graphite foil	WC
	RT-550	Acheson EG 1403 (Graphite in water)	INCO 718
FERROUS ALLOYS	RT - 1500	Glass Graphite foil	Al_2O_3 Mo plates
	> 800	Glass	Tool steel
	750-1200	Graphite foil, BN coatings	M22, Sialon
	1100	Acheson DPG 3479 Glass/styrene acrylic	Sialon, Maraging steels
	850-1100	Water and light oil	Chill cast iron, Chromium alloy steel
	800-1300	Graphite foil	WC + Ta/Ni foil
NICKEL ALLOYS	850-1150	Borate glass + BN Graphite + glass + BN	Inconel M22B TZM Molybdenum
	800-1050	Graphite - Achesons Deltaglaze 3418	Mar M246
	1100	Acheson DPG 3479 Glass/styrene acrylic	Sialon, Maraging steels
	1050-1250	Achesons DAG 2626	Mar M246 up to 1150°C
TITANIUM ALLOYS	800-1050	Borate glass + BN	Inconel M2213
	1010	Glass - Amlube 1000	Inconel
	1000	Glass - Deltaglaze FB414	Inconel
COPPER ALLOYS	450-950	Graphite	WC
	650-750	Synthetic graphite-grease mixture	H13 or H10A tool steel

Table 2: Summary of Lubricant types, applications and Tradenames

Lubricant Type	**Form**	**Trade Name**	**Temp Range**
PTFE (Teflon)	Spray Film		up to 200°C

Graphite	Foil Powder	Rocal X2102	up to 300°C 650 - 750°C
Graphite in water	Liquid	Lubeserve Aquagraf B Amlube 235 Renite S-45/S-28 Acheson EG 1403	RT - 315°C
Graphite in alcohol	Liquid	Acheson DAG 580 Lubeserve PA580	250-300°C max
Graphite/Molybdenum Disulphide	Grease	Acheson DAG 1559	up to 450°C
Molybdenum Disulphide	Dry Powder Liquid (in water)	Amlube 510 (powder) Amlube 555 (fluid)	up to 400°C
Grease	Grease	Tallow fat Lithium 3 grease	400-450°C 650-750°C
Synthetic Oil	Oil	Thermex 7015	400-450°C
Boron Nitride	Liquid (in water)	Acheson DAG 5710	500-1000°C
Glass	Fluid	Amlube 1000 Amlube 1080	up to 1010°C (Ti) up to 1310°C (steels)

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References

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