Extreme Plastic Deformation by High-Pressure Torsion

DEPARTMENT OF ENGINEERING SCIENCE

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Introduction

Strong, light materials with good thermal conductivity are crucial for applications such as aerospace, heat-sinks, rocketry, and power electronics. High-pressure torsion (HPT) is a method of deforming disc-shaped samples by applying a large compressive force and simulateously twisting one surface. HPT creates large strains and **work-hardens** the material. The high internal pressure allows deformation beyond the normal point of fracture.[2]

Insoluble composites of copper and refractory metals (such as molybdenum and tungsten) are commonly used to improve the mechanical properties versus pure copper alone. However, it is hoped that HPT can more than double the strength of these metal composites. It is necessary to better understand the thermal and elastic behaviour of this new material.

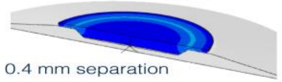
Key project goals:

1. To design and build an HPT capability in Oxford
2. Test setup with a chosen binary metal system (Mo-Cu) against results published in literature (microstructure and hardness)
3. Investigate thermal and elastic properties
4. Develop models to explain thermal and elastic behaviour

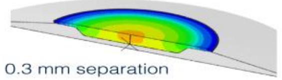
Anvil Design

The aim of the HPT anvil is to impose a high uniform pressure on the sample and to prevent slip, so that the number of rotations can be directly linked with the applied strain. High strength and hardness are necessary properties of the anvil material to prevent damage and wear to the contact surfaces. Finite element modelling has been used to estimate the contact stress and the internal pressure within the sample for the proposed deisgn. Contact stress is particularly important because it must be high enough so that there is no slippage, but not too high that the anvil yields.

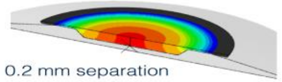
The internal pressure (shown for molybdenum) increases as the anvils (in grey) are brought closer together. Material is also squeezed outwards. The thin shoulder region at the edges effectively maintains a large pressure drop across it. The pressure distribution is closer to unform for copper because it is softer. As expected, for the same applied load, the copper sample is deformed and pressed outwards more than the molybdenum.



0.4 mm separation



0.3 mm separation



0.2 mm separation

Conclusions

- The microstructure and mechanism of fragmentation differ starkly depending on the composition of the Mo-Cu
- A strain of γ = 420 is not sufficient to reach a homogeneous state (saturation)
- TGS data for Mo70-Cu30 with 20 applied turns shows a 38% reduction in thermal diffusivity and a 4% reduction in elastic modulus
- Dislocations, grain boundaries and fibre-like elongation of the phases do not fully explain the stiffness decrease; grain reorientation is likely a factor

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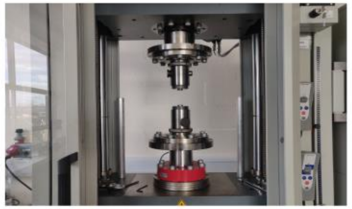
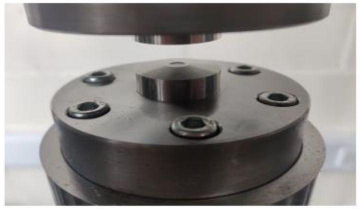
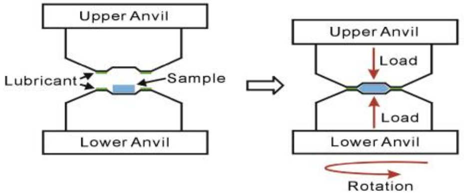
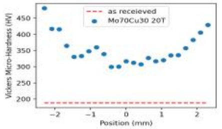






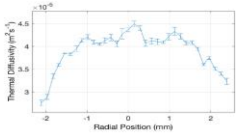
Property Evolution

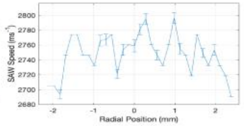
From **indentation hardness** profile across diameter of disc, the strength of Mo70Cu30 has more than doubled at the edges following HPT. The hardness is highest at the edge because the applied strain is proportional to radius. However, a higher number of turns needs to be applied to reach the steady-state (uniform hardness).

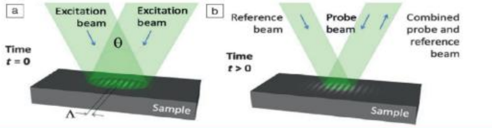


Transient grating spectroscopy (TGS) is a non-destructive method for determining thermal, elastic and acoustic properties.[1] Two overlapping lasers produce an interference pattern which rapidly heats up the sample. Thermal expansion then produces acoustic waves on the surface (SAWs) whose velocity is linked to elastic modulus.

TGS measurements of 20 turns HPT Mo70-Cu30 show a 38% decrease in thermal conductivity and a 4% decrease in elastic modulus at the edges versus the centre.





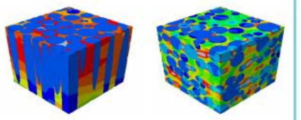


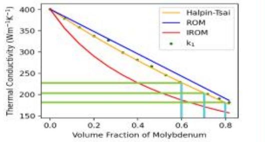
References:
1. Hofmann, F., Short, M., & Dennett, C. "Transient grating spectroscopy: An ultrarapid, nondestructive materials evaluation technique." MRS Bulletin (2019).
2. Kormout, K., Pippan, R., & Bachmaier, A. "Deformation-Induced Supersaturation in Immiscible Material Systems during High-Pressure Torsion." Advanced Engineering Materials (2017).

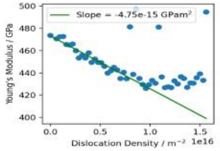
Material Modelling

A **finite-element model** was developed from the observations of the microstructure in order to better understand thermal and elastic properties. The initial state is approximated as randomly-placed spheres of different sizes, surrounded to form a cube. The packing density of the spheres corresponds to the volume fraction of molybdenum in the samples. The elongation of the particles during HPT is considered by uniformly stretching the spheres into ellipsoids. Elastic modulus is measured by applying a small strain in the vertical direction. Poisson ratio is then calculated from the horizontal displacement. Similarly, thermal conductivity is found by applying a fixed temperature difference accross the upper and lower surfaces.

The Halpin-Tsai equations are commonly used for estimating the properties of composite materials. From fitting the data, it was determined that Halpin-Tsai equations provide a good fit for thermal conductivity and elastic modulus in both the perpendicular and parallel directions.

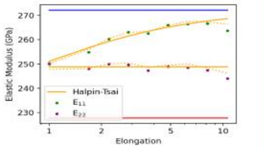






Molecular dynamics (MD) is a computational technique which models the movement of individual atoms. Using MD it has been possible to esitmate the effect of dislocation density on elastic modulus, for the pure element. This is done by inserting different sized dislocation loops into a simulation cell 50 atoms wide.

At the level of dislocations encountered during HPT, the reduction in stiffness is estimated to be negligible (1%). Hence, other features such grain boundaries and grain orientation are expected to lower the elastic modulus instead.

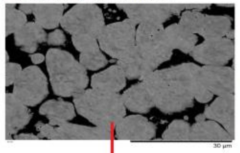


Microstructure

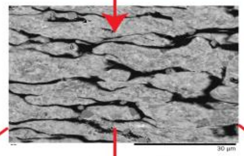
The strain experienced during HPT is hundreds of times higher than normal production methods. The heavily deformed microstructure this creates makes the material extremely strong. The grain size is reduced up to the 10s of nm scale and large numbers of dislocations are generated.[2]

The metal composite samples consist of molybdenum particles (bright) within a copper matrix (dark). When sheared, these particles get stretched to form a long, thin layers. This introduces **anisotropy** and the thermal/elastic properties will no longer be the same in diffent directions. Furthermore, because the insoluble layers restrict diffusional processes, thermal stability is improved.[2]

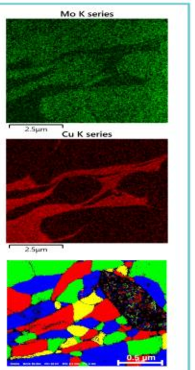
As received condition

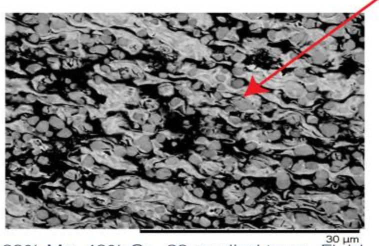


Typical, after 5 turns applied

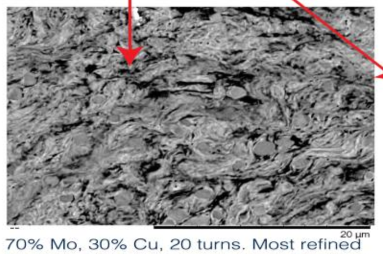


Under ordinary (equilibrium) conditions copper and molybdenum are are almost completely insoluble. This is due to their different crystal lattice structures. However, the deformation caused by HPT is so severe that significant amounts of copper may dissolve in molybdenum and vice versa, producing **supersaturated** phases. This is shown in the EDX images (right) as the appearance of Mo in the Cu rich regions. It is expected that this will lead to reduced conductivity and improved strength. The grain map from TKD (right) shows the formation of < 200 nm grains in the layered regions. This is a smaller size that what is seen in pure Mo or Cu HPT.

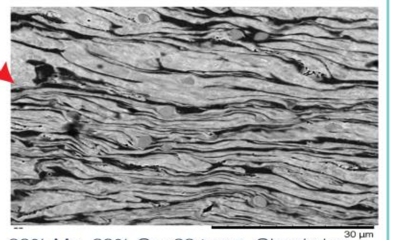




60% Mo, 40% Cu, 20 applied turns. Fluid like structure and fracturing visible



70% Mo, 30% Cu, 20 turns. Most refined microstructure with some layered regions



80% Mo, 20% Cu, 20 turns. Clearly layered structure with high elongation