Surface engineering
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2008

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Summary

Individual chapter conclusions summarise the main points of a given subject under consideration, but in order to draw a line under the thesis, we summarise here the findings of the research ‘as a whole’.

Production and processing

When we embarked on this work, one of the main considerations was to be able to replicate metallic glasses as surface layers. We have successfully synthesised metallic glasses by a range of ‘standard’ processing routes, but we have also proved that the production of thick amorphous layers by high power lasers is viable. We show that there are a number of factors effecting the final layer, but, given the right considerations and implementation, (even for a complex 6-element alloy, such as Cu_{47}Ti_{33}Zr_{11}Ni_{6}Sn_{2}Si_{1}), the resultant layers may be of a thickness that provides excellent opportunities to fabricate fully amorphous layers, on a material such as titanium, for tribological applications.

Thermo-mechanical properties of metallic glasses and shear band formation

A fascinating effect in metallic glasses is the formation of shear bands. As has been seen within this thesis, shear bands have played an important role in our investigations and we have witnessed deformation in metallic glasses in various guises. Since one of the main questions about shear bands is ‘are they connected with heat release?’ it is important to know what happens to a metallic glass upon heating. Firstly, to gain an insight into ‘fundamental’ aspects of what happens before shear band formation, various thermo-mechanical testing procedures have been utilised to initiate structural relaxation and visco-plastic behaviour in metallic glasses and to establish crystallisation in amorphous metallic alloys.
Summary

A comparative study between ‘free crystallisation’ and in-situ (TEM) heating has shown the crystal nucleation in Cu_{47}Ti_{34}Zr_{11}Ni_{8} to be limited by sample-thickness. Several microscopy techniques have been combined to provide an overview of some of the important features of shear band development and shear fracture of three metallic glass-forming compositions in the form of melt-spun ribbons. The analytical method involved in-situ TEM straining, combined with heating, followed by ex-situ (HR)TEM and ex-situ SEM observations. In-situ shear band propagation has been found to be “jump-like”. The secondary shear bands form a branch when the primary shear band stops and one of them will become the new primary shear band with the largest shear displacement, $\delta$. These jump sites act as a place where the primary shear plane is changed. This change can be a small correction, or may result in full alternation to an opposite plane of maximum shear stress.

Both TEM and SEM observations confirm the presence of a liquid-like layer on or near the fracture surface of the ribbons. The characteristic features of this layer include protruding veins and spheroidal drops which develop during the final separation. Estimations based on quantitative fractographic observations permit an evaluation of the thickness of the liquid-like layer formed due to heat evolution after shear band development. A model based on an assumption that a shear band acts as a planar source of heat has been used to estimate a maximum thickness of the liquid-like layer and its dependence on fracture parameters. Both experimental evaluation and model calculation confirmed that the thickness of a liquid-like layer present at the last moment of fracture substantially exceeds the generally accepted thickness of a shear band.

The probability of witnessing a crystal phase near the fracture surface is mainly dependent on the size of the shear displacement and a large number of parameters may influence the thickness of a liquid-like layer in the vicinity of a shear band at the moment of failure. These include the, the shear displacement, the glass transition temperature and local structural inhomogeneities that initiate meniscus instability, which may all lead to a variety of fracture mechanisms with characteristic fracture surface features. The latter explains why conflicting results appeared in the literature. From our results obtained it may be recommended to limit amorphous “features” within composite materials to $< 4 \, \mu m$ in order to avoid catastrophic fracture via meniscus instability.

Mechanical and tribological properties of metallic glasses

Shear bands are recognised by other form of mechanical testing as well. (Nano-) indentation hardness testing at low strain rates of metallic glasses is characterised by pop-ins, or steps in load-displacement curves (characteristic of a controllably developed shear band). The development of shear bands in metallic glasses has also been proven to be achieved by scratch testing. The hardness of amorphous laser-remelted layers has been found to be very high ($>700 \, H_{V0.2}$) and the indentation procedure has been seen to induce shear band formation,
which is characterised by ‘pop-ins’ in load-displacement curves. If crystals are added to the amorphous matrix, these are seen to act as deflecting obstacles to the shear band propagation. This has been shown to be particularly prevalent in the case of scratch testing. Scratch testing has also shown that the friction coefficients of amorphous metallic alloys may be as low as 0.05 for single pass scratch tests at 20 N.

Varying scratch speed, load and pass numbers are found to exhibit effects noticeable by application of the height-height correlation function. For example, varying scratch speed reveals that surface roughness attributed to shear band development, is reduced and so too the lateral correlation length (down to 0.38 at 20 mm/min from 0.6 at 1 mm/min). This implies that the increase in scratch speed increases the density of shear-bands. The latter relates well to classical theories as regards the effect of strain rates on inhomogeneous flow in metallic glasses.

The wear properties of the layers are also encouraging, with wear performance shown to be comparable to hardened 100Cr6 steel, and of the same order as some MMC layers tested under boundary lubrication conditions. Laser-clad coatings of gas-atomized glass forming alloy powders (NanoSteel) may be applied to mild steel substrates, with radical improvements attainable in both sliding (adhesive) and abrasive (3-body) wear compared to the substrate material. So much so in fact that for double-layer coatings, unlubricated sliding wear rates approach those of lubricated hardened steel.

A new method of characterising thick coatings has been introduced and we summarise that for this method (scratch profiling) to be meaningful depends on several factors:

1. the friction coefficient is greater than or equal to \( \frac{2}{\pi} \tan \beta \) where \( \beta \) is the indenter angle relative to the original surface
2. conversely, the Johnson parameter \( \Lambda \) is larger than 40
3. the pile-up (if present) is symmetric, or,
4. the indenter head is much larger than the grain size of the characterised material

Furthermore, we couple scratch profiling with orientation imagining microscopy (OIM) and it is clear that the use of OIM in scratch and indentation analysis is an interesting and novel method. Plastic deformation measured near the scratch by OIM investigation reveal that for conical indenter a value known as representative strain, \( \varepsilon_{\text{repr}} \) may be closer to 22% than 35% as generally considered.