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TOWARDS THE ROLE OF INTERFACIAL SHEAR IN SHOCK-INDUCED INTERMETALLIC REACTIONS

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Abstract. Shock-induced intermetallic reactions have previously been shown to occur on a nanosecond timescale, with the role of mass mixing processes driven by inter-facial shear at material interfaces suggested as a possible explanation. Experimental setups allowing the role of friction on these mechanisms to be considered are presented. Simulations show that the use of an impedance mismatch, shock driven experimental setup should allow sliding velocities of 50 - 100 m s⁻¹ to be attained with mechanical mixing the main reaction mechanism. A second setup utilising the oblique impact of small spherical projectiles upon a target plate is predicted to enable much higher sliding velocities of up to 2 Km s⁻¹ to be attained with thermally driven diffusion reaction mechanisms becoming dominant.

Keywords: Friction, mass mixing, intermetallic reaction

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INTRODUCTION

The reaction of intermetallic powders on a nanosecond timescale has previously been demonstrated, through the application of shock wave loading [1]. While reactions on longer, millisecond timescales can be readily explained through thermally driven diffusion an alternative mechanism is required to explain the shorter timescale of these reactions. Evidence for initiation at this timescale has previously relied upon continuum scale measurements, raising questions as to the specific micro and meso scale processes involved. The involvement of mechanical deformation and more specifically interparticle shear in driving mass mixing has been suggested as a possible explanation for the rapid initiation of these intermetallic reactions [2, 3].

The role of friction and shear in the development of these deformation processes can be further explored by considering single material interfaces. Two experiments have been designed to enable a wide

range of sliding velocities to be investigated, in the range 50 - 2000 m s⁻¹. Hydrodynamic simulations of these experiments have been performed, allowing the prediction of interfacial conditions generated, the results of which are presented here. While different conditions and mechanical processes are expected to be dominant as the sliding velocity is varied, shear is expected to maintain a significant role.

EXPERIMENTAL SETUP

To investigate shear effects at relatively low sliding velocities, between 50 and 100 m s⁻¹, we are expanding upon an experimental technique first pioneered by Juanicotena and since used by Winter et al. for research into dynamic friction [4, 5].

This experimental design revolves around a plate impact target consisting of a 12.5 mm diameter insert surrounded by a 50 mm diameter outer confining disc

FIGURE 1. (a) Friction disc target setup consisting of an aluminium insert surrounded by stainless steel with interfacial velocity measurements taken on the rear surface as marked. (b) Higher speed sliding setup - spherical projectile incident upon a tilted aluminium target plate.

of higher impedance material, as shown in Figure 1. Initial targets are designed to be 5 mm thick with an angle of 10 degrees made at the interface between the insert and outer disc, with a micrometre surface finish. An inert pairing of aluminium alloy 5083 and stainless steel 304 for the insert and confining disc respectively are modelled here, ensuring a relatively high impedance mismatch.

When subject to plate impact, interfacial shear is generated by differences in the mass velocities of the two materials, a consequence of this intrinsic impedance mismatch. This relative motion and subsequent frictional effects may be determined computationally by a set of velocity probes or experimentally by an equivalent line VISAR system focussed on the rear free surface as shown in Figure 1, providing both time and spatially resolved motion across the interfacial region.

To investigate the role of shear at much higher sliding velocities, between 1.0 and 2.0 km s^{-1} , the impact between small spherical metal projectiles and an angled aluminium surface will be considered. To allow experimental verification the projectile diameter has been set at 3.0 mm with an approximate target thickness of 8.0 mm selected to reduce the likelihood of plate penetration [6]. By varying the angle of incidence (AOI) measured from the normal as in Figure 1, the ratio of shear to contact pressure may be varied, allowing the role of interfacial shear on impact phenomena to be investigated. Simulations have been performed for oblique AOI between 60° and 70° from the normal in addition to perpendicular impacts to allow comparisons to be made. In addition to varying the AOI, simulations have also been

performed for different projectile materials including stainless steel, copper and titanium alloy Ti-6Al-4V. This has allowed us to consider the role of projectile material strength and melting point on the conditions generated along the contact interface.

Initial experimental validation has been provided through the use of high speed imaging and post-shot metallographic analysis, additionally allowing the role of interfacial melting and material transfer to be determined.

MODELLING AND DISCUSSION

Lower sliding velocities

For the experimental setup shown in Figure 1, simulations were performed for a 300 m s^{-1} plate impact using Ansys AUTODYN. An axially symmetric 2D Lagrangian mesh was utilised with 0.025 mm per unit cell spacing, verified by means of a grid resolution study to be consistently resolved over the initial $2.5 \mu\text{s}$ of interest. Standard equation of state data and Steinberg-Guinan material models were used for all components with the exception of the aluminium 5083 insert where the properties of aluminium 6061-T6 were instead used with a lower yield strength of 0.2 GPa . Gauges were attached to the rear free surface to provide a measure of the velocity and shear profile at the material interface as well as providing an insight into the experimental data obtainable through analogous line VISAR diagnostics.

Results from these models suggest interfacial sliding velocities of the order $75\text{--}100 \text{ m s}^{-1}$ are generated for up to $1.5 \mu\text{s}$ as a result of different particle velocities in the two materials. This is then seen to increase to 250 m s^{-1} relative motion upon release from the rear free surface before separation of the contact faces begins to occur at $2.5 \mu\text{s}$, marking the end of the sliding contact.

Simulated rear free surface velocity profiles immediately following shock wave break out at this surface are shown in Figure 2. Spatial velocity response across a 2.0 mm region either side of the material interface is plotted with the left hand side of the Figure corresponding to the lower impedance aluminium insert and on the right, the outer stainless steel disc. Results for both frictionless and high friction conditions are shown in green and blue respectively. With

FIGURE 2. Friction disc velocity traces, 1.0 mm either side of interface for a frictionless (a) and high friction condition (b).

increased friction coefficient the relative motion of the two components can be seen to decrease significantly, with a 50 m s^{-1} decrease in relative motion in the case shown. Additionally, spatial variations in the velocity profile are indicative of a region of shear developing in the softer aluminium material, approximately 0.3 mm in magnitude.

From previous experimental research in this area the actual interfacial behaviour is expected to be dynamic with the measured velocity profiles falling between the two extremes shown in Figure 2 [5]. It has been suggested that this dynamic behaviour is due to thermal softening processes occurring in the interfacial region due to the high temperatures generated, in excess of 350 K from our models. Recent analysis of final state deformation at aluminium - stainless steel sliding interfaces has suggested the formation of regions of deep and shallow deformation alongside each other, of millimetre and micrometre order respectively [7]. The presence of regions of highly elongated shallow deformation can likely be attributed to thermal softening, allowing sub-surface sliding to occur in the aluminium in addition to any relative motion at the material interface.

While it is acknowledged that continued experimental investigation will be required to enable further conclusions to be drawn as to the magnitude and spatial scale of any frictional and shear processes, the models presented here demonstrate the ability to resolve these properties experimentally using available line VISAR diagnostics. Additionally, temperatures obtained in the interfacial region are predicted to be significant in terms of thermal softening processes, lowering material strength in this region.

Higher sliding velocities

To consider the implications of much higher relative sliding velocities, in the $1.0 - 2.0 \text{ km s}^{-1}$ range, simulations were also performed using a second setup, as described previously. These were modelled in Ansys AUTODYN, utilising a spherical particle hydrodynamic (SPH) mesh to account for the high levels of plastic deformation. Standard equation of state and Steinberg - Guinan strength models were again utilised with the exception of aluminium alloy 5083 where modified 6061-T6 data was substituted as previously described.

As well as varying the AOI a range of projectile materials were also modelled, allowing the role of material strength and melting point to be considered. These included 3.0 mm diameter AISI 304 stainless steel, copper and Ti-6Al-4V projectiles, incident upon an aluminium 5083 target plate. A subset of these results are presented in Figure 3, including a normally incident stainless steel projectile on the left and a copper projectile incident at 60° on the right. Normally incident projectiles such as that in Figure 3 were modelled in 2D with axial symmetry and an SPH particle size of 0.05 mm. Projectiles incident at oblique angles of incidence were instead modelled in 3D with an SPH particle size of 0.20 mm to take into account the reduced symmetry of the problem.

To provide validation and further insight into the processes occurring experiments were performed using identical setups to the models shown in Figure 3, allowing comparisons to be drawn in terms of angles of ejecta and final state crater dimensions. For the normal AOI example shown in Figure 3 experimental results showed the formation of a $4.4 \pm 0.5 \text{ mm}$ diameter crater and $37 \pm 3^\circ$ angle of ejecta from the normal. This is in agreement with modelled predictions of 4.8 mm and $40 \pm 3^\circ$ respectively. Similarly for the oblique copper impact with 60° AOI, predictions of crater depth and ejecta angles of $4.2 \pm 0.5 \text{ mm}$ and $40 \pm 7^\circ$ respectively are again in close agreement to those predicted at 4.0 mm and $40 \pm 5^\circ$. While this provides an effective validation for the overall physical processes modelled it is acknowledged that certain finer scale features and temperature resolution in regions of high deformation may be limited by the available resolution.

From the range of simulations performed similar impact behaviour was observed for all three projectile materials with smaller, shallower craters formed

FIGURE 3. SPH simulations of 3mm stainless steel and copper projectiles incident upon an aluminium 5083 target plate at normal and 60° AOI respectively at 1, 4 and 12 μ s. For 12 μ s time step model shown as a crater cross section.

in the case of titanium due to its lower density and reduced ejecta evident for copper, likely due to its greater ductility. For a 60° AOI such as that for copper in Figure 3, deep, steep sided impact craters were observed to be formed with large quantities of plate material ejected. At an increased (more oblique) AOI of 75° models instead suggest the formation of a much shallower crater with significantly less aluminium plate material ejected. Increased sliding contact between the projectile and target plate surfaces is expected as a result of this, as opposed to the material penetration and removal seen for lower AOI, potentially making less oblique impacts more suited to the study of reactive shear processes.

Models additionally predict the generation of high interfacial temperatures during these processes, approaching and potentially in excess of material melting points. This prediction is further validated by ini-

tial metallography performed on experimental samples, showing signs of extremely smoothed, potentially re-solidified surface material. Thermal softening and melting in the interfacial region can therefore be expected, increasing the likelihood of diffusion driven as opposed to mechanical mass mixing processes.

SUMMARY

Simulations have been performed on experimental setups designed to allow the investigation of friction and interfacial shear at sliding material interfaces. The first of these should allow 50 - 100 m s⁻¹ sliding velocities to be attained over microsecond timescales with the role of friction able to be determined through the use of spatial rear surface velocity diagnostics. Using a separate setup, sliding velocities of the order 2 km s⁻¹ have been shown to be attainable, with thermal processes expected to allow diffusion driven mass mixing in addition to mechanical processes.

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