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Spatially resolved shock response at dry metallic multi-material interfaces

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Abstract. The high strain-rate behaviour of multi-component systems is often dominated by mediation at material interfaces. The extent to which a materials microstructure influences dynamic friction and relative sliding response remains an area of active study. Initial results from a study on the behaviour of dry metallic interfaces under the passage of a controlled loading wave are presented. Held in close contact along a single planar interface, oblique shock waves were generated along the boundary by direct copper flyer impact at velocities in the range $250\,\mathrm{m\,s^{-1}}$ - $300\,\mathrm{m\,s^{-1}}$. Both the 100 mm and 13 mm bore gas guns located at Imperial College London were utilised for this purpose. A line-imaging velocity interferometer system for any reflector (VISAR) system was used to directly record the velocity profile across the contact interface, providing a measure of any spatially dependent response while photon doppler velocimetry (PDV) was used to determine the far field response. Comparisons of these results against current generation hydrocode models are presented, with significant deviations from the computationally predicted results identified in the peak shock state immediately following shock breakout.

1. Introduction

The dynamic response of multi-component systems is an active area of current research with a particular focus on the role of material interfaces under high strain-rate loading [1–3]. Existing research has been suggestive of the dominant role of friction limited by material yielding, especially when applied to dissimilar dry metallic interfaces of interest to this study [3]. Such work has however to date been limited by the use of either time resolved point velocimetry or spatially resolved final state deformation analysis [3]. A new experimental setup is presented here utilising a velocity interferometer system for any reflector (VISAR) diagnostic focussed across a single contact interface, uniquely allowing the inhomogenous dynamic response in the direct vicinity of a material interface to be determined via spatial velocimetry measurements. Utilising this technique initial results are presented for stainless steel - aluminium pairings orientated with the interface parallel to the direction of loading. Relative sliding velocities of approximately $100\,\mathrm{m\,s^{-1}}$ were able to be generated by means of the differing shock impedances and therefore particle velocities of the two materials when impacted, in a technique pioneered by Juonicotena *et al.* [4].

2. Experimental setup

In order to investigate the dynamic response of dissimilar material interfaces during shock loading, experimental setups consisting of aluminium and stainless steel components held in

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close contact and forming a planar contact interface parallel to the direction of the incident shock wave were utilised. The two setups used are given in figures 1 (setup A) and 2 (setup B), with loading provided in each case by a light gas gun driven copper flyer plate. As can be seen the two setups are similar in design although of differing scales, the smaller of these 3 mm thick and impacted over a 12.7 mm diameter compared to the larger 15 mm thick, 100 mm diameter target in setups A and B respectively. This range of length scales allowed experiments to take advantage of both extended measurement timescales and a faster repetition rate for the large and small bore designs respectively.

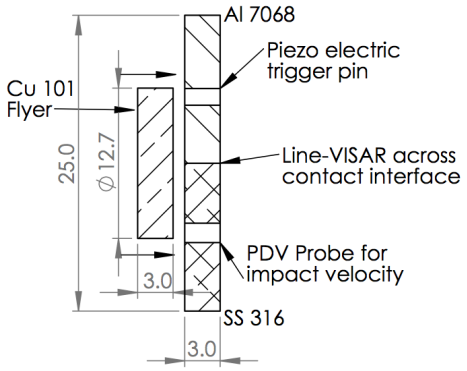


Figure 1. Setup A: Multi-material aluminium - stainless steel experimental target setup used on a 13 mm bore light gas gun.

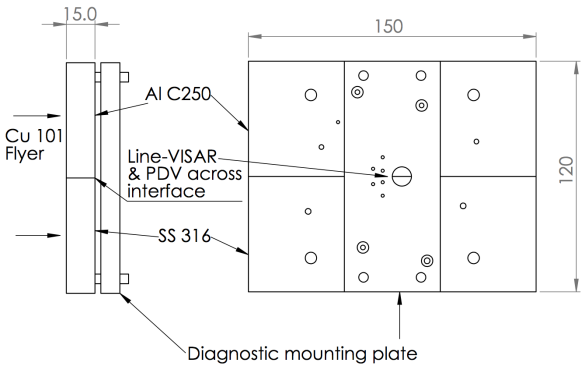


Figure 2. Setup B: Multi-material aluminium - stainless steel experimental target setup used on a 100 mm bore light gas gun.

Given the importance of the contact interfaces between the dissimilar materials to this research, particular care was taken in their preparation to ensure that they remained both consistent and well characterised throughout the setup and assembly of the associated targets. Towards achieving this the mating surfaces that form the contact interfaces between the target components were lapped as a pair until determined to be flat to <0.6 µm as determined by optical interferometry. As a result it is anticipated that the maximum gap size in the final assembled paired interfaces was less than the sum of the deviation in each component at <1.2 µm. Once assembled the individual components were affixed using two bolts, each located in the far field in order to have minimal influence on the region of interest over the measurement timescale. The setup was designed such that the normal force generated between the components by the fixing bolts was insignificant compared to that generated by the passage of the incident shock front. Assembled targets were again lapped to ensure impact and measurement surfaces were flat and parallel to within 2.0 µm and 10.0 µm respectively.

The specific material pairing of stainless steel and aluminium chosen for these experiments was selected for their intrinsic properties, notably the large impedance mismatch between the two materials while maintaining similar shock velocities. As a result a particle velocity differential is generated across the contact interface upon impact causing sliding and relative motion while still maintaining a near simultaneous breakout time at the rear surface of the two target components. Using this technique for a typical 300 m s^{-1} copper flyer plate impact a particle velocity differential of 100 m s^{-1} was able to be generated.

In order to make quantitive measurements of the dynamic response across the multi-material interfaces of interest to this research, line-imaging VISAR, as developed by Barker and Hemsing *et al.* was used as the primary diagnostic in both experimental setups [5,6]. Line-imaging VISAR was selected for its capability to provide spatially resolved velocimetry data over a 1D region, in

this case across the contact interface of interest on the rear surface of the target. Imaged regions of 1 mm and 3 mm were used for setups A and B respectively, allowing measurements to be taken over a spatial scale most appropriate for the target size. For each experiment the target was illuminated by a 2 W CW laser at 532 nm, imaged through a Mach-Zehnder interferometer with a 150 mm UV fused silica glass etalon used to time delay a single leg, in a configuration pioneered by Celliers *et al.* [7]. The resultant interference pattern, dependent upon the acceleration of the target surface was then recorded on a streak camera and associated CCD, with a 100 µm slit width and a time window of 3.8 µs.

In setup B six upshifted photon doppler velocimetry (PDV) channels were additionally used to provide rear surface velocimetry measurements in the far field, symmetrically positioned 3, 5 and 10 mm either side of the contact interface, complementing the data provided by the VISAR diagnostic. In each case a single PDV channel was also used in order to accurately determine the flyer impact velocity while piezo electric pins were used in each setup to trigger the diagnostics and additionally provide a record of the incident flyer tilt in the case of setup B.

3. Results and data interpretation

Initial velocimetry data has been captured across multi-material interfaces subject to shock loading, utilising the two experimental setups described in section 2. Results from the primary diagnostic, line-imaging VISAR, obtained for a stainless steel 316 - aluminium 7068 pairing using the setup described in figure 1 are presented in figure 3 in their captured form as an interference pattern. In the figure the horizontal axis represents time and the vertical axis spatial position, spanning 3.8 µs and 1.0 mm respectively. Shifts in the interference pattern, or fringes represent changes in velocity, with a full phase shift equal to 330 $\mathrm{m\,s^{-1}}$ as defined by the effective length and refractive index of the delay etalon used.

Figure 4 provides an interpreted velocity profile from this data, with analysis performed using a Fourier transform based method first developed by Takeda *et al.* [8]. Using this technique the phase information embedded within the interferogram was extracted and unwrapped to form the basis of the velocity profile displayed in figure 4. As anticipated, in both the raw data and the interpreted velocity profile a clear velocity differential between the two materials can be seen to be present following shock breakout with initial peak velocities of 194 $\mathrm{m\,s^{-1}}$ and 397 $\mathrm{m\,s^{-1}}$ for the stainless steel and aluminium components respectively for a 293.7 $\mathrm{m\,s^{-1}}$ copper flyer plate impact.

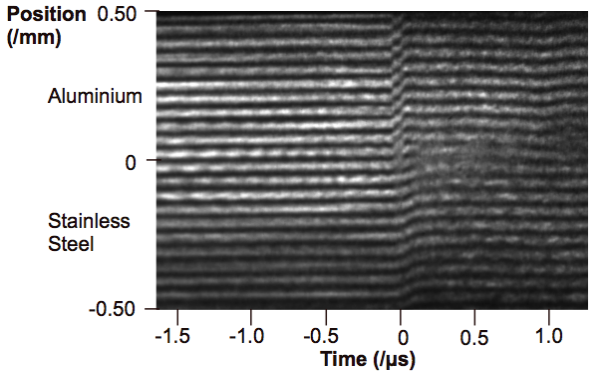


Figure 3. Raw line-VISAR interference pattern for multi-material setup shown in figure 1.

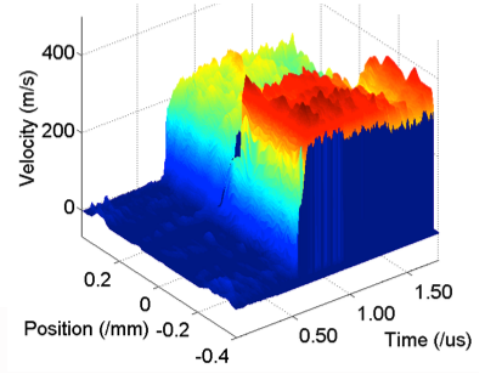


Figure 4. Resolved velocity profile from line-VISAR diagnostic for multi-material setup shown in figure 1.

To facilitate further data interpretation and comparison, two dimensional Lagrangian

simulations were performed using the Abaqus hydrocode. Johnson Cook strength models were implemented for each material and a frictionless condition initially assumed at the contact interface. Following a mesh sensitivity test a cell size of 10 µm was selected as optimal for the setup in question and used for the simulated results shown. The experimental results captured are plotted against these simulations for points 0.20 mm either side of the contact interface between the two materials as shown in figure 5. In this figure the experimental data is shown in red and the numerical simulations in blue for both the stainless steel and aluminium components.

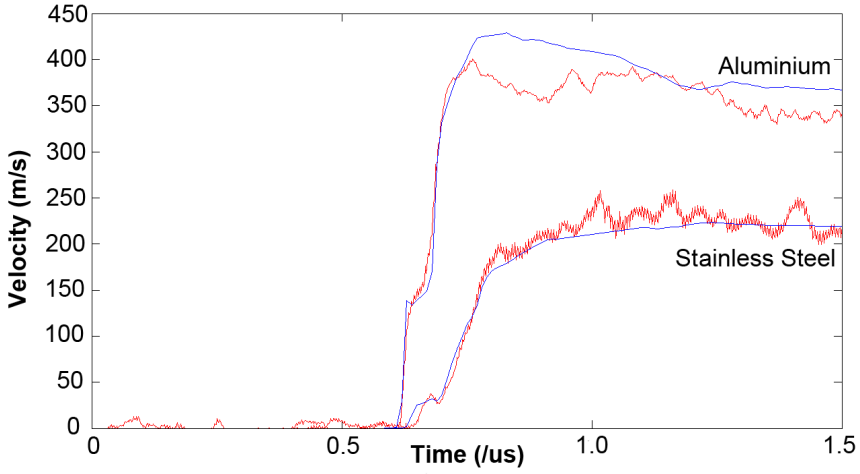


Figure 5. Experimentally determined velocity profiles taken 0.20 mm either side of the contact interface (red), plotted against simulated data using the Abaqus hydrocode (blue).

It can be seen from figure 5 that the numerical and experimental data is in close agreement during the initial elastic and shock breakout region in both materials as well as the later time behaviour in the stainless steel component. There is however a significant discrepancy between the predicted and actual peak velocity state for the aluminium 7068 component, with the experimental results being approximately 25 m s^{-1} below the predicted value of 421 m s^{-1} followed by a steeper than anticipated decrease in the velocity profile with respect to time.

Several factors have been identified as potentially contributing to such a discrepancy in the velocity profile, including frictional forces between the target components and the generation of release waves, emanating from the material interface as the shock wave travels along its length. Such physical features could however be expected to be reciprocal in each of the two target components, limiting the likelihood that these factors are responsible. Analytic reasons including inaccuracies in the numerical models and ambiguity in the phase shifts present in the captured interferogram due to intensity fluctuations could also possibly be the source. Of these, initial validation of the material properties is suggestive of the accuracy of the computational models used while phase shifts in the region surrounding that plotted in figure 5 were found to be consistent. While minimised, perturbations introduced as a result of the necessary analysis performed cannot be excluded however and quantifying these uncertainties is a continuing area of interest.

Further insight into the origin of these results is provided by experiments performed using the larger scale setup described in figure 2, with the captured line-imaging VISAR data for this setup presented in figure 6(a). Most notably significant deviations corresponding to transverse waves generated at the contact interface between the two materials can be seen to be present. The positions of these are clarified with an overlay given in figure 6(b) with the red lines representing

the breakout at the rear surface of the shock fronts and associated elastic precursors. In contrast the white lines mark transverse waves originating from the material interface, either in release or in re-shocking the material. These transverse waves can be seen to be significant in determining the velocity profile in the region surrounding the contact interface, emanating outward and can additionally be identified as a potential source of the deviation in the velocity profile shown in figure 5. Such features however appear to originate from the portions of the shock front reflected and/ or transmitted across the contact interface, which would be expected to re-shock rather than result in a decreasing velocity as observed in the VISAR trace given in figure 5.

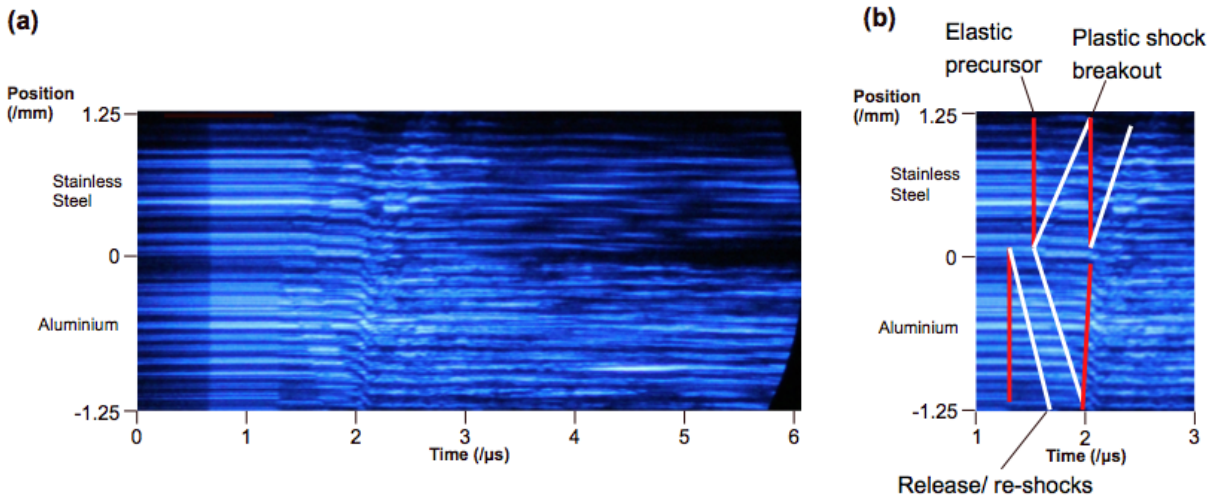


Figure 6. (a): Captured line-imaging VISAR interferogram across the interface of the multi-material setup shown in figure 2. (b): Portion of original interference pattern, marked to emphasise the key features including the breakout of the elastic and plastic shock fronts in red and the presence of release and/ or reflections originating at the contact interface in blue.

4. Conclusions

Initial experiments have been performed towards determining the dynamic response of stainless steel and aluminium contact interfaces to shock loading. Uniquely, line-imaging VISAR was utilised to provide both spatially and time resolved velocimetry over a 1D region across the contact region. Initial results suggest a significantly lower free surface velocity in the aluminium component following shock breakout than that predicted by hydrocode simulations. Further experiments are planned in order to determine the source of this discrepancy.

5. Further work

Following the successful demonstration of the experimental setups described, this work will be extended to study different material pairings, most notably aluminium alloys of varying strengths and compositions. This will allow the role of the intrinsic material properties on the shock response at contact interfaces to be considered. In addition, experiments will be performed over a range of flyer impact velocities between $100\,\mathrm{m\,s^{-1}}$ and $300\,\mathrm{m\,s^{-1}}$ with variable interface angles relative to the incident shock front to consider the role of relative sliding velocities and normal force respectively.

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