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3-D Finite Element Modelling of Water Jet Spot Welding

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Abstract— **A 3-D finite element model is used to simulate water jet spot welding. The simulation is validated using the experimental data obtained by one of authors with other workers. The simulations identify parameters which correlate well with the quality of the welds produced. In particular the levels of equivalent plastic strain (PEEQ) and shear stress directions are shown to predict whether or not two materials will weld well together.**

Index Terms— **water jet, spot welding, high velocity impact, numerical modelling, experimental test**

I. INTRODUCTION

Numerous experimental studies have been performed to investigate water jet spot welding [1-3]. In parallel with these studies some attempts have also been made to mathematically analyse the process [2]. The experimental data indicated that the central region of the impact area did not weld and that the surrounding welded area was dependant on the formation of radially diverging jets of metal from the two impacting surfaces. The welded areas were generally characterized by wavy and plain interfaces, the regions with the wavy structure generally being more strongly welded [4]. In the case of welding by a slug of water jet, Salem and A1-Hassani [1] found that the amplitudes and lengths of waves increase monotonically with radial distance from the centre of impact. Later Turgutlu et al [5] suggested that the wavy interface increases the area of intimate contact and enhances interlock between the two metal surfaces thereby forming a strongly bonded area.

This paper uses the experimental data of Al-Hassani, Salem and Turgutlu to validate a new 3-D finite element model. The model is used to identify and predict the value of parameters which can be used as welding criteria.

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II. EXPERIMENTAL ARRANGEMENT USED BY AL-HASSANI e*t al.*

The water jet spot welding tests were preformed using a water jet gun consisting of a water chamber and a nozzle with a 4.2mm diameter. The water was accelerated using a cartridge operated commercial stud driver. 50x50x1mm polished aluminium cladding plates and 10 mm thick aluminium targets were used in the experiments. The average hardness of the aluminium was 110 kg/mm^2. Fig. 1 shows the water jet gun and a spot welded specimen. A range of separation distances between target and flyer plate was used in the tests. The velocity of the water jet (typically between 650-1200m/s) was measured using high-speed photography. The specimens were sectioned along a line through the centre of the welded region, and exposed surfaces were examined using an optical microscope. The experimental test also was repeated for copper and brass specimens. Only aluminium specimens were considered for further investigation of this paper.

III. EXPERIMENTAL RESULTS [1, 2]

A. Boundary Zone

The surfaces of the sectioned specimens were polished and etched to show the structure of the interface zone. In general the interfaces were either straight or wavy with small amplitude displacements (Fig. 2). The central part and the edges of the plates remained un-bonded.

The change in the shape of the interface along a radial from the centre of the weld is probably due to the varying obliquity of the collision between the bulge in the flyer and the target which occurs because of the continuously changing impact angle and velocity (for a given water jet velocity and standoff distance). It should be noted that as the angle of collision between the bulge and the target is small at the early stages of impact (in fact it is zero at the moment of first collision), the jetting action cannot take place before a critical angle is exceeded, hence a central un-welded region results. The existence of a central plane weld interface, which is observed in many cases next to the wavy zones (Fig. 2), is believed to be a form of pressure welding rather than an oblique collision welding.

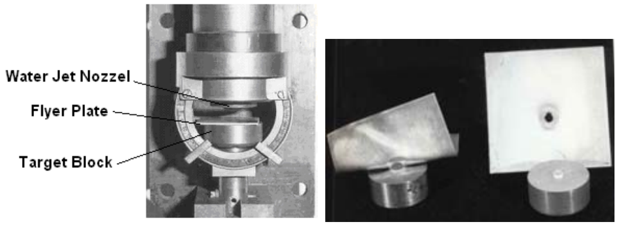


Fig. 1. Water jet gun (left) and spot welded specimens (right)

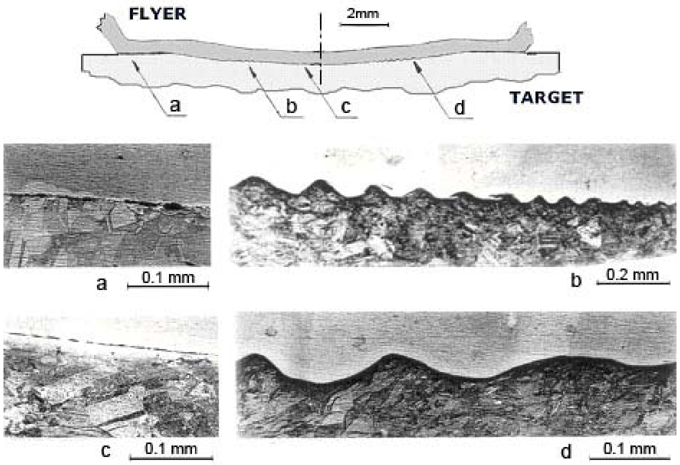
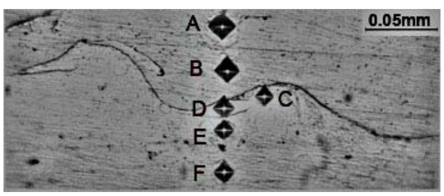


Fig. 2. Weld interface in water jet spot welding and wavy zones



Microhardness (kg/mm^2)	
A	128 (Copper)
B	141 (Copper)
C	238 (Brass)
D	187 (Mix)
E	221 (Brass)
F	221 (Brass)

Fig. 3. Microhardness readings taken from wavy zone in spot welding of copper flyer to brass target

Microhardness measurements showed that hardness values reached a maximum at the tip of the interface waves and as a consequence the tip of a wave crest near the centre was seen to be occasionally broken off. The average level of hardness at the vortex was found to be slightly less than the original materials. Fig. 3 shows microhardness readings taken from a wavy zone in a copper flyer/brass target weld. The original hardness values were 128 kg/mm^2 and 221 kg/mm^2 respectively.

B. Standoff Distance

The effect of varying standoff on the interface characteristics was investigated in previous experimental studies [5]. It was shown that the position of initial bounding and where perforation occurs were both affected by standoff distance. It was found that the flyer plate perforated beyond limitation of standoff, with a solid phase weld spot deposited on the target and the perforation of the flyer occurred when the standoff exceeded a certain distance. As an example a copper flyer with 0.89mm thickness, at large stand off distances, i.e. greater than 1.85mm perforation of the flyer plate occurred. The central un-welded region started to shrink and then tended to disappear as standoff distance increased. As standoff distance decreased a threshold was reached where welding did not take place. Furthermore, it was found that the diameter of the effective spot weld increased with increasing standoff.

C. Mushrooming, Bulging and Wave Pattern

The left hand side of Fig. 4 shows a sequence of high speed photographs taken as the water jet emerges from the nozzle. It can be seen that the water jet mushrooms as it leaves the nozzle.

It is clear that the impact of the water jet on the thin plates causes bulging, stretching and bending. At larger standoff distances the greater the stretching, and hence thinning before impact. The middle picture of Fig. 4 shows a flyer plate bulging prior to impact.

The wave pattern in the contact zone can be seen in the right hand side of Fig. 4. The wave starts from the centre with small amplitude and progresses to the corners of the plate with larger amplitude.

IV. COMPUTATION SIMULATION

Computer simulation of a flyer plate impacting onto a target was performed using the Abaqus finite element code. The numerical simulation mimics the experimental arrangement shown in Fig. 5. The flyer and target plate were modeled using a very large number (>150000) of tetrahedral elements, with three displacement degrees of freedom per node each capable of large deformation. The element mesh was locally modified to increase the number of elements close to the contact surface (see Fig. 6) to obtain the very fine localized element meshes required in the regions where the largest deformations occur [6].

The flyer was modelled as a nonlinear elasto-plastic flexible plate capable of arbitrarily large displacement (Fig. 6a). The flyer was positioned parallel above the target (Fig. 6b).

The water jet was modelled using the equations of state (EOS) embedded in Abaqus/Explicit [7]. The EOS defines the material's volumetric strength and determines the pressure as a function of the density. Note that it can be used to model a material that has only volumetric strength (the material is assumed to have no shear strength) or a material that also has isotropic elastic or Newtonian viscous deviatoric behaviour. Water was defined as a viscose fluid composed of large cubic elements (Fig. 6c). The distortion of elements was controlled in the finite element programme [7].

The progression of a stress wave on the contact surface of the flyer plate (at an impact velocity of 850m/s) is shown in Fig. 7. It can be seen that the waves starts from the centre and progress to the corners of the plate.

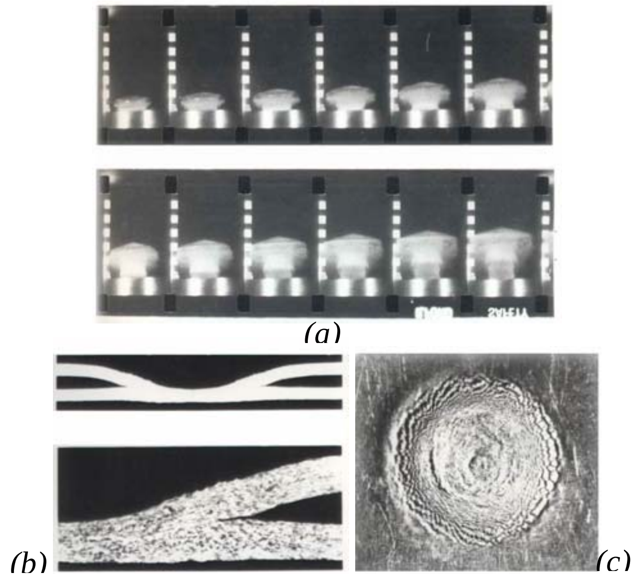


Fig. 4. High speed photograph of water injection *(a)*, bulging *(b)* and wave pattern of welded specimen *(c)*

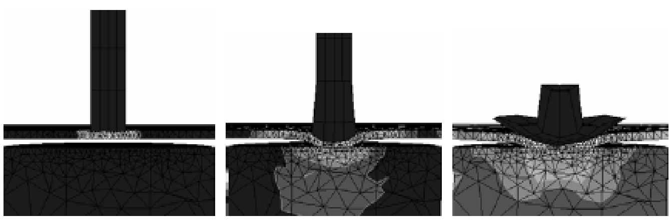


Fig. 5. Three stage in the finite element simulation of water jet spot welding

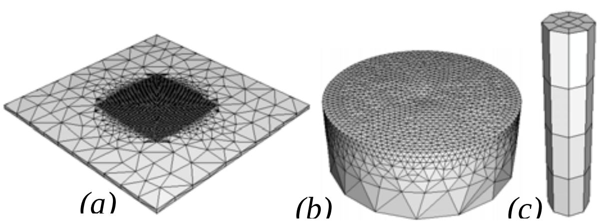


Fig. 6. Computer modeling of flyer plate *(a)* and target *(b)* using C3D4 element type and water *(c)* using C3D8R element type

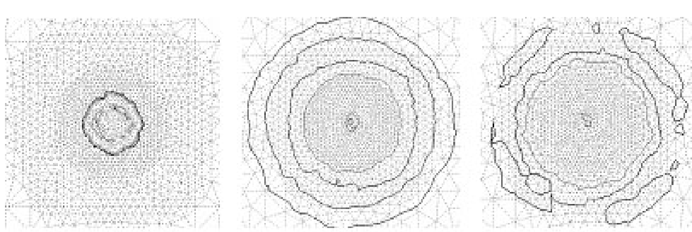


Fig. 7. Stress wave pattern in the flyer plate during the welding process. The circles signify propagation of the stress wave through three stages of impacting of the high speed water jet on the flyer plate.

V. SIMULATION RESULTS

The upper section of Fig. 8 depicts symmetric XY positions of the water's front during the computer simulation. It shows that the water front is mushroomed during the spot welding process. The lower part of Fig. 8 shows the velocity of a selected node in the water jet.

It was noticed found that the bulge in the flyer plate becomes spherical immediately after the primary impact. The central deflection of the bulge then continues to increase from zero before impact to a maximum value equal to the standoff distance. The diameter of the bulge gradually decreases with time until the bulge contacts the target.

Fig. 9 shows the bulge progress and thinning in the flyer plate. It shows normal displacement of the flyer plate. The deformation of the flyer plate stops when the flyer and target contact and join together. In cases where the standoff distance is large the flyer plate perforates.

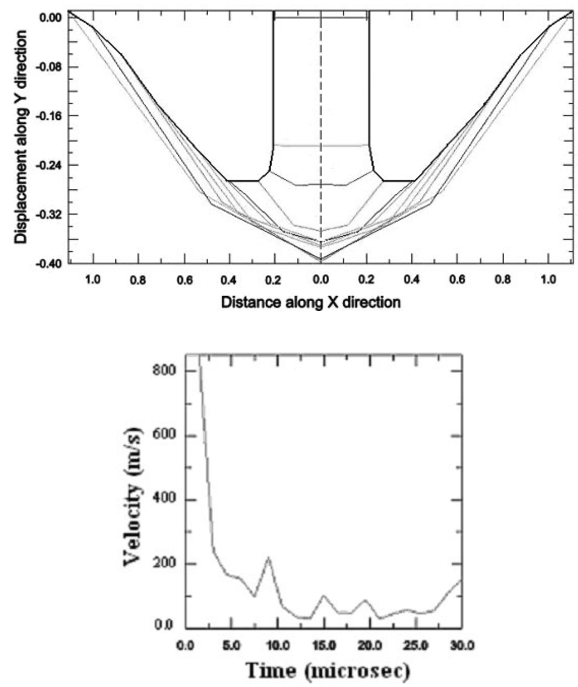


Fig. 8. The numerical profile of the front of the water jet (top) and the velocity of a selected node from water (bottom)

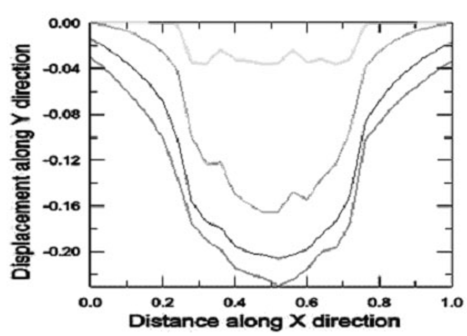


Fig. 9. Graph of displacement (Y direction is normal to the flyer plate) against distance during bulge progress.

VI. WELDING CRITERIA

The values of the two parameters, equivalent plastic strain (PEEQ) at high strain rate and shear stress at the collision point reported in a previous study [8] as being a measure of the quality of welding were examined closely in the simulations. These parameters are plotted for contact face elements in the target and flyer plate in Fig. 10. The results show that the points where the values of PEEQ in the flyer and target are both above thresholds of about 0.7 and 0.6 respectively correspond to regions of good welding. At locations where the values of PEEQ fall below these thresholds no bonding occurs.

A comparison of the values of shear stress at various points on the contact surface of the flyer and target with the experimental results indicates a threshold of about $0.4\text{x}10^{-3}$ for good welding. The shear stress at two selected facing points is shown as a function of time in Fig. 10. This figure also shows that where the shear stress on the two colliding plates at the contact point were in opposite directions the bonding was good but where they were in the same direction bonding proved to be poor.

The un-welded centre can be identified in the PEEQ and shear stress diagrams. For the un-welded zone the PEEQ is less than the nominal threshold and the shear stress does not show any reversal of sign in flyer and target at impact.

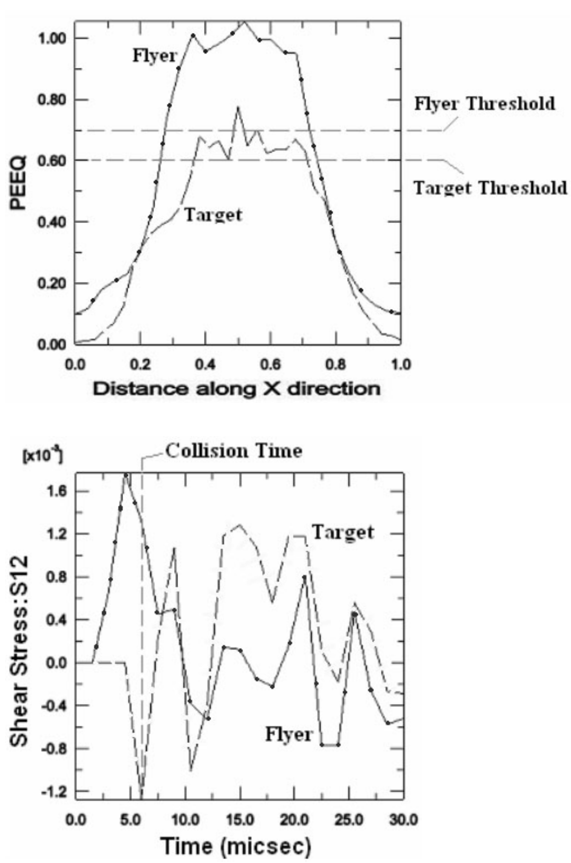


Fig. 10- Welded region- PEEQ against distance (top) and shear stress (S12) in selected elements against time (bottom) on impact velocity=850m/s

VII. CONCLUSIONS

Water jet spot welding has been simulated using a 3-D finite element code. The simulation results show good agreement with previously reported experimental data.

The results from the simulation indicate a link between the predicted values of certain physical parameters and the likelihood of bonding. The two parameters most useful as welding criteria are PEEQ and shear stress. PEEQ values above a threshold of about 0.7 in the flyer and 0.6 in the target appear to be necessary for good bonding (for HS30 aluminium).

Levels of shear stress in the two colliding plates above a threshold value of about $0.4\text{x}10^{-3}$ at the collision point also appears to be necessary for bonding.

Where bonding occurs the directions of shear stress on the two plates, at the contact point are in opposition. In non-bonded regions the shear stresses in the two colliding metals are predicted to be in the same direction.

The Equation of state (EOS) for water in Abaqus/Explicit appears to be applicable to high velocity water jets.

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