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EXPLOSIVE WELDING SIMULATION OF MULTILAYER TUBES

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Summary. *Explosive welding is a process which uses explosive detonation to propel the flyer plate material into the base material to produce a sound joint. Experimental tests have been performed to explosively welded aluminum 5056, aluminum 1015 and stainless steel 304 tubes in one step. The tests have been carried out using various stand-off distances and explosive ratios. Various interface geometries have been obtained from these experiments.*

In this study, all the experiments carried out were simulated using the finite element method. The Williamsburg equations of state were used to describe the behavior of explosive. The Williamsburg equations of state have been previously developed for low explosive mixture. These equations were coded into the FEM software. The Johnson-Cook constitutive equations were used to model the behavior of tubes. The Williamsburg equation of state parameters and Johnson-Cook constitutive equations constants were obtained by experiments.

Most aspects of the explosive welding parameters were properly simulated. The flyer plate and collision velocities obtained from the analysis were validated by the pin-measurement experiments. The numerical results showed that very high localized plastic deformation produced at the bond interface. The temperature at the interface just after impact was predicted to be lower than the melting temperature of both materials, but high enough for phase changes to occur, i. e. similar to what happens in tempering or martensetic formation in steels. This temperature increase is of very short duration and drops after the impact.

1 INTRODUCTION

Explosive welding is an area of study that represents a truly multidisciplinary research as it deals with the dynamics of collision at high velocities and pressures, the transient fluid like behavior of metals at extremely high strain rates, metallurgical and other physical aspects of colliding metals, modeling of material behavior, sources of high rate energy and the geometrical parameters of colliding system of metals.

To analyze the process, the hydrodynamic analogy were used by various authors[1,2,3] due to the creation of the high localized pressure and the material fluid like behavior at the collision zone. The process parameters are the impact velocity, the collision point velocity, the dynamic angle, the stand-off distance, the type of the explosive used and the detonation velocity, density and size and distributions of the explosive mix. Welding windows were proponed to show the weldability ranges of process parameters i.e. impact velocity (or collision point velocity) versus the dynamic angle for various materials[3,4,5,6]. Nevertheless, the data were obtained by means of large number of experiments performed. However, the process could be simulated using the finite element method and most aspects of the welding process could be obtained. Few attempts have been reported in the literature to simulate the process. Al-Hassani[7] treated the problem as a normal transient loading of plane stress elements of rectangular shape. In this analysis, kinematically equivalent concentrated loads at the nodes represented the uniformly distributed explosive load. Explosive welding process was simulated by Oberg[8] by means of Lagrangian finite difference computer code, but only produced jetting. The explosive welding process was also modeled by Akihisa[9]. He only produced waves but no jetting. In addition, the author assumed that symmetric or asymmetric shear flow distribution was generated in the flyer and parent plates and the modeling was performed based on this supposition. Akbari mousavi[10] modeled the explosive welding of the plates and produced waves and jetting.

No attempts have been made in the literature to analyze the explosive welding of multilayer tubes. This matter would be presented in this paper.

2 GENERAL SPECIFICATIONS

Experimental tests have been performed to explosively welded aluminum 5056, aluminum 1015 and stainless steel 304 tubes in one step. The welded tubes had an external diameter of 135mm and internal diameter of 113mm. The outer layer was made of 304-stainless steel, with the external diameter of 135 and thickness of 4.5mm. The middle tube was made of Al-1015 and its thickness was 1.5mm. The inner tube was made of Al-5056 with 5mm thickness. The tests have been carried out using various stand-off distances and explosive ratios. Various interface geometries have been obtained from these experiments. The explosive material was positioned inside the inner tube.

In this study, all the experiments were simulated using the finite element method. The Williamsburg equations of state were used to describe the behavior of explosive. The Williamsburg equations of state have been previously developed for low explosive mixture[10]. The explosive properties used were tabulated in Table 1. These equations were coded into the FEM software. The Johnson-Cook constitutive equations were used to model the behavior of tubes. The Johnson-Cook equations were described as:

$$s = (A + Be^{n})(1 + C\ln\dot{e}_{p})(1 - T^{*m}) \qquad (1)$$

Where e is equivalent plastic strain, $\dot{e}_{p}$ is plastic strain rate for $\dot{e}_{0} = 1\ \mathrm{s}^{-1}$, $T^{*} = \frac{T - T_{room}}{T_{melt} - T_{room}}$ that T is absolute temperature for $0 \le T^{*} \le 1$ and A, B, C, n, m are constants. Constants in this equations is obtained from simple mechanical tests such as isothermal tension and torsion tests, that is given in Table 2 for the materials used in this study.

Hexagonal elements were used in the simulations with the adaptive meshing techniques. ALE formulations were used to model the explosive and materials. The proper contact mechanisms were used between the tubes and the explosive materials.

Material	*A, MPa*	*B MPa*	*C*	*N*	*m*
Stainless steel	310	350	0.02	0.3	0.5
6061 aluminum alloy	275	500	0.02	0.3	1
5056 aluminum alloy	265	426	0.015	0.34	1

Table 1: The Johnson-Cook equations parameters for the materials used

Explosive material	*Density, kg/m^3*	*Detonation velocity, m/s*	*Detonation energy, MJ/Kg*	*Volume CJ, Cm^3/gr*
Anfo Silica	0.85	2500	3500	0.78

Table 2: The physical properties of the explosive use

3 RESULTS AND DISCUSSIONS

The effects of process parameters (stand-off distances and explosive ratios) on the physical parameters such as pressure, plastic strain, shear stress, impact velocity, dynamic angle and temperature at the collision zone were investigated. Typical simulation of the process at an elapsed time of 30μs for the stand-off distance of 2.5mm between al-1015 and stainless steel, and stand off distance of 6mm between al-5056 and al-1015 were shown in Figure 1. The highest pressures occur at the collision point. The pressures obtained for the first collision were higher than that obtained for the second impact. The typical pressure-time variations for the 3mm stand-off distance between the stainless steel and al-1015 tubes (rectangular) and the 7.5mm stand-off distance between the al-1051 and al-5056 (circular) at an elapsed time of 30μs were depicted in Figure 2. Simulation results also showed that the value of the plastic strain was reached to its maximum at the collision point. Comparison of the experiments with the simulations showed that the value of the plastic strain had to be more than a minimum value in order to welding occur. The minimum plastic strains obtained from the simulations for welding of al-5056 to al-1015 and al-1015 to 304-stainless steel was found to be 0.32, and 0.4, respectively. The typical plastic strain profiles for the second impact (al-1015 to 304-satinless steel) were plotted in Figure 3. The typical shear stress profiles at an elapsed time of 27μs for the 4mm stand-off distance between al-1015 (rectangular) and al-5056 (circular) were shown in Figure 4. The results showed that the shear stress had opposite signs for the cases were bonding take place. The flyer plate velocity and dynamic angle were also monitored and compared with the experimental results. The typical flyer plate velocity profiles for the 7.5m stand-off distance between the al-5056 flyer tube and al-5056 base tube were shown in Figure 5 (zero displacement represents the maximum flyer tube velocity obtained at the collision point). The dynamic angle profile for the 3mm stand-off distance between the al-5056 flyer tube and al-5056 base tube were shown in Figure 6 (zero displacement represents the maximum dynamic angle obtained at the collision point). Various values were obtained by changing the stand-off distance. The temperature at the collision point was also investigated. Typical temperature profiles between the al-1015 and 304-stainless steel tubes for the stand-off distance of 1.5mm for various elapsed times during the process were depicted in Figure 7. The results showed that the temperature was not reached to the material melting point. However, the temperature obtained was high enough to produce the metallurgical phase transformations. Therefore, this study supports the idea that the explosive welding process is a solid state process and is not a fusion process.

12 CONCLUSIONS

- The simulations showed that the temperature at the collision point was not reached to the material melting point. But, it was high enough for phase transformation to occur. Therefore, this study supports the idea that the explosive welding process is a solid state process.
- This study suggests that the minimum plastic strain may be required to bonding take place.
- The results showed that the shear strain profiles at the surfaces of the tubes bonded had opposite sign at the collision points.

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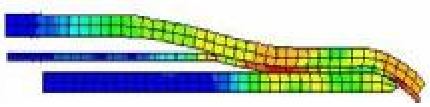
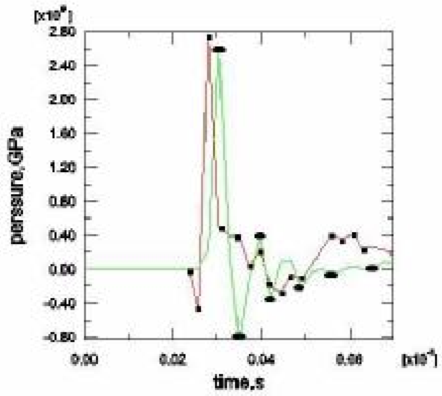


Figure1: Typical simulation of explosive welding of three layer tubes during the welding process (t=30s) for the stand-off distance of 2.5mm between al-1015 and stainless steel tubes, and the stand off distance of 6mm between al-5056 and al-1015 tubes



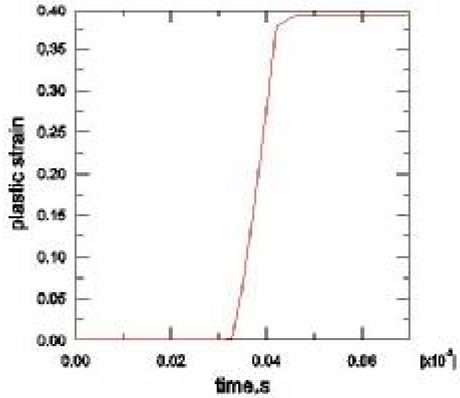
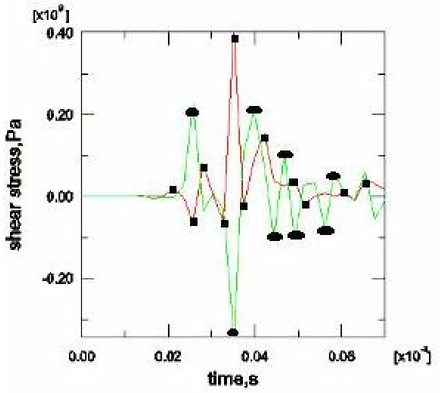


Figure 2: Typical pressure profiles for the 3mm stand-off between the 304-stainless steel and al-1015 tubes (rectangular) and 7.5mm stand-off distance between the al-1051 and al-5056 (circular)

Figure 3:Typical effective plastic strain profile between the al-1015 and 304-stainless steel tubes, stand-off distance=1.5mm



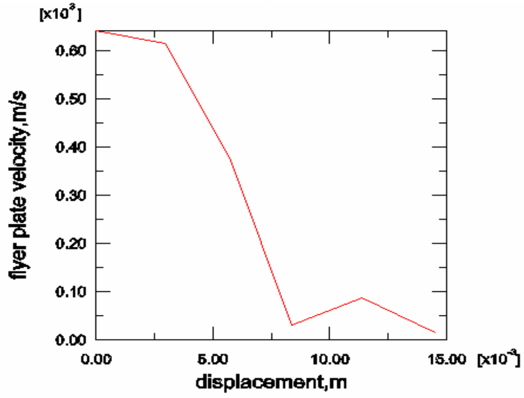
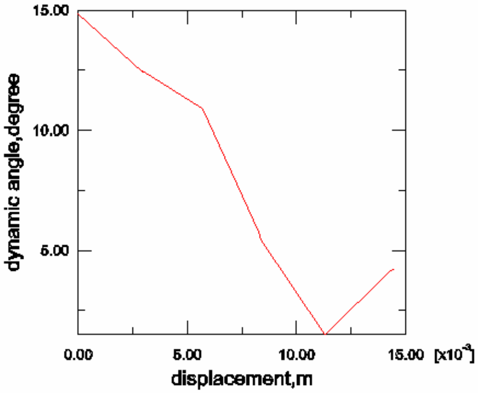


Figure 4: Typical shear stress profiles for the 4mm stand-off distance between al-1015 (rectangular) and al-5056 (circular).

Figure 5: Typical flyer plate velocity profile for the 7.5m stand-off distance between the al-5056 flyer tube and al-1015 base tube (zero displacement represents the highest flyer plate velocity obtained at the collision point).



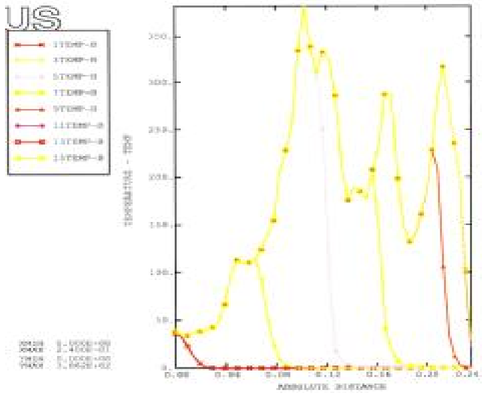


Figure 6: Typical dynamic angle profile for the 3mm stand-off distance between the al-5056 flyer tube and al-1015 base tube (zero displacement represents the highest dynamic angle obtained at the collision point).

Figure 7: Typical temperature profile for the 1.5mm stand-off distance between the al-1015 and 304-stainless steel tubes