EFFECT OF IMPACT PARAMETERS ON EXPLOSIVE WELDING OF TUBE TO A PLUG

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Abstract Effects of important parameters like impactor factor, plug geometry and initiation points on bonding aluminum tubes to aluminum plugs were studied. The impact velocity and dynamic angle between tube and plug should be precisely managed to achieve an optimum bonding condition. A new explosive bonding technique with the use of two material impactors was proposed. Results are especially suitable for using high-speed explosive materials to bond welded parts having dissimilar properties. A welding window was first presented for bonding aluminum tube to aluminum plug with the help of the experimental data. Numerical simulation was then performed to understand the effect of impactor on flat and curved plugs. However, due to limited data analysis systems used to register explosive welding parameters, it became evident that numerical analysis was necessary. The important findings were explosion modeling and fast tube deformation. For low process duration time and fast deformation, the modeling is very difficult. Numerical analysis with Abaqus software was performed to investigate the bonding conditions. The calculated impact velocity of the tube and the dynamic angle between the tube and the plug were compared with the numerical results under the same conditions. It was shown that the numerical analysis was consistent with the predicted data. Eventually we concluded that in explosive welding, curved plugs were more advantageous than flat plugs. It can be recommended that due to having a connection surface in high-speed explosives, the use of plastic impactors is more favorable than using hypoelastic impactors.

Key Words Explosive Welding, Impactor, Impulse Loading, Simulation

چکیده در این مقاله، اثرات تعدادی از پارامترهای مهم فرآیند جوشکاری انفجاری مانند ضربه‌گیر، شکل هندسی توپی و همچنین نقطهٔ شروع انفجار لوله به توپی آلومینیومی، بررسی شده است. برای اتصال قوی در فرآیند جوشکاری انفجاری لوله به توپی می‌بایست سرعت برخورد و زاویهٔ دینامیکی بین لوله و توپی در نقطهٔ برخورد در داخل یک محدودهٔ خاصی بنام پنجرهٔ جوشکاری قرار گیرند؛ لذا در ابتدا پنجرهٔ جوشکاری برای اتصال قطعات آلومینیومی به کمک روابط تجربی رسم گردید و سپس اثرات پارامترهای فوق روی تغییر وضعیت اتصال در داخل پنجرهٔ جوشکاری بررسی شد. این تحقیق بخصوص برای فرآیندهای انفجاری که از مواد منفجرهٔ سرعت بالا استفاده می کنند، بسیار مناسب و مفید است. از آن جایی که دستگاههای ثبت و اندازه‌گیری پارامترهای مربوط به جوشکاری انفجاری، بسیار محدود و دشوارند، ضرورت انجام مدلسازی این فرآیند آشکار گشت. بنابراین مدلسازی انفجار و تغییر شکل لوله در نرخ کرنش بسیار بالا از نکات مهم این تحقیق بود که بدلیل کوتاه بودن زمان فرآیند و بالا بودن سرعت تغییر شکل، مدل نمودن چنین فرآیندی دشوار است. در این تحقیق به مدل کردن جوشکاری انفجاری لوله به توپی به کمک نرم افزار اباکوس برای بررسی شرایط اتصال پرداخته شد. سرعت برخورد و زاویهٔ دینامیکی بین لوله و توپی بدست آمده از مدلسازی، با اطلاعات حاصل از روابط تجربی مقایسه شد. این مقایسه بیانگر پیش بینی خوب و قابل قبول نتایج مدلسازی بود. همچنین با مقایسهٔ بین توپی‌های انحنادار و صاف، استفاده از توپی‌های انحنادار، نسبت به توپی‌های صاف مناسب تر بود. نهایتاً هنگام استفاده از مواد منفجرهٔ سرعت بالا، استفاده از ضربه‌گیرهای کاملا پلاستیک بجای استفاده از ضربه‌گیرهای هایپرالاستیک برای داشتن اتصال مطلوب، قابل توصیه تشخیص داده شد.

1. INTRODUCTION

Materials can be bonded together by high velocity oblique collision in which high transient pressure is produced at the collision region. The process uses an explosive detonation as the energy source to propel a flyer plate towards a base plate Figure 1. The impact velocity, V_p in Figure 1, determines the pressure.

This pressure results in the formation of a jet, which contains the surfaces of the two materials and serves to bring them together to create a metallurgical bond. The velocity of the collision point, Vc, governs the time available for bonding. Considerable progress has been made to establish the optimum operational and physical parameters required to produce an acceptable bond and welding windows (of various parameters such as flyer tube velocity – dynamic angle and impact pressure – dynamic angle etc.) have been proposed by different authors.

Explosive welding can be used to clad cylinders on their inside or outside surfaces. One application of such process is the internal cladding of steel forging with stainless steel to make nozzles for connection to heavy - walled pressure vessels.

Explosion welding can be used for plugging leaking tubes in heat exchangers. Electric utilities and petrochemical companies use the process because it is quick, easy, and reliable (Figure 1).

Techniques for welding tubes to plug employ a small explosive charge, which on detonation effects their high velocity collision, whereupon under controlled conditions, a good bond is secured between the tube and the plug.

Basically, two different geometric shapes are available, the use of which is dependent upon the type of explosive material of high or low detonation velocity.

The geometric shape using a high detonation velocity of explosive material has a mutual inclination between the tube and the plug, Figure 2 [1].

The other geometrical arrangement, where the surfaces to be welded are kept parallel to each other [1], and at a short distance apart, Figure 3, requires a velocity explosive material that has a detonation velocity less than the sonic velocity of the materials being welded.

The parallel set up with an impactor is preferred because high detonation velocity material can then be used, which are generally more consistent in detonation, more contact and more easily handled than low detonation velocity explosive materials.

Due to limitations of data analysis systems for registration of explosive process, the necessity for numerical analysis arose. Therefore numerical work was carried out to study the technique of welding a tube to a plug using a parallel and curve setup, an impactor (hyper elastic and perfectly plastic) with a high detonation velocity explosive material.

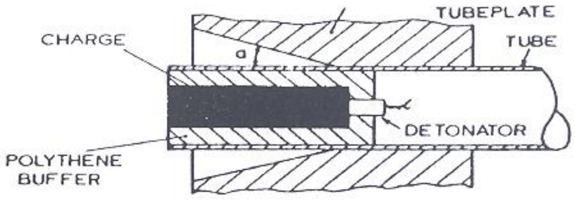

Figure 2. Inclined tube to tube plate welding geometry.

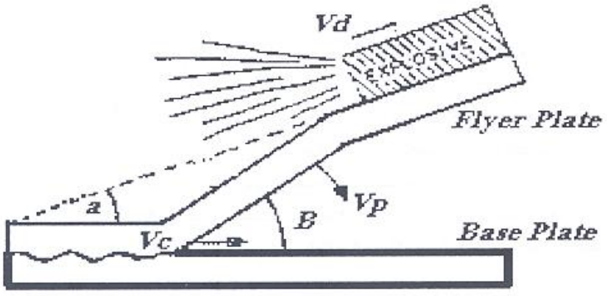

Figure 1. Model of explosive welding of two plates.

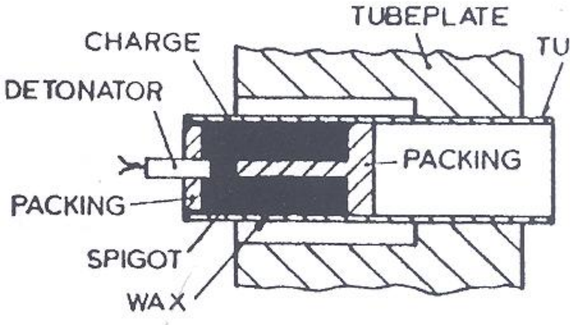

Figure 3. Parallel tube to tube plate welding geometry.

Measurements of tube inward velocities and collision angle were been carrying out with ABAQUS software, for comparison of the effect of impactor and plug geometric shape.

2. IMPORTANT PARAMETERS IN EXPLOSIVE WELDING

Stand Off Distance A minimum stand off is required to sufficiently accelerate the flyer and for surface jetting. Although it is possible to reduce the explosive loading at higher stand off, the edge instability and end effects are pronounced resulting in unbounded regions particularly while cladding large size. Short stand off operations are suitable for metal foil, metal sheet or thin metal plates and cylindrical geometric shapes. Suggestions for stand off vary widely from fraction of flyer thickness to more than twice of it [2].

Impact Velocity The flyer velocity has to be carefully chosen so as to, on one hand, satisfy all the requirements of bonding and on the other hand to set aside all chances for weld defects. Too high a velocity is undesirable due to inherent possibilities of defects and flyer damage.

From conservation of momentum it follows that for two dissimilar metals A and B impacting at a relative velocity of V_p, and sound velocity V_s, the impact pressure is given by [3]:

$$p_I = p_A = p_B = \frac{\rho_A V_p V_{SA}}{1+\rho_A V_{SA} / \rho_B V_{SB}} \tag{1}$$

For similar materials:
$(\rho_A = \rho_B = \rho, V_{SA} = V_{SB} = V_S)$

This reduces to:

$$p_I = \tfrac{1}{2} \rho V_p V_S \tag{2}$$

The minimum impact velocity to generate this pressure can be found from [1]:

(i) For dissimilar metals (with A the stronger component): $V_{P(\min)} \cong 10\sigma_{yA}[\frac{1+\rho_A V_{SA} / \rho_B V_{SB}}{\rho_A V_{SA}}]$

$$\tag{3}$$

(ii) Similar metals, since $V_{SA} \cong \sqrt{\frac{E_A}{\rho_A}}$

$$V_{P(\min)} \cong \frac{20\sigma_A}{\rho_A V_{SA}} \cong \frac{20\sigma_{yA}}{\sqrt{\rho_A E_A}} \tag{4}$$

Where E_A = Young's modulus of A.
Therefore For aluminum is:
$V_{p(\min)} = 490$ m/s

Attempts have been made to predict a maximum impact velocity in terms of such quantities as the flyer thickness, the collision point velocity and the thermal conductivity of the metals.

The maximum impact velocity that related with impact energy is give by [2]:

$$V_{P(\max)} = (\frac{2IE}{\rho_f t_f})^{1/2} \tag{5}$$

Where IE is the maximum permissible energy Values, for aluminum, equal 4.05 Mj/m^2, ρ_f is the density of the flyer metal and t_f is the thickness of the flyer metal. For aluminum, $V_{P(\max)} = 980$ m/s.

Optimum values of impact velocity, V_P, are obtained by:

$$V_P = V_{P(\min)} + 0.1(V_{p(\max)} - V_{p(\min)}) \tag{6}$$

For aluminum, $V_p = 531$ m/s.

Dynamic Angles For successful explosive Welding associated with the interfacial waves, a proper obliquity angle β must be obtained.

Walsh, Shreffler, and Willing have shown experimentally, that below a certain angle β_L, the reentrant jet is absent [4], therefore, the interface wave is not formed below a critical angle β_L.

The higher limit angle β_h and optimum values of dynamic angle β_o show a dependence

TABLE 1. The Limits of Dynamic Angle.

	$V_{p(min)}$=490 m/s	$V_{p(max)}$ =980 m/s
β_L	2.5°	4.5°
β_o	11°	22.5°
β_h	16°	32.2°

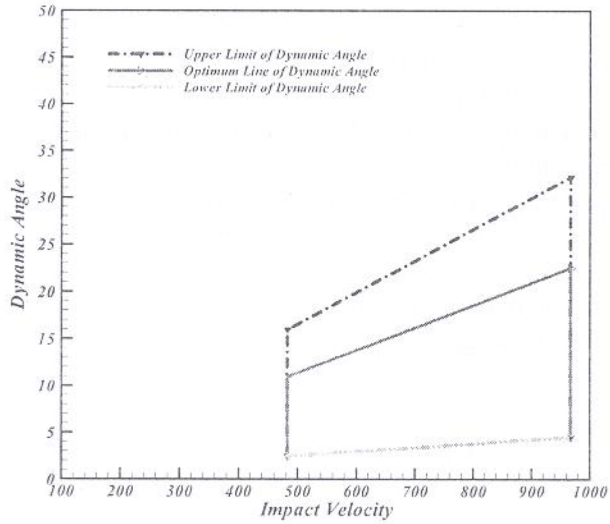

Figure 4. Design of quality explosive welding for Al -Al.

TABLE 2. Properties in Elastic Range of Aluminum.

Modulus of elasticity (E)	80 Gpa
Sound velocity (V_{sf})	5300m/s
Poison's Ratio (ν)	0.34
Material density (ρ)	2770 kgm^{-3}

on specific pressure P_s. It is expected that β_L also depend on p_s.

The following equations are obtained from experimental results is [4]:

$$\beta_L = 6 p_s^{-0.4}$$

$$\beta_o = 32 p_s^{-0.5} \qquad (7)$$

$$\beta_h = 46 p_s^{-0.5}$$

Where the specific pressure, p_s, is given by:

$$p_s = \frac{2\sigma_{yd}}{\rho V_p^2} \qquad (8)$$

Here σ_{yd} is dynamic yield strength of material.

The β_L and β_h for aluminum, specify in Table 1.

The welding window drown by using the data presented in this work is shown in Figure 4. This welding diagram can be employed for the design of parameters for aluminum- aluminum systems.

While any point within the window would mean successful bonding with a wavy interface.

3. SPECIFICATION OF MODEL

The base metal used for studying the explosive welding parameters is BAL 157-T6 aluminum alloy tubes. This was selected; because it represented a family of high strength, heat treatable alloys that would be used more extensively in lightweight structural applications if the alloys were joined by conventional fusion welding techniques. The mechanical properties and material properties of the plug and the tube are assumed to be made of aluminum (BAL157-T6) with properties in elastic range defined Table 2.

In the plastic range under quasi-static loading, the material isotropic work hardening is replaced by a best-fit curve of the type:

$$\overline{\sigma} = A(B + \varepsilon)^n \qquad (9)$$

The values of the material constants are given in Table 3.

The geometry of aluminum tube and plugs, for the set-up used in the present FE simulation is shown in Figure 5 and listed in Table 4.

Calculation of The Mass Of Explosive The Blazynski and Dara [1] approach is concerned,

TABLE 3. Material Isotropic Work Hardening Characteristics (Aluminum BAL 157-T6).

$\sigma_y(Nmm^{-2})$	431.0
$\sigma_{yd}(Nmm^{-2})$	2640
$\sigma_u(Nmm^{-2})$	479.2
$\bar{\varepsilon}_f^{p}$	0.120
$\bar{\varepsilon}_{offset}^{p}$	0.100
$A(Nmm^{-2})$	655.9
B	0.222
n	0.2790

TABLE 4. Geometric Parameter of Aluminum Tube and Plugs.

Tube outer diameter	72 mm
Tube thickness	3 mm
Explosive outer diameter	86 mm
Plug length	42 mm
Plug ends disc height	3 mm
Plug concave inward radius	61.844 mm
Tube length	78 mm

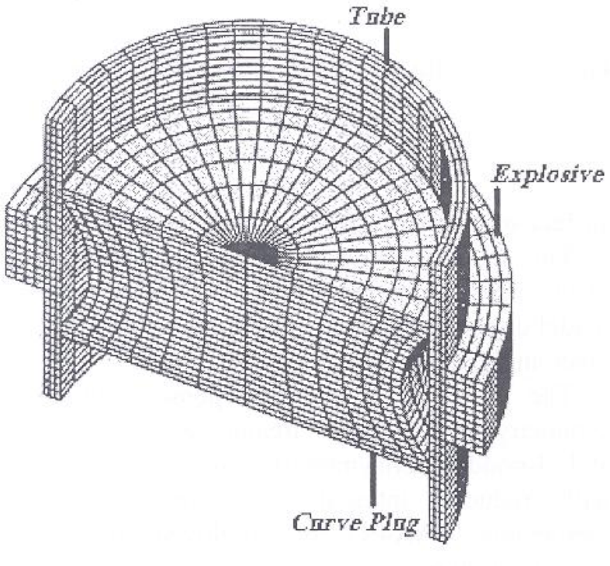

Figure 5. Section of curve plug, tube and explosive assembly.

mainly with the geometry and mechanical properties of the system. If the diameter of the outer cylinder is D_o, the energy of the charge is E_e, the length of the assembly is L, the wall thickness of the inner cylinder is t, the detonation velocity is V_d, for short cylinders (L<150mm), the energy of the charge is [1]:

$$E_e = 0.1^{1.1}\rho\sigma_y^{-0.1}V_d^{2.2}t^3\left(\tfrac{D_o}{t}\right)^2\left(\tfrac{L}{t}\right)^{5/6} \qquad (10)$$

This simplified expressions energy will be given only approximate values of charge energy that for Al-Al welding is:

$$E_e = 340311.87J$$

And the mass of explosive charge, m, may be obtained by dividing the value of the energy needed for welding, E_e, by the Gurney energy for T.N.T., E_G., therefore,

$$m = \frac{E_e}{E_G} = \frac{340311.87}{4080} = 83.42gr.$$

4. EXPLOSIVE WELDING SIMULATION-ABAQUS EXPLICIT CODE

The computer code has three parts: pre–processor, processor and post – processor.

Pre Processor The pre–processor is used to define the initial state of the problem. Here the mesh is generated and all the basic material data necessary for the computations were stored. Included in the material specifications were the Johnson-cook equations. From these equations quantities such as hydrostatic pressure and temperature were derived for a given state. The pre–processor utilized different equations for different parts of the system (i.e. flyer tube – base tube). The base tube was restrained at the bottom edge so that it did not move in the axial direction. The Johnson–Cook strength model and shock equations of state were used to represent the properties of all materials considered. In the Johnson – Cook constitutive equations, the Von–Mises flow stress of the materials under loading was expressed as a function of plastic strain, strain rate and temperature. The material constants were determined from experimental tests.

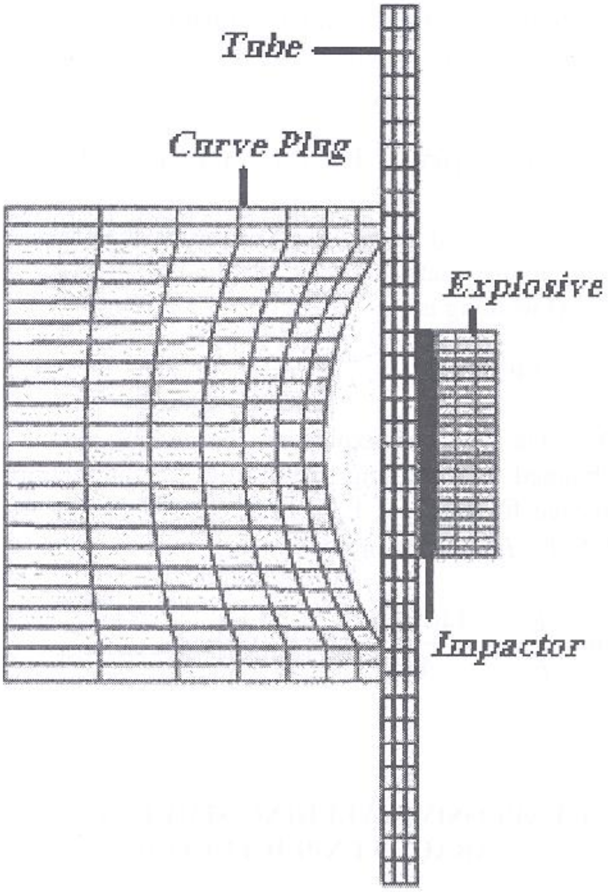

Figure 6. Model curve Plug, Tube Explosive and Impactor.

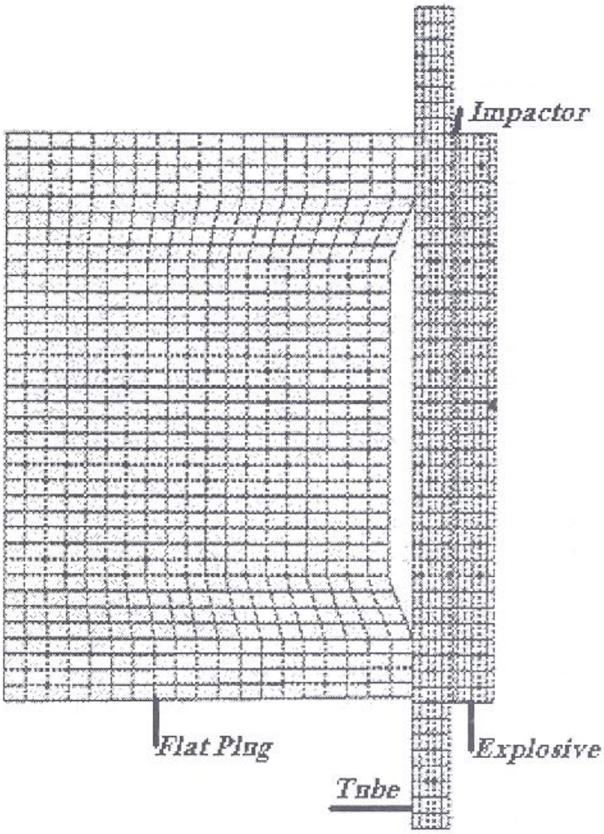

Figure 7. Model flat Plug, Tube Explosive and Impactor.

Processor The actual calculations were performed in the processor. Here the constituent differential equations were solved. In any iteration, each quantity was calculated and stored for use in the next iteration. At certain predetermined intervals the processor stored the most recent values into the post processor for output.

Post processor The post processor is an iterative plot program, which puts the saved data into graphics. Some types of plot facilities are plotting of contour maps, the following quantities can be mapped; pressures, tensile stresses, shear stresses, principal stresses, plastic strain, strain rate, internal energy, velocity components, temperature, kinetic energy, and total energy.

As an example of explosive welding simulation using FEM a plug of a specified outer profile internally caps an aluminum tube. The outer surface of the tube is covered with explosive.

The assembly consisting of plug, tube, and explosive is shown in Figures 6 and 7. The general model dimensions of its individual components are given in the data input file.

The model is assumed to possess rotational symmetry and hence is treated as axisymmetric and 4-nodded axisymmetric continuum element with reduced integration scheme (ABAQUS Designator CAX4R) is employed in model discretization process [9].

The explicit FE procedure is employed in the subsequent solution scheme. The model as shown in Figure 6 and 7 is comprised of three different parts: plug, tube and explosive.

To remove the shortcoming the outer surface of the plug is targeted against the explosive inner surface. The complemented detail is given in the accompanying data input file and it's recommended to be referred to by the reader.

The loading material is treated as high explosive and Equation of State (EOS) of JWL type defines its pressure-time. The numerical values of the required parameters of the EOS are given in the data input file. It is a prudent precaution for the reader to refer to ABAQUS/ Explicit user's manual to make sure of the implication and the influence of these parameters.

The plug and tube are considered to be made of hard aluminum alloy with properties of:

a. Linear elastic in elastic range defined by modules of elasticity (E) and Poisson's ratio (υ).

b. This is followed by isotropic non-linear work hardening with strain rate dependency, which is defined by enhancement of yield ratio as a function of strain rate.

5. EQUATIONS OF STATE

Equations of state in ABAQUS/Explicit provide a hydrodynamic material model in which the material has only volumetric strength (the material is assumed to have no shear strength); determine the pressure (positive in compression) as a function of the density, ρ, and the internal energy per unit mass, E_m of explosive, $P = f(\rho, E_m)$

The basic equations for the numerical calculation are based on the mass, momentum and energy conservation.

Aluminum tube used for in the simulation is assumed to be work hardening elastic plastic material. The work hardening condition can be described by the following equations:

$$\frac{\partial \rho u}{\partial t} = \frac{\partial (P + q - s_x)}{\partial x} + \frac{\partial \tau_{xy}}{\partial y}$$
$$\frac{\partial \rho v}{\partial t} = \frac{\partial (P + q - s_y)}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} \qquad (11)$$

Where u, v, are x, y-directional velocity components; ρ, P, q, indicate density, static hydrodynamic pressure, and artificial viscous pressure. S_x is stress deviator in x direction. S_y is the stress deviator along the y direction. τ_{xy} is shear stress.

The Mie –Grumeisen equation of state solves the pressure. Mie - Gruniesen equations of state, thus provide the linear U_s - U_P Hugoniot form or the JWL high explosive equations of state [5].

Mie - Gruniesen Equations of State A Mie - Gruniesen equation of state is linear in energy. The most common form is

$$P - P_H = \Gamma \rho (E_m - E_H) \qquad (12)$$

Where P_H and E_H are the Hugoniot pressure and specific energy (per unit mass) along some reference path and are functions of density only and

$$\Gamma = \Gamma_o \frac{\rho_0}{\rho} \qquad (13)$$

That Γ_0 is a material constant and for aluminum is 2.0. [5].

The equation of state and the energy equation represent coupled equations for pressure and internal energy. ABAQUS/Explicit solves these equations simultaneously at each material point.

All input quantities for energy in ABAQUS/ Explicit are units of energy per unit volume. Linear equations of state can always be written in the form

$$p = f + \; gE_m \qquad (14)$$

Where f (ρ) and g (ρ) are functions of density only and depend on the particular equation of state model.

Linear U_s - U_P Hugoniot Form A common fit to the Hugoniot data is given by

$$P_H = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^{2,}} \qquad (15)$$

Where $\eta = 1 - (\rho_0 / \rho)$ is the nominal volumetric

TABLE 5. Constants in JWL Type Equation.

A	348.6Gpa
B	11.29Gpa
ω	0.24
R_1	7.00
R_2	2.00
E_{mo}	5.7MJ kg-1

compressive strain and c_o and s define the relationship between the linear shock velocity, U_s, and the particle velocity, U_P as follows:

$$U_s = c_o + sU_{P.} \tag{16}$$

For aluminum c_0 and s are 5330 m/s and 1.34. With the above assumptions the linear U_s - U_p Hugoniot form, is written as [6]:

$$p = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2}(1 - \frac{\Gamma\mu}{2}) + \Gamma_0 \rho_0 E_{m.} \tag{17}$$

There is a limiting compression given by the denominator of this form of the equation of state or

$$\eta_{\lim} = \frac{1}{s} \tag{18}$$

$$\rho_{\lim} = \frac{s\rho_0}{s - 1.} \tag{19}$$

At η = 1/s there is a tensile minimum; thereafter, negative sound speeds are calculated for the material.

JWL High Explosive Equation of State The Jones - Wilkens - Lee (or JWL) equation of state models the pressure generated by the release of chemical energy in explosive. This model is implemented in a form referred to as a programmed burn, which means that the reaction and initiation of the explosive is not determined by shock in the material. Instead, the initiation time is determined by a geometric construction using the detonation wave speed and the distance of the material point from the detonation point.

The JWL equation of state can be written in terms of the initial energy per unit mass, E_m, as [7]:

$$\begin{aligned} P &= A(1 - \frac{\omega\rho}{R_1\rho_0})\exp(-R_1\frac{\rho_0}{\rho}) \\ &+ B(1 - \frac{\omega\rho}{R_2\rho_0})\exp(-R_2\frac{\rho_0}{\rho}) + \frac{\omega\rho^2}{\rho_0}E_{m,} \end{aligned} \tag{20}$$

Where A, B, $R_{1,}$ R_2, ω and E_m are material constants that are defined in the *EOS option along with a pressure cutoff.

The explosive material (PETN) properties are:

Density $\rho_{exp.}$ = 880 kgm-3
Detonation Velocity V_d = 5170 ms-1

Constants used in JWL type equation of state (ESO), shown in Table 5.

For the calculation of detonation of explosive, the C-J volume burn method is used [8]. The C-J volume burn is described in the forthcoming. When the volume of the cell of the original explosive in the calculation becomes equal to the volume of the detonation products at Chapman – Jouguet (C-J) state, the solid explosive is assumed to be completely decomposed into the gaseous products. Let V_0 represents the initial volume of explosive (the reciprocal of the initial density), V_{CJ} be the volume of the detonation products at the C-J state, and the reaction rate of the explosive is simply expressed as [8]:

$$\begin{aligned} W &= 1 - \frac{V_0 - V}{V_0 - V_{CJ}} \\ P &= (1 - W)p_g \end{aligned} \tag{21}$$

Where W stands for the mass fraction of the unreacted explosive, thus, before and after reaction, W=1 or 0, respectively, P_g is the pressure of the detonation products. The pressure, P, correspondingly, is assumed to be equal to that of the detonation products of the party reacted explosive over the whole cell. The pressure,

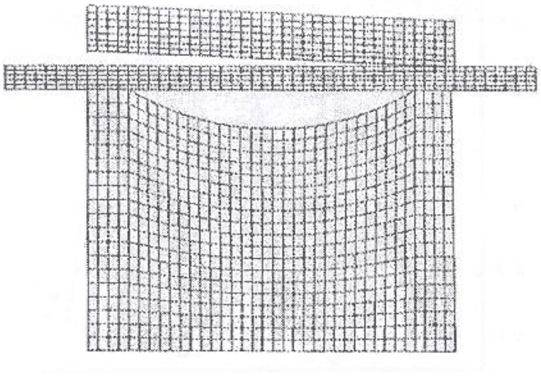

Figure 8. Curve plug with ablıque perfectly plastic impactor.

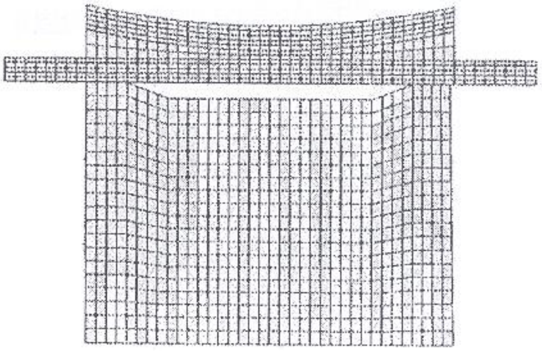

Figure 9. Flat plug with hyperelastic impactor.

volume, and energy of the reacted explosive are correlated by the JWL equation of state described in the foregoing.

6. EXPLANATION OF MODELS

Due to non-uniform radial velocity around the tube when two front of detonation touch each other, it produces the Dutrich effect, which causes the crack and fracture in the tube wall.

With regards to the models, there is no recommendation in available publications for the starting point of explosion in welding of tubular structures.

As it has been pointed out in the experimental tests, it has been suggested that the start of explosive be in a ring form, where it can be placed at the beginning or at the middle of plug.

Each of the two above initiations with two different impactor materials, by choosing the same type and mass of explosive material, will produce different impact velocity and dynamic angles.

To find the effect of using the impactor, a variety of methods was modeled using ABAQUS, with regards to the two different geometric shapes of plugs (curve plug, flat plug) was modeled (ABAQUS) for different cases. Two kinds of impactor material, hyper elastic and perfectly plastic material were used in these models. Four cases of them are:

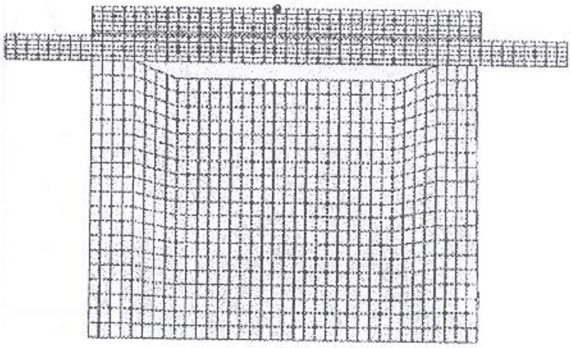

Figure 10. Flat plug with parallel perfectly plastic impactor.

1- Curve plug with space uniform thickness (parallel), perfectly plastic impactor that initiation was started from the first of explosive material is shown in Figure 8.

2- Flat plug with hyperbolic geometric and perfectly plastic material impactor that initiation was started from middle of explosive material is shown in Figure 9.

3- Flat plug with uniform thickness (parallel) and hyperelastic material impactor that initiation was started from the middle of explosive material is shown in Figure 10.

4- Flat plug with one end supported and used oblique hyperelastic impactor used that initiation

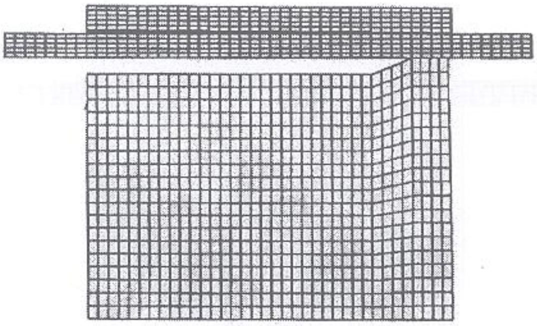

Figure 11. Flat plug with hyperelastic impactor.

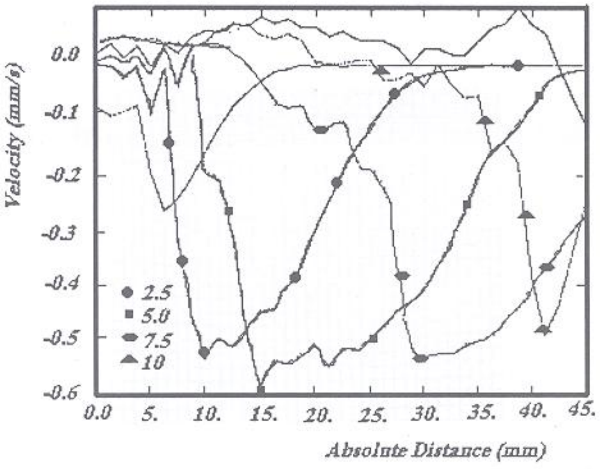

Figure 12. Impact velocity in perfectly plastic impactor at various times from 2.5 to 10 μs.

was started from the beginning of the explosion is shown in Figure 11.

7. RESULTS AND DISCUSSION

Impact velocity and collision angle is the most important variables in explosive welding.

In this work variable angle techniques are carried out with the use of concave plugs. Thus a position within the region of Al-Al welding window can be provided. This maintains successful welding.

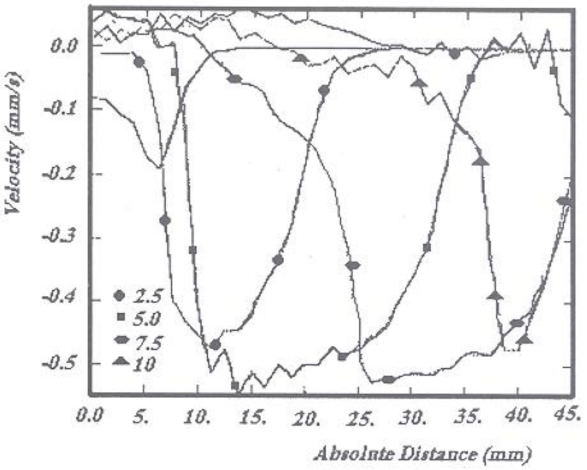

Figure 13. Impact velocity in hyperelastic impactor at various times from 2.5 to 10 μs.

For this the abaqus/explicit FE code is used successfully to model the contact response between two similar materials at a very high strain rate. The loading is simulated using a JWL type equation of state.

The welding window for bonding aluminum tube to aluminum plug was made with help of experimental formula and the position of the effect of those parameters with the welding window were checked. Six different arrangements of flat and curve plugs were modeled, three with parallel and three with concave curve plugs. Explosive material was used is PETN. In both flat and curve plugs attempt have been made to compare the effect of perfectly plastic and hyperelastic impactor in explosive welding tube to plug.

Two series of output simulation models were considered. One was a dynamic angle and the other, an impact velocity in collision points.

a) From Numerical Analyses The results derived from those models can be illustrated as following.

In this investigation two types of impactors were used, perfectly plastic and hyperelastic. Distributions of impact velocity versus the distance of plug length for two different impactors are shown in Figures 12 and 13. With perfectly plastic impactor and 550m/s for hyperelastic impactor, the maximum impact velocity is 600 m/s at 5μs.

Distributions of dynamic angle versus the distance of plug length for two different impactors are shown in Figures 14 and 15. Dynamic angle is

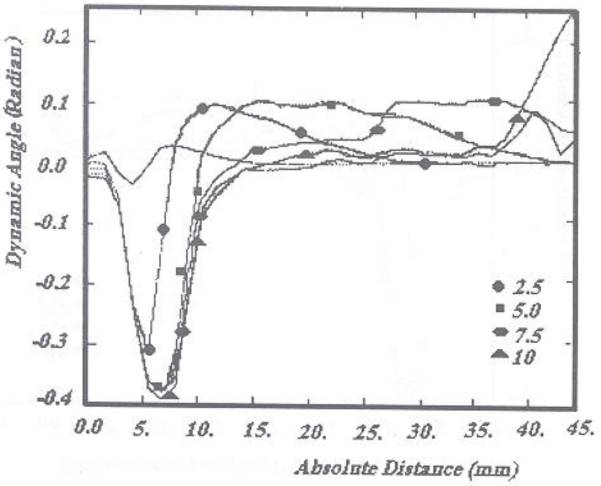

Figure 14. Dynamic angle in perfectly plastic impactor at various times from 2.5 to 10 μs.

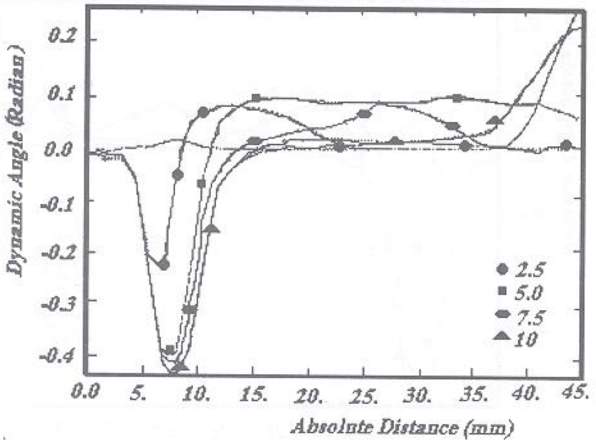

Figure 15. The dynamic angle in hyperelastic impactor at various times from 2.5 to 10 μs.

21.7 degree at 10μs, when uses perfectly plastic impactor and 25.8 degree for hyperelastic impactor.

By comparing the results of the two material impactors - perfectly plastic and hyperelastic - it can easily be seen that the perfectly plastic material causes more impact velocity and also reduces the dynamic angle; because the shock pressure acting on the flyer plate is higher with perfectly plastic impactor. The reason for lower dynamic angle is that the moving velocity of collision point is faster so that the flyer tube collides with the plug at the shallow angle.

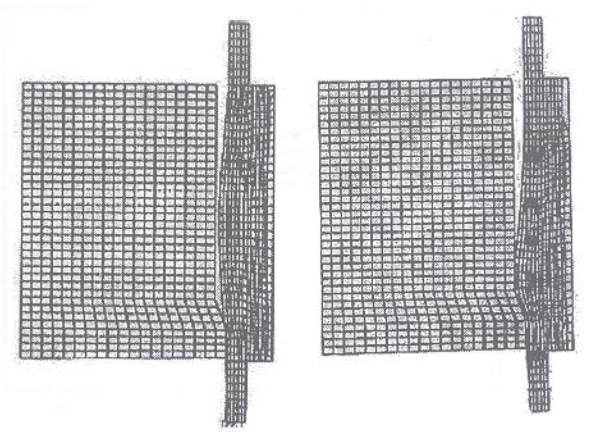

Figure 16. Flat plug with middle initiation and beginning initiation.

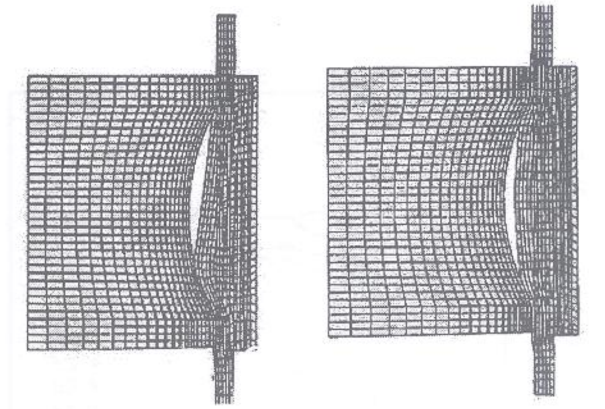

Figure 17. curve plug with beginning initiation and middle initiation.

Figure 16 shows the flat plug with middle initiation and beginning initiation. For omitting the zero amount dynamic angles in collision point, it requires the initiation take place at the beginning of the explosive material.

Figure 17 shows the curve plug with beginning and middle initiation. To have a wavy interface and being inside the welding window, the dynamic angle should have minimum value.

Therefore, in implosive welding of tube to curved plug the initiation must commence at the center of the explosive material to achieve a low dynamic angle.

Dynamic angle in the welding window area must be observed. Figures 18 and 19 show distributions of dynamic angle versus the position of distance for being considered impactor or not. Therefore as you see at the graphs, for the above-

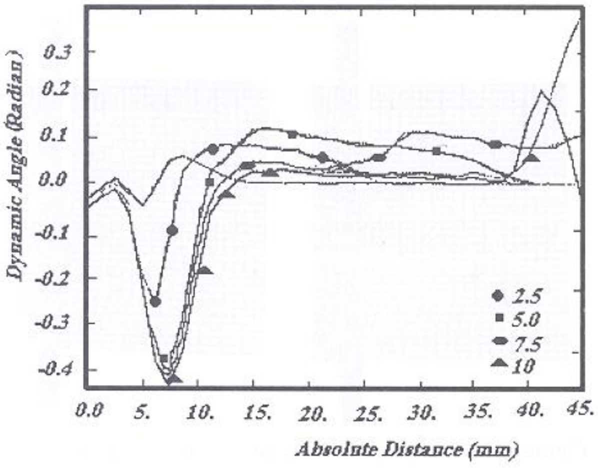

Figure 18. The dynamic angle without impactor at various times from 2.5 to 10 μs.

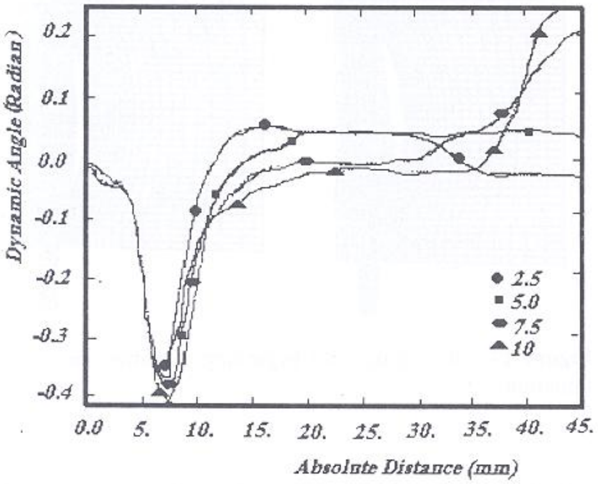

Figure 19. The dynamic angles with impactor at various times from 2.5 to 10 μs.

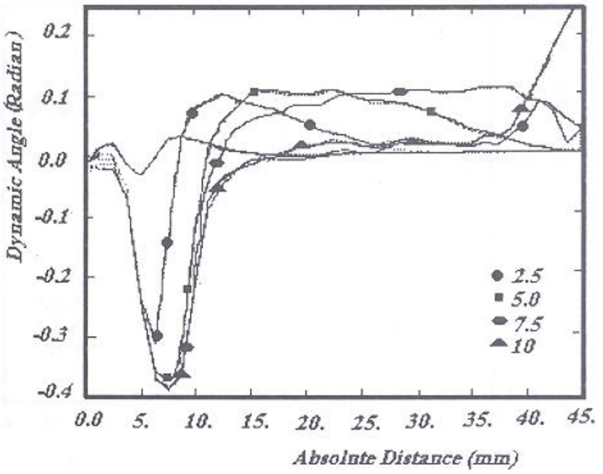

Figure 20. The dynamic angle with parallel impactor at various times from 2.5 to 10 μs.

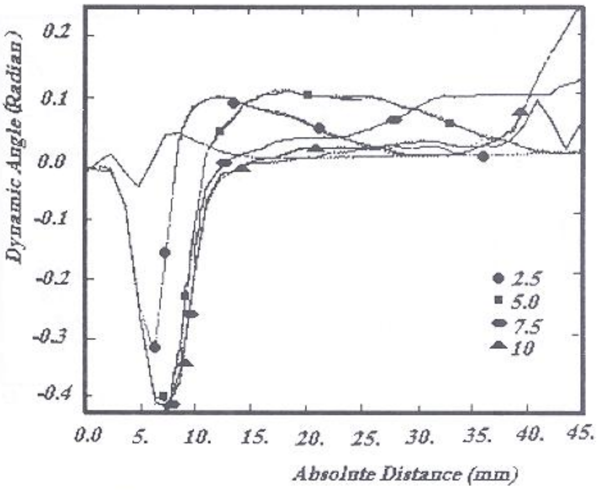

Figure 21. The dynamic angle with oblique impactor at various times from 2.5 to 10 μs.

mentioned data, the flyer tube may obtain a considerable deflection when the setup is without impactor. Therefore the usage of the impactor with the existing models causes dynamic angle in the welding window to minimize.

Figures 20 and 21 show distributions of dynamic angle versus the absolute distance for parallel and oblique impactor. Their setups are shown in Figures 8 and 10.

Both parallel and oblique impactors change the collision velocity. The parallel impactor reduces the dynamic angle more because the moving velocity of shock wave acting on the flyer tube is faster when the inclined angle is small, and then moving velocity of collision point is higher than oblique impactor.

In reviewing these models, the collision velocity is not uniform during the length of the process, and in order to maintain uniform collision velocity, the impactor must be used.

b) Experimental Data The simulation lines of impact velocity and dynamic angle were added into Figure 4, so called weldability window for aluminum to aluminum welding, and all of them were shown in Figures 22 and 23, together.

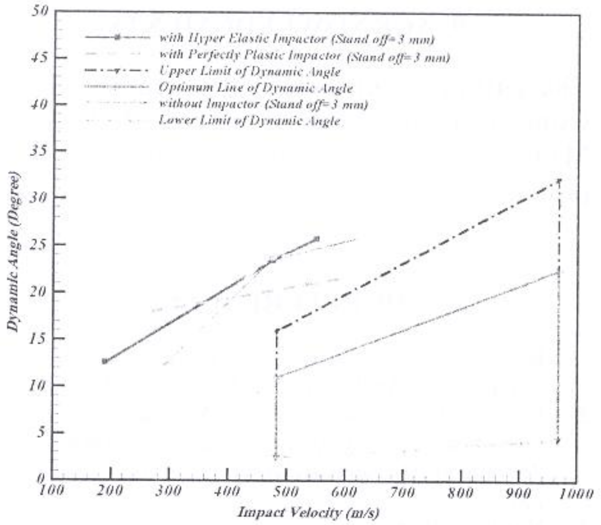

Figure 22. Abaqus model welding of tube to flat plug in welding window Al –Al.

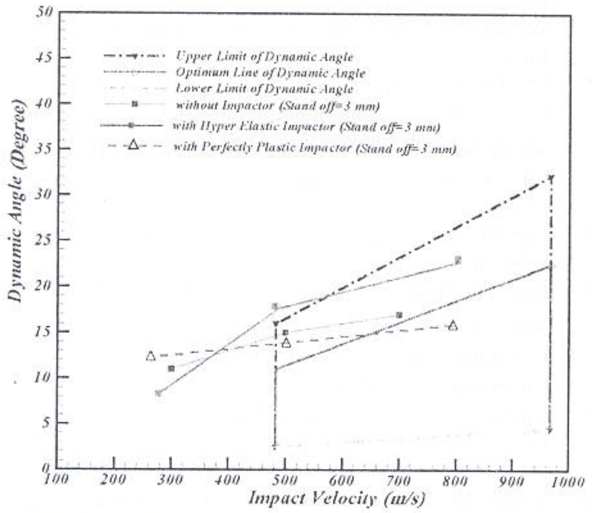

Figure 23. Abaqus model welding of tube to curve plug in welding window Al –Al.

Figure 22 shows that the data obtained when using flat plugs with different impactors, are outside the window.

It can be seen in Figure 23 that the results obtained when using curved plugs are inside the window, indicating that the flyer and base tubes can achieve a wavy Interface and therefore a good bonding.

Perfectly plastic impactors are preferred over hyperelastic impactors; because the perfectly plastic impactors produce a uniform small dynamic angle along the process. These are shown in Figures 22 and 23.

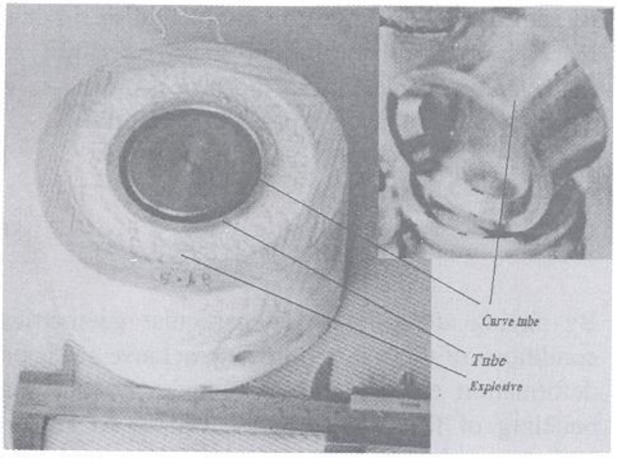

Figure 24. Setup for the explosive welding of tube to curve plug.

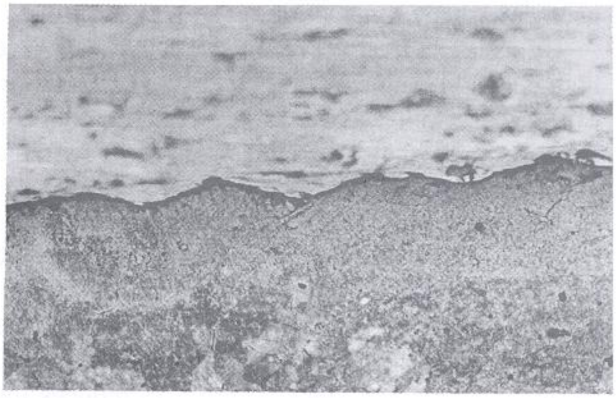

Figure 25. Micrograph of the bonded interface of tube to curve plug (× 100).

Wave interface of bonding Al – Al with using curved plug are obtained from experiments of this research [10]. Figure 24, shows the experimental setup for the curve plug. Figure 25 shows the photographs of the interface between the welded aluminum tube and aluminum curve plug. The interfacial wave begins to turn out at dynamic angle (β) equal 14 degree, and then, as the angle decreases, the wavelength of the interfacial wave becomes shorter and shorter.

In addition to the above-mentioned results, the numerical results agree with the experimental data on the impact velocity, pressure distribution and dynamic angle at collision point [11]. This illustrates that a good quality of bonding is difficult to achieve under these conditions and in order to reach the weldability region, due to variability of the dynamic angle during the process, the use of curved plugs are more suitable than flat plugs.

8. CONCLUSIONS

By paying attention to the particular geometrical conditions of the tube in order to achieve sufficient deformation energy, and prevent the fracture and buckling of the tube [12], as well as to achieve sufficient velocity, high pressure is required from the explosion and low stand off is needed from the geometrical conditions. Hence it is necessary to use high-explosive material as suggested for cylindrical geometric shape.

By using high-explosive materials we will have high-collision velocity, which is problematic in explosive welding, as in this process the collision velocity must not exceed the material's sound velocity. In order to reduce the collision velocity, contrary to our expectation, the use of an external material called impactor could not affect the collision velocity.

Both material impactors are changing the collision velocity and the perfectly plastic material causes more impact velocity and also reduces the dynamic angle. Both parallel and oblique impactors change the collision velocity and the parallel impactor reduces the dynamic angle more.

In order to reach the weldability region, use of curved plugs is more suitable than flat plugs, and to maintain uniform collision velocity, the impactor must be used, and according to the experimental results, the use of perfectly plastic impactor is preferred over hyperelastic impactor.

The numerical results agree with the calculated data from experimental formula. Thus, the simulation method is shown to be appropriate for solving these types of problems. The simulation technique employed here is not shape dependent and therefore can be applied to any geometrical configuration of two or more materials of the same or different types without any difficulties.

9. ACKNOWLEDGMENTS

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10. REFERENCES

1. Blazynski, T. Z., "Explosive Welding, Forming and Compaction", Applied Science Publishers LTD, 1983.
2. Reid, S, R., "Wake Instability Mechanism For Wave Formation In Explosive Welding,", ***International Journal of Mechanical Science,*** Vol. 20, (1978), 247-251.
3. Vaidyanathan P. V. and Ramanathan, P. V., "Computer Aided Design of Explosive Welding Systems", Communicated To ***Journal Mech. Work Tech***., (1991).
4. Gupta R. C. and Kainth G. S, "Permissible Range of Parameters for Interface Wave Formation in Explosive Welding", Indian Institute of Technology, Kanpur, India.
5. McQueen, G., Marsh, S. P., Taylor, J. W., Fritz, J. N. and Carter, W. J., "The Equation of State of Solids from Shock Wave Studies", High Velocity Impact Phenomena**,** Ed., R. Kinslow, Academic Press, New York, NY, (1970), 230.
6. Hibbitt, Karlsson and Sorensin, "ABAQUS Explicit Method", Printed in U.S.A., (1998).
7. Lee, E., Finger, M., and Collins, W., "Jwl Equation of State Coefficients for High Explosives", Lawrence Livermore National Laboratory Report Ucid 16189, Livermore, Ca., (1973).
8. Mader C. L., "Numerical Modeling Of Detonations" University of California Press, Berkeley, California, (1979).
9. Nouri M. D., Al Hassani S T S, Kormi K, "An Investigation on Explosive Bonding Process**",** Research Report, UMIST, U.K., (March 1999).
10. Liaghat G. H., Darvizeh A. and Nouri M. D., "An Experimental Investigation on Explosive Welding Tube To Plug", Research Report, Tarbiat Modarres University, Tehran-Iran, (May 2000).
11. Darvizeh A., Liaghat G. H. and Nouri M. D., "Two Dimensional FE Simulation of High Rate Deformation of Tube In Explosive Welding Process", Accepted For ***Modarres Engineering Journal***, Iran, (February 2002).
12. Liaghat G. H., Nouri M. D., "Buckling and Instability of Cylindrical Geometric Shape by Lateral Explosive Loading***", Proc. 5th Int. Conf. Mechanical Engineering,*** Gillan, Iran, (2001).