Explosive Welding Parameters

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Introduction

1. Explosive welding was first recognised as a remote possibility in 1957 in the United States, when it was observed that metal sheets being explosively formed occasionally stuck to the metal dies. During the intervening decade, the process has been developed from remote possibility to a well understood process, which has found considerable application to plate cladding, particularly applicable to the cladding of very large areas which can only be done less effectively by roll cladding. The process is entirely different from the other recognised processes, in that it does not depend on melting the two metals to be joined with the resultant metallurgical problems, nor on gross plastic deformation of the surfaces in contact as with the various forms of cold and hot pressure welding. In explosive welding process, the surfaces of the plates are stripped off to form a high velocity jet which picks up the contaminant surface layer of the plates by surface traction, to leave two virgin surfaces which then adhere in solid phase welding. It is therefore possible to explosively weld metals of entirely different melting points temperature and metals of entirely different plastic properties which could not be welded by cold pressure welding.

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Mechanism and Experimental set up

2. The mechanism of explosive welding has been extensively studied by many research workers and most of them are of the view that the three conditions to be met to achieve successful explosive welding are—

(a) The pressure at the contact point must be sufficiently large. The actual magnitude of the pressure required probably depends on the strength of the metal being welded though not the static strength but that under the rate of loading experienced in the contact area.

(b) The condition of the collision should be such as to ensure jetting even if jet is trapped in the vortex area.

(c) The collision point velocity should be less than the sonic velocity in the parent plate material. It is considered that this condition is necessary to ensure that a wave can be generated in front of the collision point either to increase the scouring action of the jet and or cause sufficient surface deformation to break up the contaminant surface layer and expose clean surfaces to joint in solid phase welding.

3. From the review of the literature on explosive welding, it appears that a really fundamental based set of parameters for satisfactory explosive welding is not yet feasible and hence empirical relationships of proven value are needed. In order to determine the relationship between important explosive welding parameters,

explosive welding experiments were carried out at Institute of Armament Technology, Pune. Both welding of similar and dissimilar metals was done. The following combinations were used :—

(a) Mild Steel to Mild Steel.
(b) Copper to Copper.
(c) Aluminium to Aluminium.
(d) Brass to Mild Steel.
(e) Copper to Mild Steel.
(f) Aluminium to Mild Steel.
(g) Aluminium to Brass.

4. The angular set up was used for the welding experiments as shown in Fig. 1. The results are given in Table 1. Rubber and wood buffers were used. The amount of explosive and set up angle were varied and *welded joint tested for yield strength.*

Welding Parameters

5. From the explosive welding experiments, it was concluded that following parameters are important :—

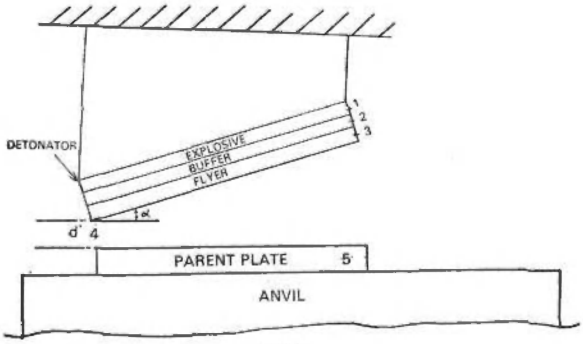


Fig I(a)

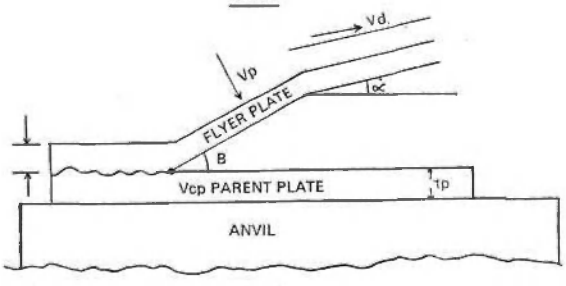


Fig I(b)

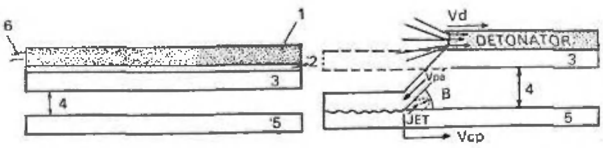


Fig I(c) Fig I(d)

EXPLOSIVE WELD DETAIL :- 1.EXPLOSIVE ; 2.BUFFER ; 3.FLYER ; 4.STAND-OFF DISTANCE ; 5.PARENT PLATE ; 6.DETONATOR

B-COLLISION ANGLE, Vcp-COLLISION VELOCITY ; Vpa-FLYER VELOCITY RELATIVE TO POINT OF IMPACT ; Vd-DETONATION VELOCITY OF EXPLOSIVE ; Vp-PLATE VELOCITY

PARALLEL SET UP

(a) **Parameters of Explosive (High Explosive)**

(i) Thickness of high explosive = (te)
(ii) Density of high explosive = (Se)
(iii) Detonation velocity = (Vd)
(iv) Explosive mass / accelerated mass = C/m

(b) **Parameters of Flyer Plate**

(i) Thickness, area and weight = tf, af, mf
(ii) Density = (P_f)
(iii) Hugoniot curve
(iv) Sonic velocity = (C_f)
(v) Specific acoustic resistance = $(P_f C_f)$

(c) **Parameters of the set up of welding**

(i) Stand off distance = (d)
(ii) Stand off angle = (α)
(iii) Impact velocity = (Vcp)
(iv) Dynamic impact angle = (β)
(v) Flyer plate velocity = (Vp)
(vi) Pressure at the contact point = (P)
(vii) Anvil or back up set up and its specific acoustic resistance (P_bC_b)

(d) **Parameters of parent plate**

(i) Thickness and area = tp, ap, mp
(ii) Density = (Sp)
(iii) Hugoniot curve
(iv) Sonic velocity = (C_p)
(v) Specific acoustic resistance = (S_pC_p)

(e) **Other important parameters**

(i) Temperature at the interface
(ii) Condition of jet at the interface i.e.
 (a) escaped jet
 (b) trapped jet
(iii) Impact Time.

Explosive for Explosive Welding

6. The different high explosives used for explosive welding are powder and plastics. One of the conditions for successful explosive welding is that the collision point velocity should be less than the sonic velocity in the metals being welded. The explosives of low detonation velocity are of special interest in explosive welding. The detonation velocity of well known explosives is much higher than the sonic velocity of the metal of our interest. In order to get collision point velocity within the range of bulk sound velocity, the angular plate arrangement

TABLE I

Srl. No.	Combination Flyer—Parent	Minimum Explosive loading for Welding: $C/_m \times 100$	(a)	Vp m/sec (b)	Vcp m/sec (c)	Tensile str. ratio (d)	Explosive loading for maximum strength: $C/_m \times 100$	(a)	Vp m/sec (b)	Vcp m/sec (c)	Tensile str. ratio (d)	Maximum Explosive loading for Welding: $C/_m \times 100$	(a)	Vp m/sec (b)	Vcp m/sec (c)	Tensile str. ratio (d)	Bulk sound velocity: Flyer m/sec	Parent m/sec
1.	Mild Steel to Mild Steel	14.06	4	250.32	2637.4	.89	22.5	6	383.6	3523.9	1.63	32.66	6	530.5	4793.65	1.00	4990	4990
2.	Copper to Copper	11.6	4	209.25	2398.6	1.23	17.6	6	307.63	2519.5	1.41	29.2	9	482.04	2765.4	1.13	4000	4000
3.	Aluminium to Aluminium	15.0	12	265.74	1173.6	.81	15.0	8	265.74	1524.5	1.22	18.7	6	325.03	2646.9	.812	5500	5500
4.	Brass to Mild Steel	13.6	4	243.86	2795.3	1.03	15.9	3	280.37	4016.8	1.65	21.7	4	394.03	4516.7	1.0	3500	4990
5.	Copper to Mild Steel	15.0	5	265.74	2538.7	1.01	17.5	4	306.04	3373.2	1.47	24.82	5	418.44	3997.6	1.23	4000	4990
6.	Aluminium to Mild Steel	12.8	6	229.42	1878.99	.80	16.6	4	291.65	3177.4	1.19	18.9	4	328.17	3761.7	1.0	5500	4990
7.	Aluminium to Brass	12.85	12	230.25	1079.8	.87	16.0	6	281.99	2484.2	1.283	16.0	3	281.99	4040.17	.80	5500	3500

NOTES :

(a) For explosive loading the stand off angle was varied, this was the maximum angle at which welding was noticed.

(b) The formula used to calculate Vp is $Vp = Vd \times \frac{Z-1}{Z+1}$, $Z = \sqrt{1 + \frac{32}{27}\frac{C}{m}}$

(c) The formula used to calculate Vcp is $Vcp = \frac{Vp}{2 \sin \beta/2}$ & $\beta = \alpha + 2 \text{ arc Sin } \frac{Vp}{2\,Vd}$

(d) Ratio of tensile strength of welding to Original Tensile Strength of weaker material of the two.

(e) For an explosive loading the stand off angle was varied, this was the minimum angle at which the welding was noticed.

(f) Test configuration is shown in fig. 2.

TABLE II(a) Initial Condition

Half hard 70/30 brass welded to Mild Steel Yield Strength = 45 tsi

Half hard 70/30 Brass

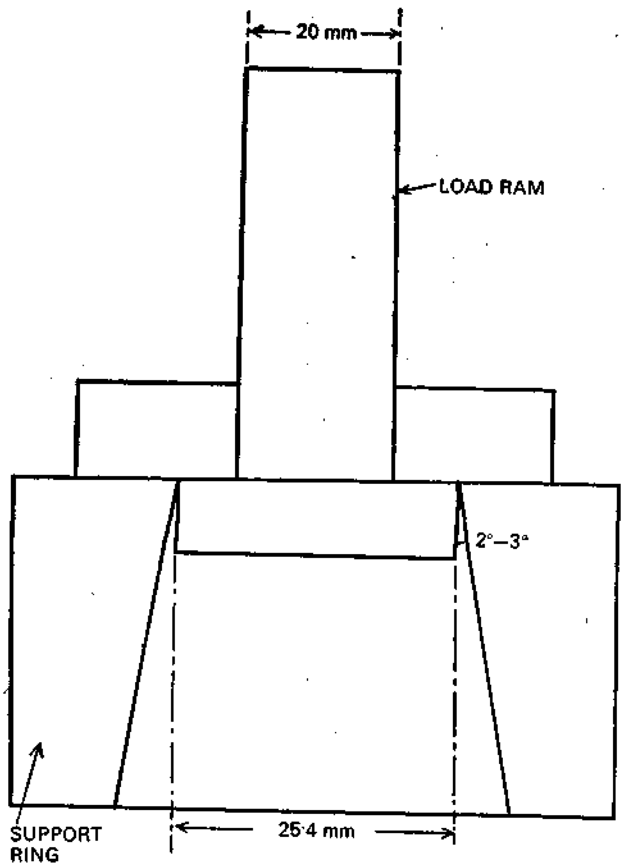
Tensile Strength	= 62,000 psi — 427.42 MPa
Yield Strength	= 52,000 psi — 358.488 MPa
Elongation in 2 inch %	= 23
Rockwell hardness	= B 70
Shear Strength	= 40,000 psi — 275.76 MPa

TABLE II(c)

(Effects of angle on Tensile Strength)

$C/_m = 0.159$

Angle (degree)	Tensile psi	Strength MPa
2	94320	650.2
3	96500	665.3
4	90200	621.8
5	83150	573.236
6	64210	442.7



WELD TEST CONFIGURATION

Fig. 2

not catch up with the shock wave in the plate before it has traversed the plate thickness. If the shock is not sufficiently strong to melt the materials, the advance part of the expansion wave is an elastic wave which travels with velocity higher than that of the plastic wave. Hence it is essential to use parallel or contact arrangement in larger thicknesses. In order to have an acceptable value cf the angle of obliquity, for thick plates it is important to have as low value of detonation velocity as possible. Two explosives are commonly used, the first being trimonite a mixture of ammonia nitrate, TNT and atomised aluminium. Velocity of detonation is in the range of 2 to 3.8 Km/sec depending upon the thickness of the explosive layer. The second is ammonia nitrate with 6 to 12% of fuel oil which has the corresponding velocity of detonation ranging from 1.5 to 2.4 Km/sec. Both these explosives require a booster charge for steady state detonation.

TABLE II(d)

Effects of angle on tensile Strength

$C/_m = 0.2020$

Angle	*Psi*	*MPa*
3	76000	523.9
5	57000	392.95
7	48320	333.1

TABLE II(b)

$C/_m$ = Explosive Weight/Total accelerated mass

Explosive loading $C/_m \times 100$	*tensile strength* psi	MPa	*Hardness rock-well* B	*Elongation in* %	*Shear strength* psi	MPa	*Yield Strength* psi	MPa
13.6	54000	372.3	108	5	32910	226.9	48000	330.9
15.9	96500	665.3	109	5	59320	409.0	65000	448.1
17.5	87200	601.2	113	3	48930	337.3	63000	434.3
18.1	80000	551.5	112	3	45320	312.4	63000	434.3
20.2	76000	523.9	112	3	45000	310.2	63000	434.3
21.7	62000	427.4	110	3	45000	310.2	57000	393.0

was used for our experiment but this is unsatisfactory for large plate with thickness in excess of say 5 mm because unstable edge displacement under explosive propulsion results in excessive interfacial melting and cracking of flyer plate. The maximum thickness is determined by the condition that the expansion wave originating from the back surface of the flyer plate must

7. PEK I military explosive was selected for the explosive welding experiments and as its detonation velocity (Vd) is 6.5 Km/sec the angular seperation method was used. The minimum explosive thickness (t_f) for steady state detonation was found tc be 1.2 mm. The detonation velocity of explosive varies with thickness and density, the compact roll sheets of PEK I, density (ρ_e)

1.55 gm/cc were used. The thickness of roll sheets varied from 1.2 mm to 6 mm depending upon the explosive loading and the corresponding detonation velocity is in the range of 6.37 Km/sec to 6.9 Km/sec.

Parameters of the Flyer Plate & Parent Plate

8. The maximum thickness of the flyer plate which could be welded by the angular set up was found to be 5 mm; above this thickness excessive interfacial melting and cracking of the flyer plate took place. The specific acoustic resistance ($P_f C_f$) of the flyer plate should be

9. When a longitudinal stress wave strikes a boundary between two dissimilar materials, a part of the stress will be transmitted and part will be reflected. The partitioning of momentum among the three waves involved, the incident wave of stress level σI, the reflected stress σR and transmitted stress wave σ_T is governed by the respective physical properties of the medium. The following relationship can be applied for computering reflected and incident stress—

$$\frac{\sigma R}{\sigma I} = \frac{P_p C_p - P_f C_f}{P_p C_p + P_f C_f} = K \qquad \text{—(2)}$$

When $P_p C_p = P_f C_f$ indicating that material is same on bothside of boundary, K is Zero. There is no reflected wave, all wave being transmitted. When $P_p C_p > P_f C_f$ the ratio K is positive implying that σ_I is originally a compressive wave. The reflected wave will also be compressive. For $P_p C_p < P_f C_f$ compressive wave will be reflected as tensile wave and vice versa. In case of explosive welding, the incident wave is compressive and if the weld is to be sustained, the reflected wave should also be compressive, otherwise reflected wave will separate the weld. So in that case $P_p C_p > P_f C_f$ and same is the case with tooling/anvil; otherwise reflected wave will damage the parent plate, hence $S_p C_p < S_f C_f$ and anvil should be massive to dissipate the shock wave.

10. The buffer used over flyer plate should have sufficient hardness and its specific acoustic resistance should be less than the specific acoustic resistance of the flyer plate; hard rubber, wood, card board have been used with success. The thickness of the buffer plate should not be less than the thickness of flyer plate to avoid damage to the flyer plate by the explosive charge. The equations relating to the plate velocity and $\frac{C}{m}$ are available. Gurney obtained from conservations of energy the relation between plate velocity (V_p), Detonation Velocity (V_d) and $\frac{C \text{ (explosive mass)}}{m \text{ accelerated mass}}$

$$V_p = \frac{V_d \sqrt{2}}{4} \sqrt{\frac{3\frac{C}{m}}{5 + 2\frac{C}{m} + 4\frac{m}{C}}} \qquad \text{— (3)}$$

while Duvall and Er K Mann using hydrodynamic theory obtained—

$$V_p = V_d \left[1 + \frac{27}{16}\frac{m}{C}\left(1 - \sqrt{1 + \frac{32}{27}\frac{C}{m}}\right)\right] \qquad \text{— (4)}$$

Gurney used conservation of momentum to derive the relation

$$V_p = V_d \frac{0.612 \frac{C}{m}}{2 + \frac{C}{m}} \qquad \text{— (5)}$$

and Chadwick gave empirical adjustment to this equation for explosive welding loading conditions.

Where

$$\frac{C}{m} = .1 \text{ to } .2 \quad V_p = V_d \frac{0.578 \frac{C}{m}}{2 + \frac{C}{m}} \qquad \text{— (6)}$$

Aziz and Co-workers calculated the velocity by the following equations :

$$\frac{V_p}{V_d} = \frac{Z-1}{Z+1} \text{ when } Z = \sqrt{\left(1 + \frac{32}{27}\frac{C}{m}\right)} \qquad \text{— (7)}$$

The velocity calculated by this equation is in good agreement with the measured plate velocity by the high speed camera methods. Hence this equation can be used to determine plate velocity. If no stand off distance (d) is kept, the initial few mm of the plates remain unwelded because the plate being accelerated has to travel certain finite distance to achieve the velocity. It is observed that the plate acquired 70% of its velocity within the first 12.5 seconds after the detonation first reaches the plate. This gives the value of the stand off distance equal to 0.2 to 0.54 times the thickness of flyer plate

$$d = [0.2 \text{ to } 0.5]\, t_f \qquad \text{— (8)}$$

depending upon the explosive and loading conditions.

Parameters of the set up of Welding

11. The collision point velocity (Vcp) is one of the most important factors which influence the type of bond at the interface. The consideration that $Vcp < Cf$ is essential for a good weld. The collision point velocity can be calculated from the following equations :—

If buffer is used—

$$Vcp = \frac{Vp \operatorname{Cos} \operatorname{arc} \tan \left[\frac{Vp}{CB} \operatorname{Sin} \left(\beta + \operatorname{arc} \operatorname{Sin} \frac{CB}{Vp} \right) \right]}{\operatorname{Sin} \left\{ \alpha + \operatorname{arc} \tan \frac{Vp}{CB} \sin \left(\beta + \operatorname{arc} \sin \frac{CB}{Vd} \right) \right\}} \qquad (9)$$

If no buffer is used—

$$Vcp = Vd \frac{\operatorname{Sin} (\beta - \alpha)}{\operatorname{Sin} \beta} \qquad (10)$$

In order to determine the collision point velocity, the dynamic angle should be known. It is seen that the flyer plate is of complicated form with the double curvature owing to the finite velocity of the detonation and also of the fact that the velocity of the plate near the edge is less than in the middle. An expression for angle β is obtained from the geometrical consideration in the theory of cumulative charges—

$$\beta = \alpha + 2 \operatorname{arc} \frac{Vp}{2\,Vd} \qquad (11)$$

The equation that $\beta = \alpha + \tan \frac{Vp}{Vd}$ is also found to be true within the accuracy for the application. The initial set up angle (α) is selected such that $Vcp < Cf$ which will depend on $\frac{C}{m}$ ratio and buffer used.

12. The consideration of the welding process shows that the pressure should be high enough. The problem of the pressure in the point of contact is very difficult since the two dimensional picture of impact and properties of metals are unknown at high pressure and the model of collision is not yet clear. The minimum pressure required at contact point for a successful weld as determined by experiments is—

.0217	mega-bar	— Aluminium to Aluminium
.03472	,,	— Aluminium to Steel
.02913	,,	— Aluminium to Brass
.04172	,,	— Brass to Steel
.04001	,,	— Copper to Mild Steel
.04179	,,	— Mild Steel to Mild Steel
.02871	,,	— Copper to Copper

13. The pressure at the collision point is dependent on volumetric strain and internal energy. Many models have been suggested by different research workers. The range of pressure can be estimated by the following equation :—

$$P = \frac{Vp}{2} Cf\ Pf \qquad — (12)$$

Other Important Parameters

14. Three types of bonds are possible. They are described below :—

(a) Jet escapes completely; in this case no intermediate layer is formed and jet removes the surface layer and brings the two clean metals together in solid phase bond.

(b) Jet does not escape, which happens in parallel plate arrangement and low dynamic angle or when the time of bond is very small; a continuous layer of melted material is formed between the plates. In this case the trapping of jet generates sufficient heat to melt a layer of material in which the surface oxides are digested. The amount of melted layer (mm) can be determined from the energy dissipated by the jet at the interface by the following equation :—

$$mm = \frac{\frac{1}{2}\, mf \left\{ \frac{mp}{mp + mf} \right\} Vp^2}{Hm + K\, c\, (Tm - To)} \qquad — (13)$$

Hm = Heat of Fusion
Tm = Melting temperature
To = Initial Temp
K = Excess heat in the melting zone.
c = Specific heat.

by taking excess heat factor in the melting zone (K) equal to 1.2 for aluminium, 1.4 for brass and copper and 1.8 for steel. For dissimilar metal bonding, the ratio of the metals in the melted zone will depend on the ratio of the (Hm+K. c (Tm—To)). The reported results are in agreement. The melting should be avoided by having lower Vcp by taking explosive of lower detonation velocity, lower $\frac{c}{m}$ and high stand off angle. The limit can be established by experimentation.

(c) Wavy interface is produced by oscillation of the jet flow/instability of the jet/non-coherent jet.

Wavy interface is of two types, one without any apparent intermediate layer and other with region containing melted material; this occurs at supersonic collision velocities and high impact angle; it should be avoided.

15. Equally good strengths have been noticed in all three types of bond but (a) type of bond and wavy interface without any apparent intermediate layer seems to be best due to its solid phase bond and absence of metallurgical problems and interface defects.

Metallurgical Aspects

16. Trapped jet type of welding results in rippling as shown in Fig. 3(a). The interface is extended by the length of the order of 74%. The presence of fused nuggets has been noticed just in front and some times just behind the crest of the wave. In these areas, there is mixing of dissimilar metals. By modification of the process parameters, oxide concentrations in these areas, layer formation and blow holes can be eliminated. The wave length and amplitude of wave increase with increase in explosive loading (Fig. 3(b)).

17. Variation in explosive loading at a constant stand off angle will produce variation in collision point velocity and peak pressure at explosive loading. As might be expected, the weld tensile strength exhibited a wide fluctuation as the explosive loading was varied. Significantly the maximum weld tensile strength was greater than the tensile strength of the unshocked parent metal by 64% and hardness measurement at the welded interface and surface indicated a similar increase. This is attributed to the combined effects of shock and strain hardening. Metallographic examination shows that wavy

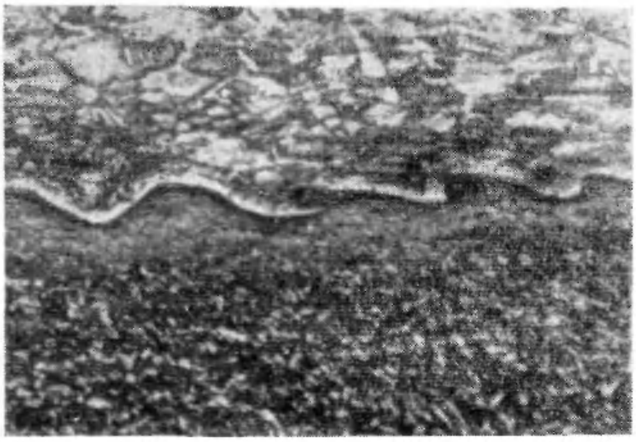


Fig. 3a. Copper to Brass × 75 (magnification)

$\frac{c}{m} = 130 \quad \alpha = 2^{\circ}$

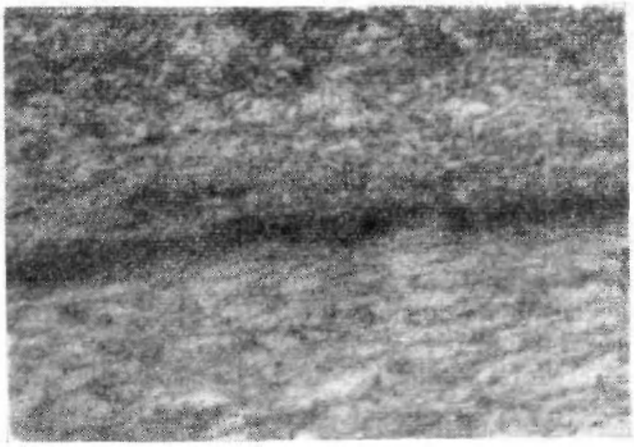


Fig. 3b. Copper to Brass ×75 (magnification)

$\frac{c}{m} = {}^{\circ}142 \quad \alpha = 2^{\circ}$

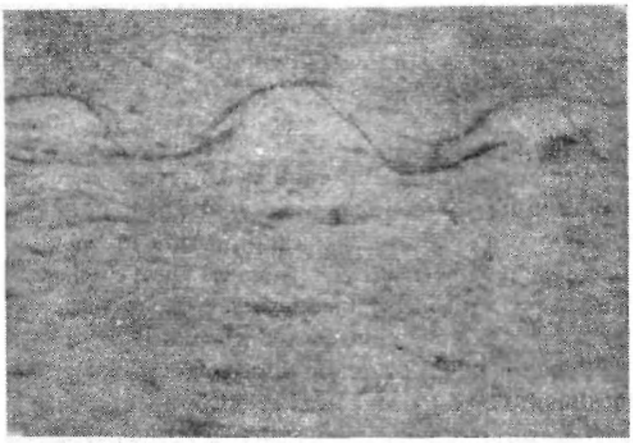


Fig. 3c. Mild Steel to Mild Steel ×75 (magnification)

$\frac{c}{m} = {}^{\circ}18 \quad \alpha = 3^{\circ}$

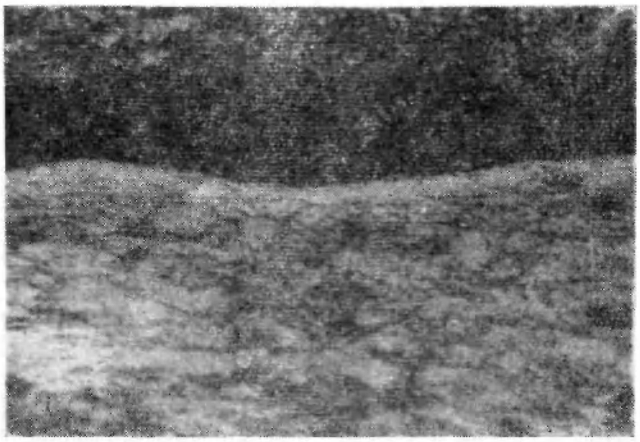


Fig. 3d. Brass to Mild Steel ×75 (magnification)

$\frac{c}{m} = {}^{\circ}136 \quad \alpha = 2^{\circ}$

flow deformation is limited to the weld zone, exceeding only .4 mm to .6 mm maximum either side of the weld interface.

18. The weld tensile strength is observed to fluctuate widely with explosive load even though the surface hardness was nearly the same. This would indicate that features at the weld interface must be responsible for controlling weld tensile strength. Metallographic examination of the weld interface at different explosive loading shows that the wave amplitude and weld defects increase as explosive loading increases. The major weld defects are associated with interfacial melting. The solidified melt pockets contain numerous solidication voids for thermal contraction. Details of properties at various explosive welding and stand off angles is given in Table II for Brass and Mild Steel welds. Fig 3(c) & (d) show metallograph of Mild steel to Mild Steel and Brass to Copper respectively.

Conclusion

19. The experimental results show that there is a limited range of bonding conditions which produce a good bond and best mechanical properties are obtained at critical parameters, (Refer Table I). These can be established for a given combination. The explosive loading for a given combination can be calculated for a given combination by the equations discussed in the paper. The maximum Vcp can be taken as bulk velocity of the sound in the materials and minimum Vcp is that which gives the minimum pressure required at the interface for the welding and a value between maximum and minimum should be chosen which gives the best results. Some suggested values are given in Table I. It must of course be realised that explosive welding does not replace conventional welding process but only supplements them and extends the range of applications.

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