EXPLOSIVE WELDING OF ALUMINUM, TITANIUM AND ZIRCONIUM TO COPPER SHEET METAL

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ABSTRACT

The main material properties affecting the explosive weldability of a certain metal combination are the yield strength, the ductility, the density and the sonic velocity of the two metals. Successful welding of the metal combination depends mainly on the correct choice of the explosive welding parameters; i.e. the stand-off distance, the weight of the explosive charge relative to the weight of the flyer plate and the detonation velocity of the explosive.

Based on the measured and the handbook values of the properties of interest, the explosive welding parameters were calculated and the arrangements for the explosive welding of the Al-alloy 6061-T6, titanium and zirconium to OFHC-copper were determined. The relatively small sheet metal thickness (1/8") and the fact that the thickness of the explosive layer must exceed a certain minimum value were considered during the determination of the explosive welding conditions. The results of the metallographic investigations and the measurements of the shear strength at the interface demonstrate the usefulness of these calculations to minimize the number of experimental trials.

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INTRODUCTION AND OBJECTIVES

Cladding of dissimilar sheet metals can be achieved by explosive welding (1-4). The parallel configuration shown in Figure 1 is used when the sheet metals are of relatively large planar dimensions. The main explosive welding parameters are the detonation velocity of the explosive, the weight of the explosive charge relative to that of the flyer plate (c/m ratio) and the stand-off distance between the flyer and the base plate. The determination of the explosive welding parameters, which produce good metallurgical bond at the interface, is governed by the density, the sonic velocity, and the plastic properties of the flyer and base plate materials besides the thickness of the flyer plate.

The objectives of this program were to clad OFHC-copper plates to plates of the aluminum alloy 6061-T6, titanium (ASME SB265GR2) and zirconium (ASTM B551-79). The explosive welding parameters were calculated and the quality of the resulting bond was evaluated.

MATERIAL PROPERTIES

The yield strength ($\sigma_{0.5}$), the ultimate tensile strength σ_u and the percent elongation δ of the materials used in this program were measured, while the density, the sonic velocity C and the melting temperature T_m are the handbook values (5), Table 1.

Table 1: Material Properties

Property	Material			
	Al6061-T6	OFHC Copper	Titanium ASME SB 265 GR2	Zirconium ASTM B 551-79
$\sigma_{0.5}$ (N/mm^2)	276	277	353	416
σ_u (N/mm^2)	334	243	492	534
δ (%)	10	40	24	20
ρ (g/cm^3)	2.7	8.96	4.54	6.44
ρC (m/s)	5105	3580	5100	3600
ρC (g.m/cm^3.s) (Impedance)	13784	32077	23154	23184
T_m (^{o}C)	660	1083	1725	1850
Thickness (mm)	3.18 (1/8")			

SELECTION OF THE WELDING PARAMETERS

The explosive welding parameters were selected using the approach summarized by Ezra (2) and experimentally verified by Hegazy and Badawi(6).

The stand-off distance, i.e. the initial gap between the two plates, was taken equal to the thickness of the flyer plate = 3.175 mm. The detonation velocity of the explosive should be between 1/2 and 2/3 of the sonic velocity of the slower of the two metals. Since copper is the common material and it has the lowest sonic velocity of 3580 m/s, Table 1, the detonation velocity of the explosive in the three metal combinations Cu/Al, Cu/Ti and Cu/Zr should be higher than 1790 m/s and lower than 2386 m/s. Amatol with 80% ammonium nitrate and 20% TNT was used in the powder form as an explosive. The detonation velocity of Amatol was found to change with the thickness of the explosive layer as indicated in Figure 2. Explosive layers with a thickness less than 25 mm may produce unreliable detonation. The choice of the thickness of the explosive layer is governed by the density and the thickness of the flyer plate. This is evident from the following relation

$$\frac{c}{m} = \frac{\rho_{ex} \cdot t_{ex}}{\rho_f \cdot t_f} \qquad (1)$$

Where c = weight per unit area of the explosive
m = weight per unit area of the flyer plate
t = density and thickness
The subscripts ex and f refer to the explosive and the flyer plate respectively.

Copper is chosen as a flyer plate for the following reasons:

i. Copper has the highest ductility, Table 1, and hence it can withstand the higher plastic deformations due to double plastic bending.

ii. Copper has the highest density, Table 1, and hence the c/m ratio, Eq (1), can be kept as low as $c/m = 0.9$ taking into consideration that the thickness of the explosive layer may not be less than 25 mm and the density of the explosive ρ_{ex} 1 g/cm^3. Higher values of c/m will reduce the bonding strength (6).

Referring again to Figure 2, the detonation velocity corresponding to an explosive layer of 25 mm is about 3500 m/s. This value is higher than the maximum allowable detonation velocity of 2386 m/s. Addition of salt to Amatol reduces the detonation velocity as shown in Figure 3. Using an Amatol-salt mixture of 18% salt gives in the average a detonation velocity of V_d = 2300 m/s.

The estimated values of the explosive welding parameters are therefore as follows:

stand-off distance = 3.175 mm
c/m ratio = 0.9
(copper as flyer plate)
detonation velocity V_d = 2300 m/s

These values will be used to check the resulting plate impact velocity Vp and the resulting impact pressure P at the interface. The approximate relation (2)

$$P = \frac{\rho_1 C_1 \cdot \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} V_P \qquad (2)$$

can be used to obtain the impact pressure, where $_1$, c_1, and $_2C_2$ are the acoustic impedances of the colliding plates and Vp is the impact velocity. Figure 4 shows a graphical representation of Eq (2) for the required material combinations Cu/Al, Cu/Ti and Cu/Zr using the values of the impedence given in Table 1.

The plate impact velocity may be related to the detonation velocity and the c/m ratio through the empirical equation of Deribas et al. given in Reference (2)

$$V_p = 1.2\ V_d \frac{x-1}{x+1} \qquad (3)$$

$$\text{where } x = (1+1.185\ \frac{c}{m})^{\frac{1}{2}}$$

Substituting the values of c/m = 0.9 and V = 2300 m/s gives V = 496 m/s. From Figure $4_2$the plate impact pressure will be 4850 N/mm for Cu/Al and 6600 N/mm^2 for Cu/Ti and Cu/Zr. Comparing those values with the static yield strength of the metals $(\sigma_{0.5})$, Table 1, the impact pressure is about 18 times the yield strength of the stronger Al-alloy (Cu/Al) and about 19 times the yield strength of the stronger titanium (Cu/Ti) and about 16 times the yield strength of the stronger zirconium (Cu/Zr). These figures are higher than the values reported by Ezra(2) of 10-12 times the yield strength of the stronger of the two metals. However, an analysis carried out by Hegazy and Badawi(6) of the experimental results of Zhengkui et al.(7) showed that good welding is achieved at impact pressures which are up to 25 times the yield strength of the stronger of the two metals.

EXPLOSIVE WELDING EXPERIMENTS

The calculated explosive welding parameters were checked experimentally using plates of 150 x 300 mm planar dimensions. A No. 8 detonator and 10g Detasheet booster are used to initiate the explosive reaction along the plate length. A 19-mm thick hard board is used as an energy sink. Before assembling the mating surfaces of the metal plates were cleaned and degreased.

QUALITY OF WELDMENTS

The quality of the weldments was evaluated through metallographic investigations and shear strength measurements at the interface. Figures 5, 6 and 7 show the shape of the interface along sections parallel and normal to the direction of detonation for the metal combinations Cu/Al, Cu/Ti and Cu/Zr respectively. A straight interface resulted between copper and aluminum, a uniform wavy interface resulted between copper and titanium and nonuniform wavy interface was achieved between copper and zirconium. Satisfactory welds can be obtained with all three types of interfaces (8) provided no excessive melting takes place at the interface. Theoretical and experimental analysis of wave formation during explosive welding has been the subject of many publications, e.g. (9,10)

The shear strength at the interface was also measured parallel and normal to the direction of detonation in the way shown schematically in Figure 8. The cross-sectional area of the tested interface ranges between 3 and 20 mm^2. The results of the shear tests are summarized in Table 2 together with the shear strength $(\approx \frac{1}{2} \sigma_u)$ of the metals before cladding.

Table 2: Results of the shear tests at the weld interface for the three metals combinations

Metal combination	Initial shear strength N/mm^2	Shear strength at the interface N/mm^2	
		parallel	normal
Cu/Al	121/167	148	140
		143	162
Cu/Ti	121/246	174	134
		193	132
Cu/Zr	121/267	191	204
		201	203

It can be seen from Table 2 that the shear strength at the interface of all material combinations is higher than the initial shear strength of the weaker metal.

CONCLUSIONS

1. The calculated explosive welding parameters for the used material combinations produced high-quality weldments after the first shot.
2. The impact pressure at the interface can be as high as 19 times the yield strength of the stronger of the two metals without causing excessive melting.

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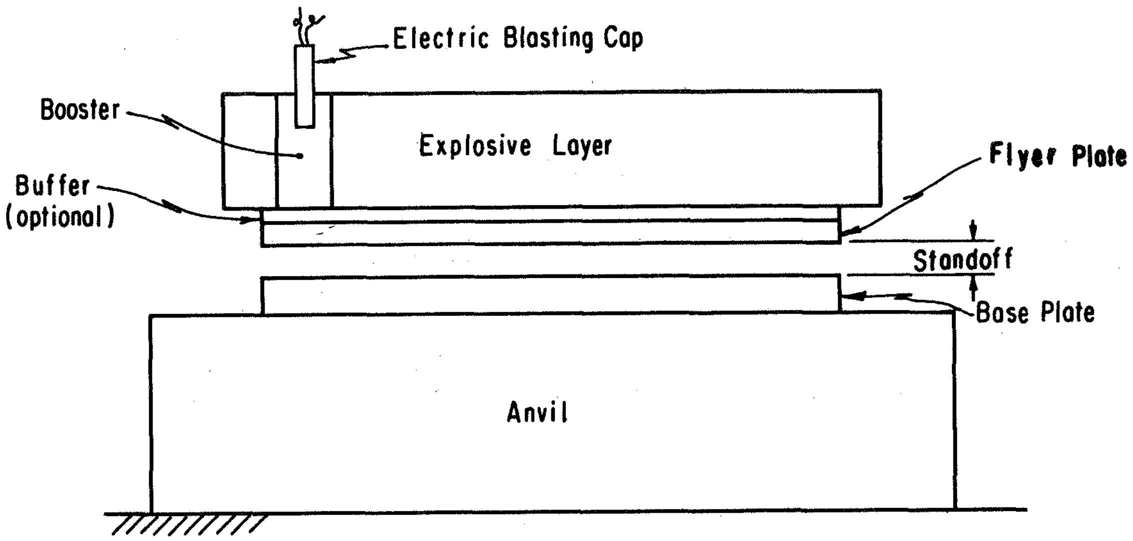


Figure 1: Parallel configuration for the explosive welding of two plates

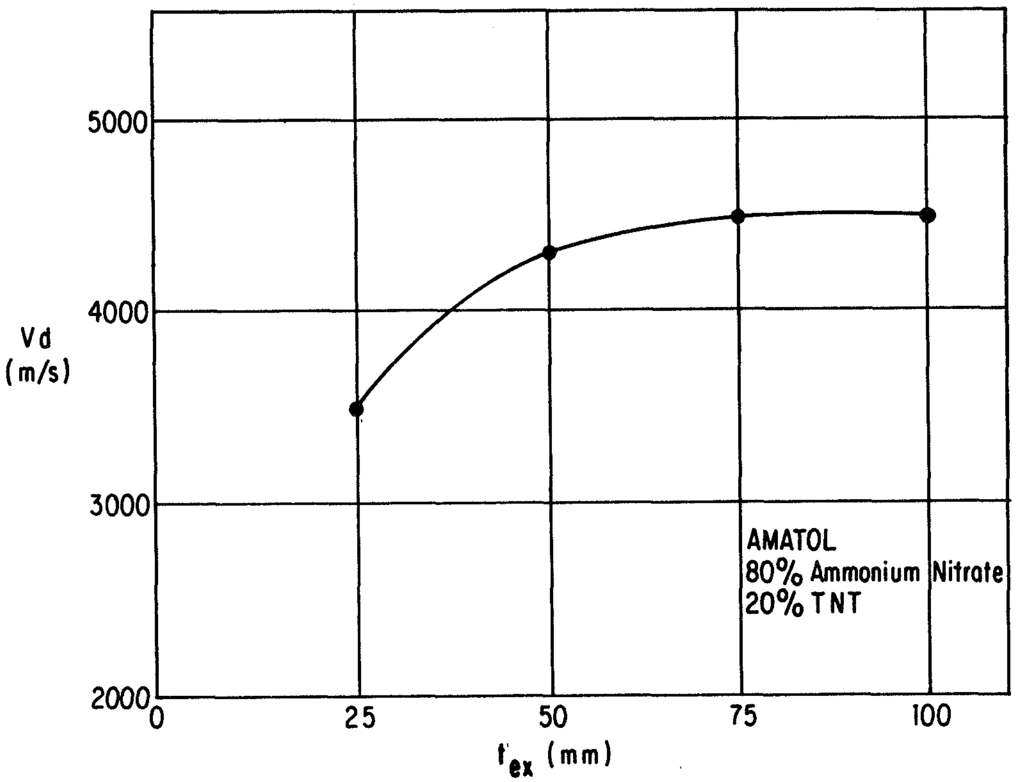


Figure 2: Effect of the thickness of the explosive layer t_{ex} on the detonation velocity Vd

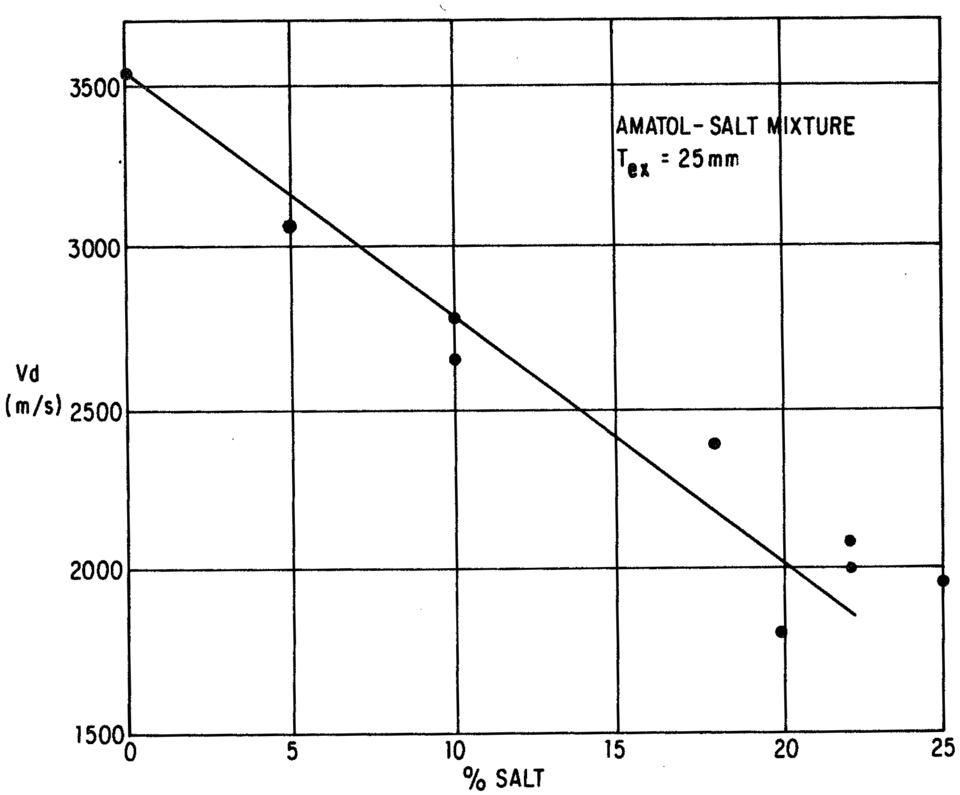


Figure 3: Effect of the percent salt on the detonation velocity Vd for an explosive layer of a thickness of 25 mm

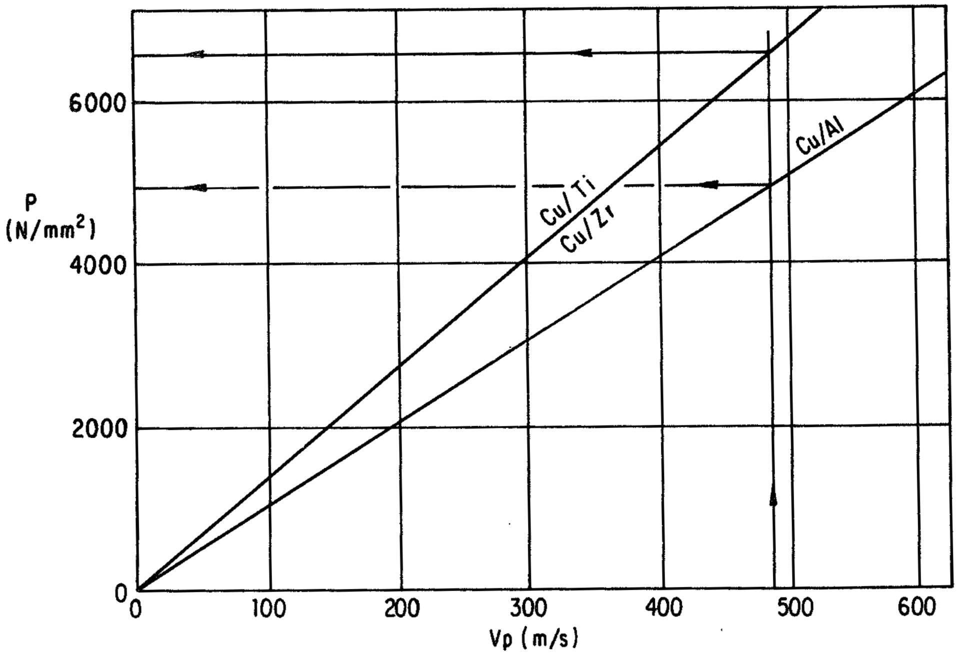
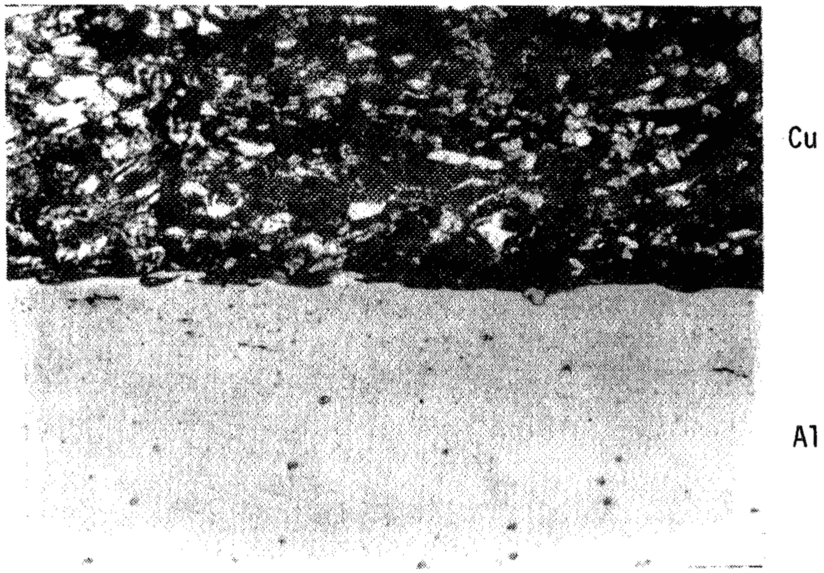
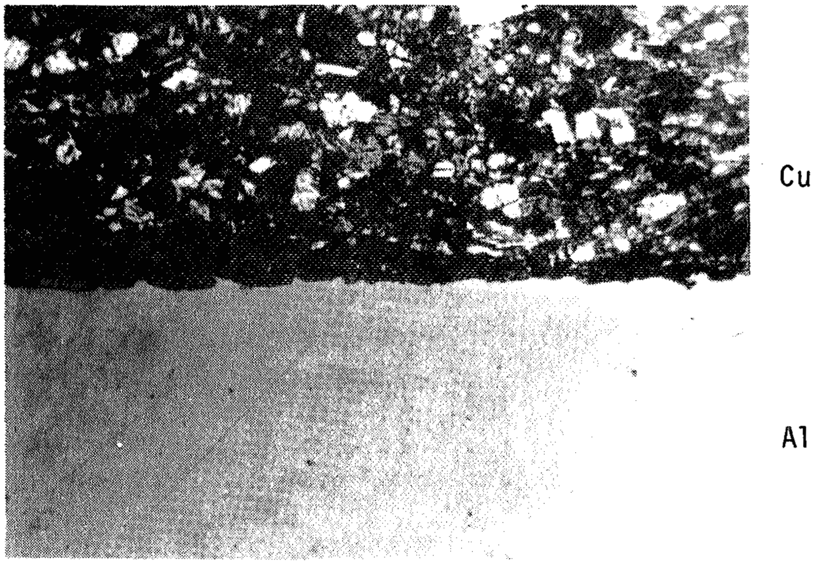


Figure 4: Relations between the impact velocity Vp on the impact pressure P at the interface for the material combinations Cu/Al, Cu/Ti and Cu/Zr

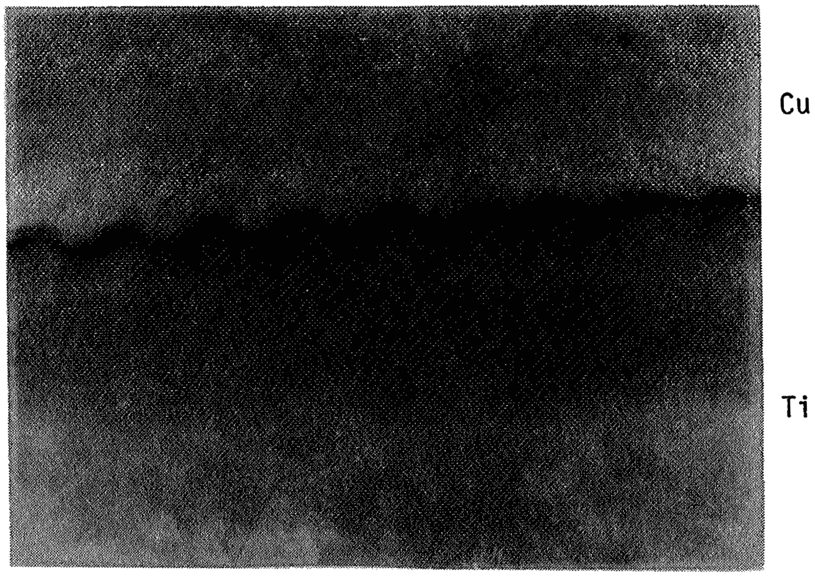


parallel



normal

Figure 5: Cu/Al-interface parallel and normal to the direction of denotation. Copper is etched for contrast, 150X



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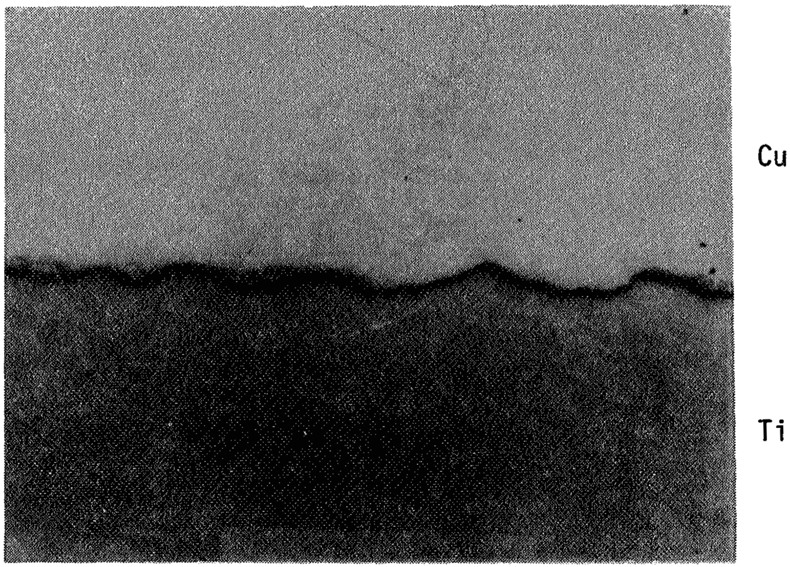
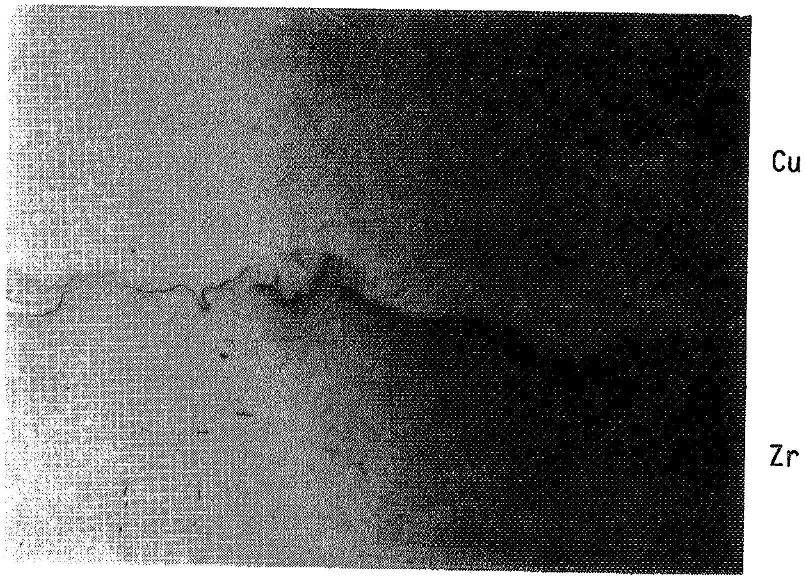


normal

Figure 6: Cu/Ti-interface parallel and normal to the direction of detonation, 77X

parallel



normal

Figure 7: Cu/Zr-interface parallel and normal to the direction of detonation, 150X

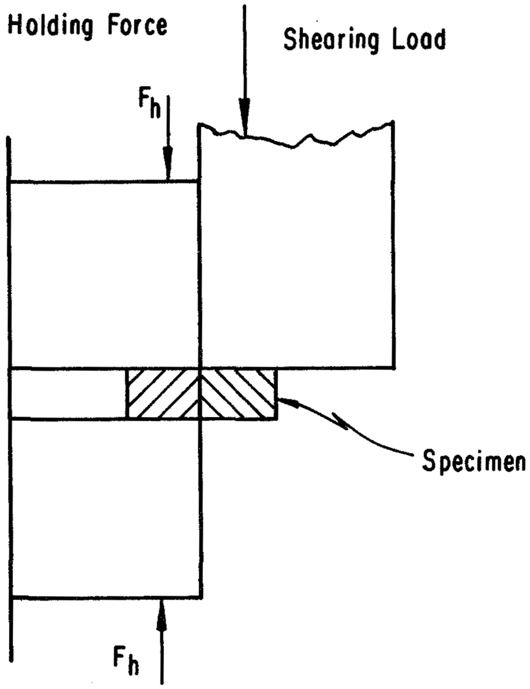


Figure 8: Schematic representation of the shear strength measurement at the interface