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CONF-821101--3

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LA-UR--82-1021

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TITLE: EXPLOSION BONDING: ALUMINUM-MAGNESIUM ALLOYS BONDED TO AUSTENITIC STAINLESS STEEL

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SUBMITTED TO: ASME 1982 CONFERENCE, PHOENIX, ARIZONA, NOVEMBER 1982

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FORM NO. 836 R4

Explosion Bonding: Aluminum-Magnesium Alloys
Bonded to Austenitic Stainless Steel

By

R. A. Patterson

## ABSTRACT

The explosion bonding of 5000 series aluminum alloys to 300 series stainless steel alloys is summarized. The process technique involves a parallel gap arrangement with copper or aluminum bonding aids. Successful bonds have been achieved using either a single shot process for joining the trilayer clad or a sequential shot technique for each metal component.

Bond success is monitored through a combined metallographic and tensile strength evaluation. Tensile properties are shown to be strongly dependent upon process parameters and the amount of intermetallic formation at the aluminum bond interface. Empirical data has been compared with experimental and destructive test results to determine the optimum procedures.

## Introduction

Explosion bonding is becoming a viable technique for the production of dissimilar metal welds not readily produced by conventional fusion welding processes. The autogenous and diffusionless characteristics of explosion bonding enhance the formation of metallurgical bonds between incompatible metals through atomistic bonding mechanisms. Thus the formation of deleterious brittle intermetallic phases is minimized generating bond properties approaching or equal to base metal mechanical properties.

Explosion bonding mechanisms based upon empirical and theoretical relationships have been the subject matter of several articles.[1-7] Typical bonding techniques employ either a gapped parallel plate or pressed angle plate arrangement with contact explosive charges.[6] Consensus is that the progressive detonation process produces a high pressure, high velocity oblique collision between the two metal constituents. Large pressure gradients along the detonation front surpass the metal constituents dynamic shear strength and produce an inviscid fluid flow of the metal surface regions. When the collision obliquity is beyond a threshold angle,[8-10] hydrodynamic flow of the metal surfaces will generate a jetting action which is considered to be critical for explosion bonding. The jet acts to efface surface contamination (oxides and foreign films) thus creating clean metallic surfaces at the collision apex. Compressive pressure then forces the metallic surfaces together to promote atomistic solid-state bonding. A characteristic interlocking of surface deformation zones produces a wavy bond morphology resultant from jet instabilities and fluctuating pressure gradients.[8,9]

Bonding parameter boundaries have been modeled based upon the onset of jet formation, the deleterious effects of shock wave rarefaction and interfacial melting.[7] This report evaluates the utilization of bonding models through examination of 5000 series aluminum to 300 series stainless steel explosion bonds.

Process Parameters

Figure 1 illustrates the arrangement used in the parallel gap explosion bonding process. The explosive charge is placed in contact with the flyer plate and detonated from one end to generate a linear detonation front. Pressure generated by gas expansion accelerates the flyer plate downward and results in the desired impact on the stationary base plate. Principal parameters affecting bond success are:

1. Stand-off distance
2. Explosive density
3. Quantity of explosive

4. Physical and mechanical properties of the metal constituents.

Interpretation of experimental results has resulted in several empirical explanations for the explosion bonding process and has produced working models for parameter selection.[4,7]

The stand-off distance is only important to the extent that full flyer plate acceleration is achieved. As such, the stand-off distance used during these studies has been set at twice the flyer plate thickness for thin components (up to 6.5 mm) and reduced to approximately the flyer plate thickness for thick components (up to 13 mm) to compensate for the increased impact energies.

Figure 2 illustrates an intermediate view of the explosion bonding process where the incremental nature of explosive detonation has accelerated the flyer plate to produce an oblique collision with the base plate. Geometry and conservation of momentum indicate that the detonation velocity, $V_D$, is equal to the collision point velocity, $V_c$, and related to the flyer plate velocity, $V_p$, through the dynamic bend angle, $\beta$, as given by the following expressions:

$$V_D = V_c \qquad [1]$$

$$V_p = 2\ V_D\ \mathrm{Sin}\ \beta/2 \qquad [2]$$

These two equations produce the basis for modeling the explosion bonding process with the boundary conditions imposed by shock wave interactions and hydrodynamic flow which produces jetting.

Shock waves are produced when the pressure impulse is delivered at velocities greater than the metal bulk sound velocities (i.e., sonic or supersonic impulses). Supersonic pressure impulses generate instantaneous stress and density gradients which possess a sharp dividing line between affected and unaffected material known as a shock front. Shock front interaction with the explosion bond can cause fracturing and as such should be avoided.[11] Two techniques are available to avoid shock interactions: subsonic collision or the use of buffers.

Subsonic collision velocities are desirable since a gradual redistribution of pressure and associated stress is accomplished. Subsonic detonation velocities can be achieved through the proper explosive selection with respect to the desired metal system. Representative bulk sound velocities for several metals and alloys, listed in Table I, indicate that collision velocities should be less than approximately 5000 m/s. Equation 3 shows the empirical relationship developed for nitroguanidine (NQ) explosive which indicates that the detonation velocity is linearly related to the explosive density.[12]

$$V_D = 0.144 + 0.402\ \rho \qquad [3]$$

The typical operating ranges is 2000 to 3000 m/s for manually compacted NQ explosive, which is less than the bulk sound velocity for most metals, Table I.

The explosive pressure, P, is also related to the explosive density, $\rho$, as shown in Equation 4.[12]

$$P = 1/2\ V_D^2\ \rho \qquad [4]$$

Thus, when higher pressures are required to produce satisfactory bonds the influence of shock effects becomes increasingly important. Impedance - matching buffers placed between the explosive charge and the flyer plate help to attenuate shock waves through an absorbing action. Compressive shock waves intersecting the flyer plate free surface (metal-air interface) are almost completely reflected back toward the bond line as tensile waves which may cause bond fracturing. Buffers reduce the reflected waves magnitude by allowing the wave to pass into the buffer material.

Minimum detonation velocity boundaries have been postulated to conform with a laminar to turbulent hydrodynamic flow transition. An empirical relationship has been developed to predict the transition velocity, $V_T$, as shown below:[13]

$$V_T = \left[\frac{2\ R_E\ (H_F + H_B)}{(\rho_F + \rho_B)}\right]^{1/2} \qquad [5]$$

where

$R_E$ = reynolds number

$H_F$ = flyer plate hardness

$H_B$ = base plate hardness

$\rho_F$ = flyer plate density

$\rho_B$ = base plate density.

Turbulence or jet oscillation results in a wavy bond interface which increases bond strength.[11,14,15]

Minimum flyer plate velocity or the critical impact pressure to produce jetting has been investigated and related to the metals physical and mechanical properties.[7] Equation 6 shows the expression for determining the minimum flyer plate velocity:

$$V_p = (\sigma_{uts}/\rho)^{\frac{1}{2}} \qquad [6]$$

where $\sigma_{uts}$ is the ultimate tensile strength and $\rho$ is the density of the stronger metal constituent.

Actual flyer plate velocities resulting from the mass ratio of flyer plate, m, to explosive, c, are then calculated with the Gurney Equation:[16]

$$V_p = \sqrt{2E}\left(\frac{3}{1 + 5\frac{m}{c} + 4\frac{m^2}{c^2}}\right)^{\frac{1}{2}} \qquad [7]$$

where $\sqrt{2E}$ is the characteristic Gurney velocity for a particular explosive.

Figure 3 shows a typical plot of dynamic bend angle versus detonation velocity to estimate bonding parameters. Boundaries defined by the metals bulk sound velocity, laminar to turbulent flow transition and minimum pressure for jet formation are set on a family of flyer plate velocity curves to predict operating regimes for explosive density and load factor. Curves similar to these significantly reduce the amount of experimentation required to produce explosion bonds and as such will be used for reference during the ensuing discussion on experimental results.

## Discussion

Satisfactory bonds between aluminum and stainless steel are not easily produced with conventional fusion welding techniques. However, explosion bonding has proven to be a suitable technique for this task and has produced mechanically sound clads between the 5000 series aluminum and 300 series stainless steel alloys. Direct bonds have been fabricated with limited success. Therefore, the experimental results will examine bonds produced with interlayer bonding aids of 3003 aluminum and oxygen free-high conductivity - copper (OFHC Cu).

Preliminary evaluation of explosion bonding OFHC-Cu to 304L stainless steel was performed to establish bonding and evaluation techniques.

Optimum bonds were produced between 3 mm thick copper and 6 mm thick stainless steel with nitroguanidine explosive at a density of 0.3 g/cc ($V_D$ = 2600 m/s). Mass ratios of 0.8 (mass flyer plate/mass explosive) with a stand-off distance of 6 mm produced bonds which were stronger than the OFHC copper. Tensile test performed on top hat tensile specimens in a punch and die fixture shown schematically in Fig. 4, failed at an ultimate tensile strength of approximately 290 MPa.

Base metal failure, shown in Fig. 5a, was typical for this clad arrangement. Direct evidence of bond integrity was indicated by the characteristic wave formation at the interface (Fig. 5a) and the ductile void coalescence base metal failure mode shown in the scanning electron fractograph of Fig. 5b.

Having established appropriate parameters for the OFHC-Cu to 304L stainless steel bond, parameters for a 304L stainless steel - OFHC-Cu - 5052-0 aluminum trilayer with a single explosive detonation were evaluated. Figure 6 shows a composite graph of specific bond attempts superimposed on the detonation velocity versus dynamic bend angle predictions for 5052-0 aluminum to OFHC-Cu system. The range of parameters evaluated were all within the predicted acceptable parameter boundaries, but yielded significantly different bond properties.

Explosive load factor plotted versus resultant bond tensile strength (Fig. 7) indicates that bond integrity is extremely sensitive to variations in bonding parameters. An optimum load factor was found to exist which implies that a critical dynamic bend angle and/or flyer plate velocity (Equations 2 and 7) must be obtained. Published results have also indicated that maximum bond strengths are achieved at an optimum dynamic bend angle.[16]

Metallographic examination of the aluminum/copper/stainless steel trilayers revealed that the copper to stainless steel interface had the desired wave formation while the aluminum to copper interface had extremely shallow waves and a laminar melt zone (Fig. 8). Tensile failures always occurred in a brittle mode in the aluminum - copper melt zone indicating the formation of a brittle intermetallic phase. Therefore, an alternate interlayer material (3003 aluminum) was evaluated.

Bonding between 316L stainless steel - 3003 aluminum and 5083 aluminum were performed by a sequential two shot technique. First thin section (0.5 mm thick) 3003 aluminum was bonded to 12.7 mm thick 316L stainless steel using nitroguanidine explosive. Then 6.4 mm thick 5083-0 aluminum was bonded to the 3003 Al/316L stainless steel clad. Table II lists the explosive parameters used and the resultant bond strengths as measured with top hat tensile specimens (Fig. [illegible]).

Figure 9 shows the bond zone between 3003 Al and stainless steel was laminar while the 5083 Al to 3003 Al bond shows substantial wave formation. Bond strengths equal to the ultimate tensile strength of the 3003 Al (112 MPa) were routinely achieved. Tensile failures were typically ductile in nature and initiated in the 5083 Al - 3003 Al bond. Figure 10 shows that bond failure is controlled by the 3003 Al and the fracture propagates along the 5083 Al - 3003 Al wave line (Fig. 10a).

Tensile failures at stresses greater than the 3003 Al ultimate tensile strength (Table II) were achieved when the wave height was increased to greater than half the original 3003 Al thickness (0.5 mm). This result implies that bond restraint imposed by the higher yield strength 5083 Al (145 MPa) reduces the macroscopic effects of the interlayer material as observed with brazed components. Thus improved bond properties can be produced through the proper selection of parameters even when weak interlayer materials are used.

## Summary

Mathematical models for predicting explosion bonding parameters are available and appear to be satisfactory for predicting start up procedures. Model predictions have significantly reduced the amount of empirical development required to produce acceptable bonds, but do not predict optimum parameters. Bond strength appears to be extremely sensitive to detonation velocity, bend angle and flyer plate velocity. Therefore, further effort is required to produce the appropriate relationships before explosion bonding can be transformed into a predictable science.

Explosion bonds between the 5000 series aluminum and 300 series stainless steel are possible. Relatively high bond efficiencies are produced by the explosion technique, but base metal strengths were not achieved with the OFHC-Cu interlayer or 3003 interlayer systems. Brittle intermetallics limit the use of copper bonding aids, while the 3003 system is limited by the interlayer mechanical properties.

## Conclusions

1. Explosion bonds between OFHC-Cu and 304L stainless steel are stronger than the copper base metal properties.

2. An optimum explosive load factor exists for the explosion bonding of the 5052 Al-OFHC Cu-034L stainless steel trilayer.

3. Wave formation and morphology is an extremely important parameter which can increase bond strength through the appropriate distribution of stress and strain.

4. Explosion bonds of 5083 Al-3003 Al - 316L stainless steel possess mechanical properties equal to the 3003 Al ultimate tensile strength but can be improved through optimization of the bond morphology.

## Acknowledgements

The author wishes to acknowledge the valuable assistance of the following Los Alamos National Laboratory personnel: J. O. Archer, A. J. Gray and A. D. Rollett of the Chemistry and Materials Science division; and M. J. Urizar and M. L. Clancy of the Dynamic Testing Division. Lois E. Rael for typing the report. Work was performed under the United States Department of Energy contract W7405-Eng 36.

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TABLE I

Bulk Sound Velocities of Metals, m/s

| Metals | | Alloys | |
|---|---|---|---|
| Uranium | 2400 | | |
| Zinc | 3000 | Monel | 4400 |
| Zirconium | 3800 | Hastelloy | 4400 |
| Copper | 4000 | 300-Stainless Steel | 4500 |
| Magnesium | 4500 | Bronze | 4000 |
| Aluminum | 5500 | | |

TABLE II

Parameters and Bond Strengths
5083 Al - 3003 Al - 316L SS

| Clad Type | Explosive Density (g/u) | Load Factor (m/c) | Bond Morphology (Wave Height / Original 3003 Thickness) | Ultimate Tensile Strength (MPa) |
|---|---|---|---|---|
| 3003 Al - 316L SS | 0.2 | 2.0 | Laminar | N. M. |
| | 0.2 | 1.3 | Laminar | N. M. |
| 5083 Al-3003 Al-316L SS | 0.3 | 2.0 | 0.3 | 110 |
| | 0.3 | 1.6 | 0.5 | 130 |
| | 0.3 | 1.3 | 0.6 | 170 |

N. M. = not measured

List of Figures

Figure 7 - Explosive load factor (flyer plate weight, m, /explosive weight, c,) versus bond strength for the 5052 aluminum - OFHC Cu - 304L stainless steel clads.

Figure 8 - Metallographic section of the 5052 Al - OFHC Cu - 304L stainless steel bond zone.

Figure 9 - Metallographic section of the 5083 Al - 3003 Al - 316L stainless steel bond zone.

Figure 10 - Scanning electron micrograph of the 5083 Al - 3003 Al - 316L stainless steel tensile failures showing the ductile 5083 Al - 3003 Al bond fracture.

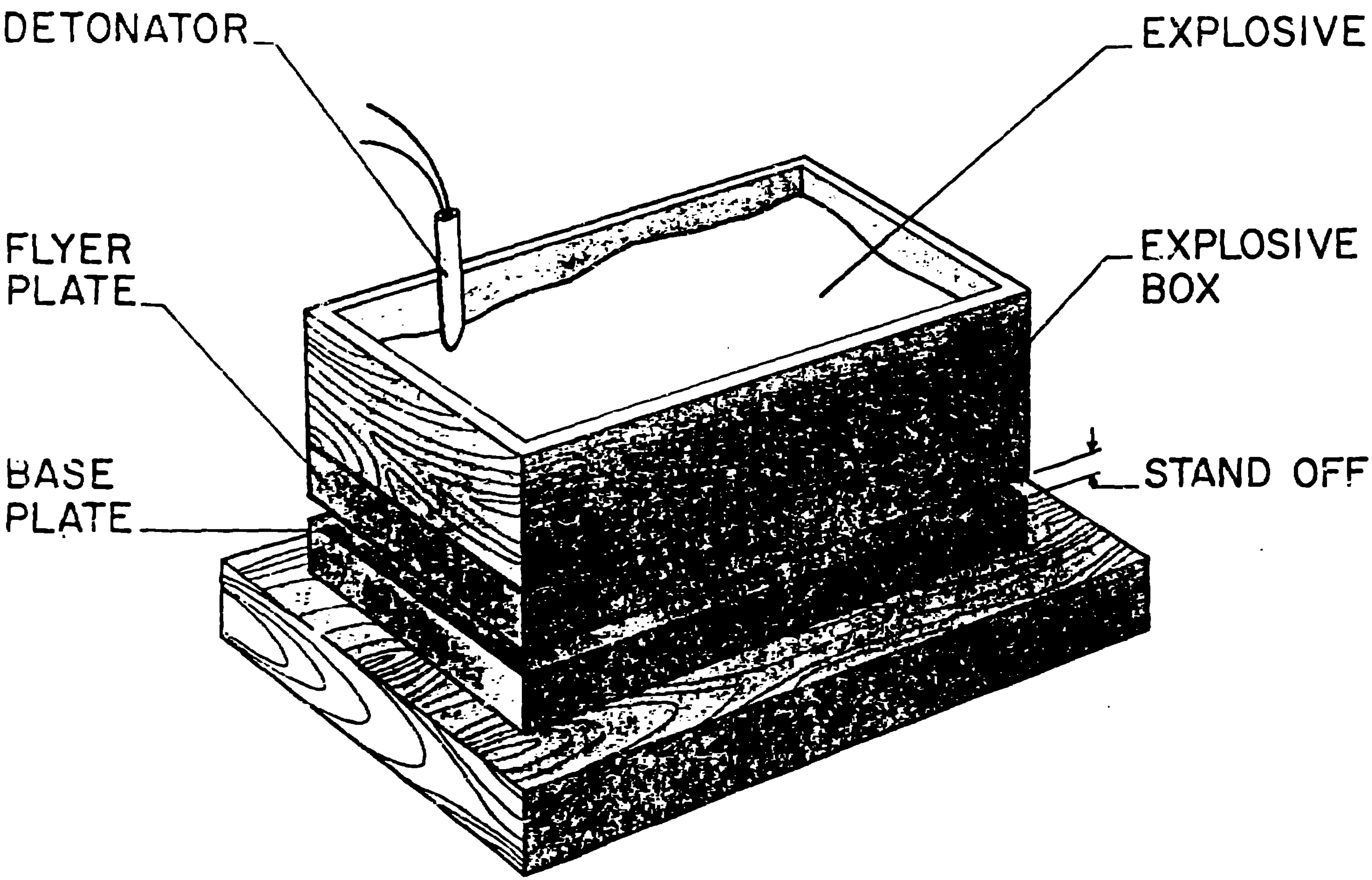
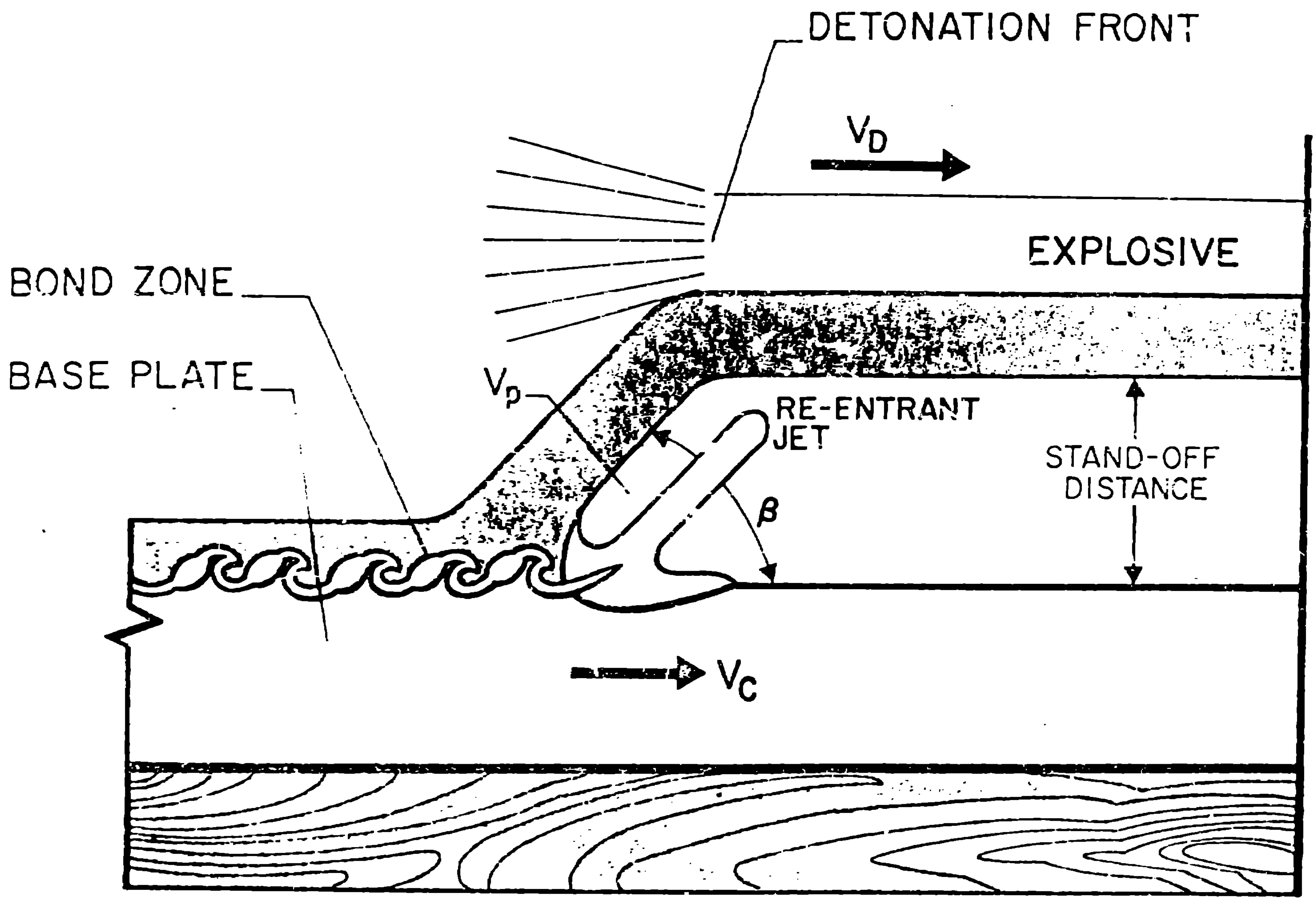
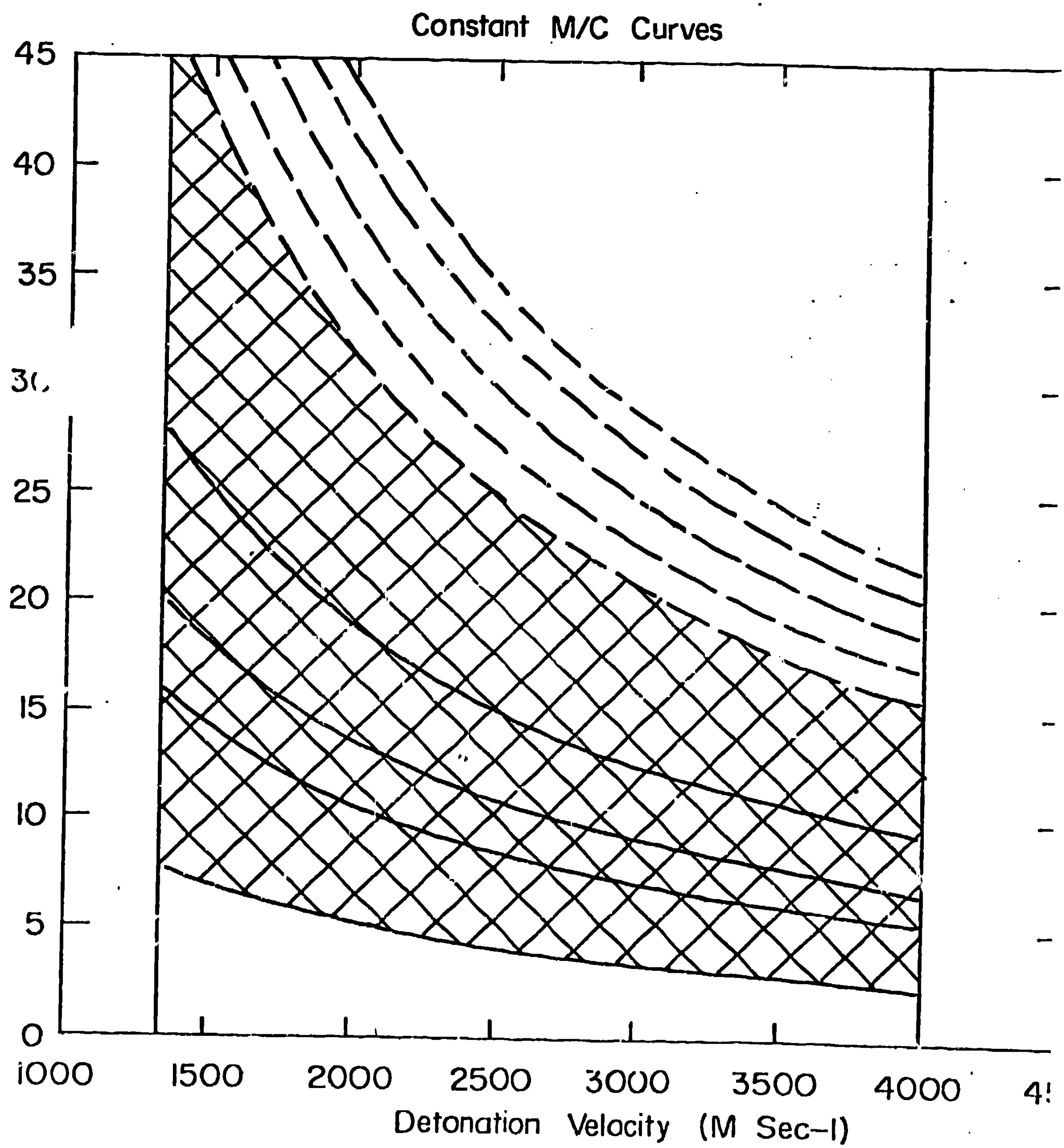

DETONATOR
EXPLOSIVE
FLYER PLATE
EXPLOSIVE BOX
BASE PLATE
STAND OFF

Fig 1



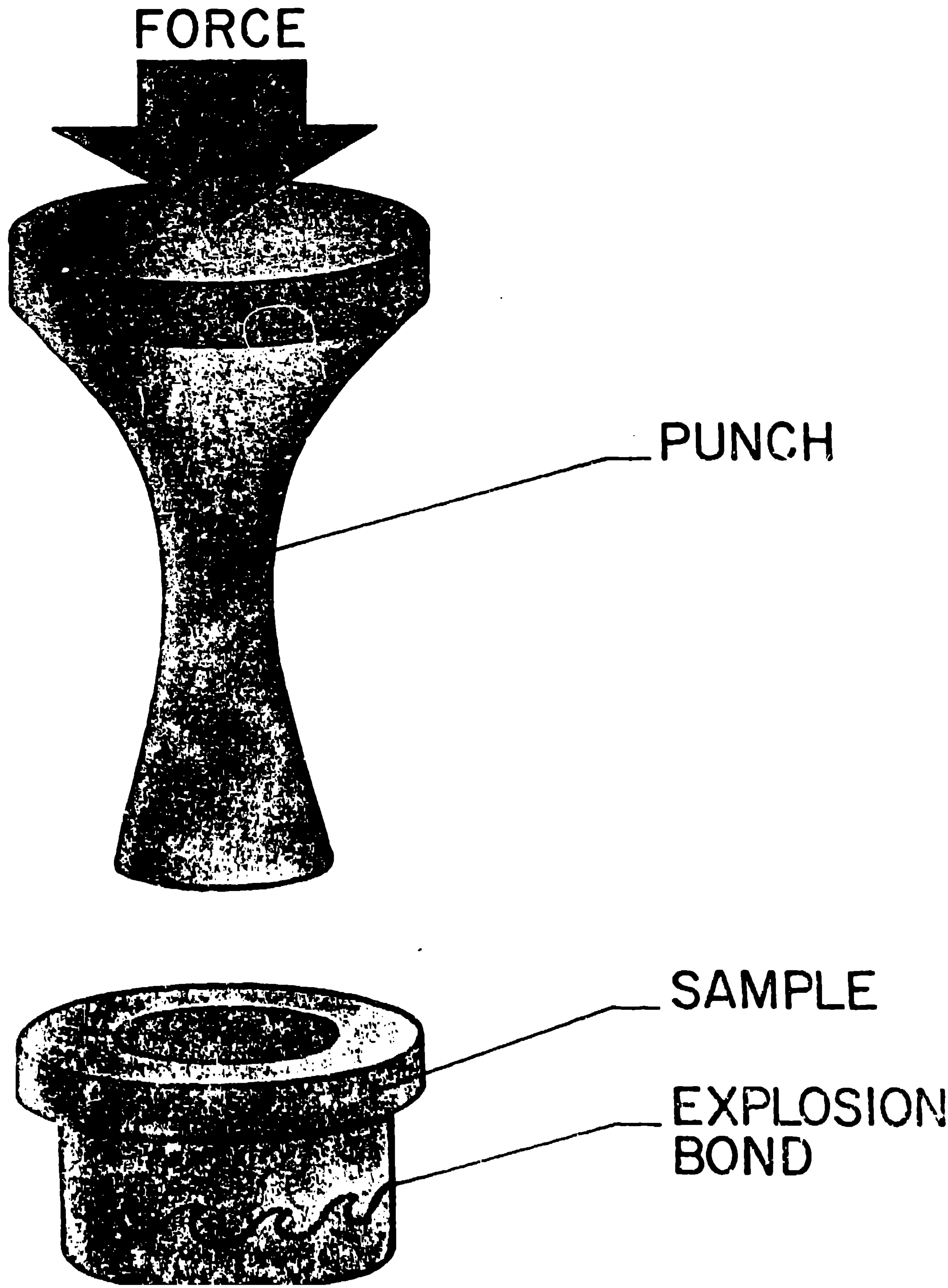
DETONATION FRONT
$V_D$
EXPLOSIVE
BOND ZONE
BASE PLATE
$V_p$
RE-ENTRANT
JET
STAND-OFF
DISTANCE
β
$V_C$


Fig. 2



Constant M/C Curves
45
40
35
30
25
20
15
10
5
0
1000
1500
2000
2500
3000
3500
4000
Detonation Velocity (M Sec-1)


Fig 3


FORCE
PUNCH
SAMPLE
EXPLOSION
BOND

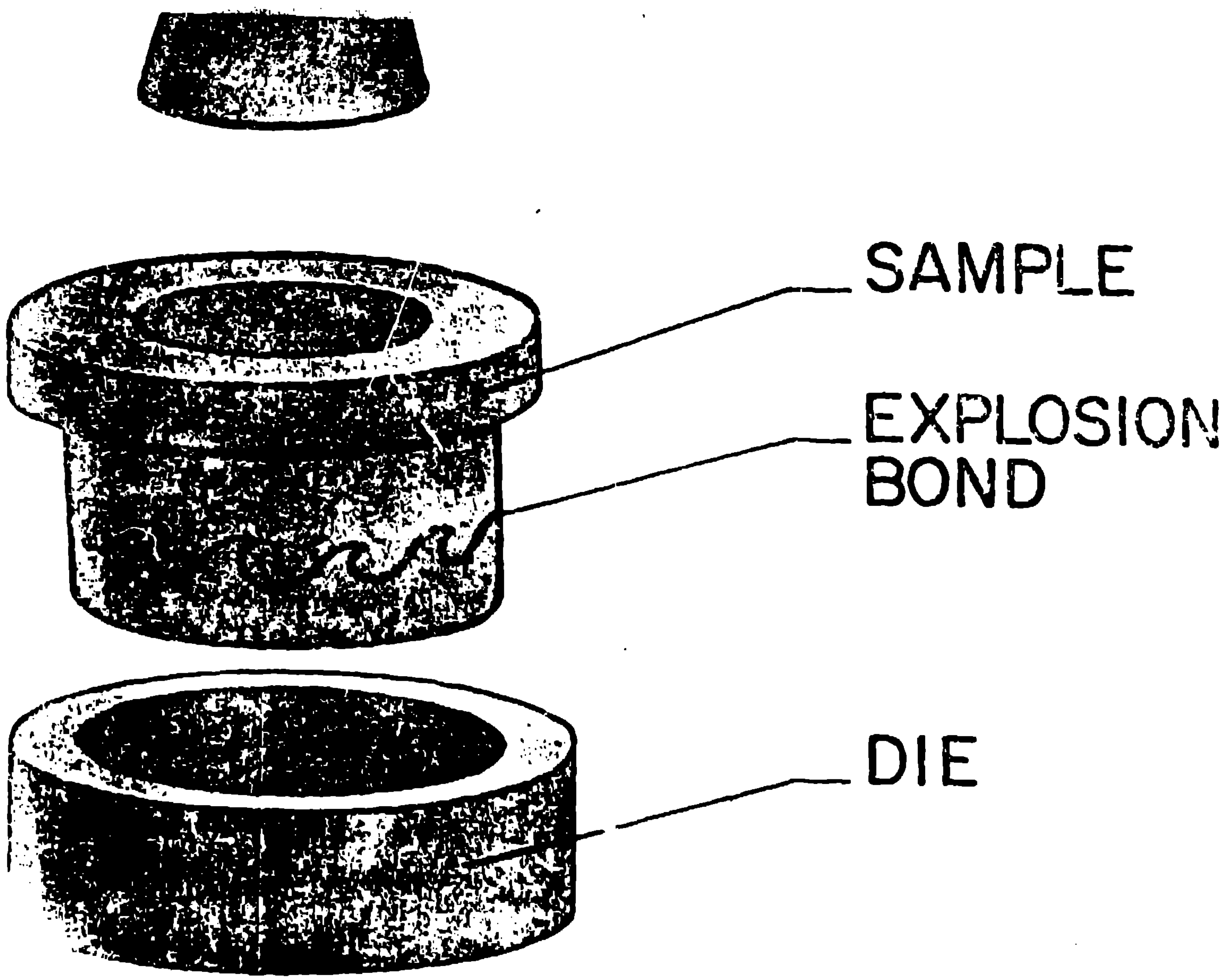



Fig 4

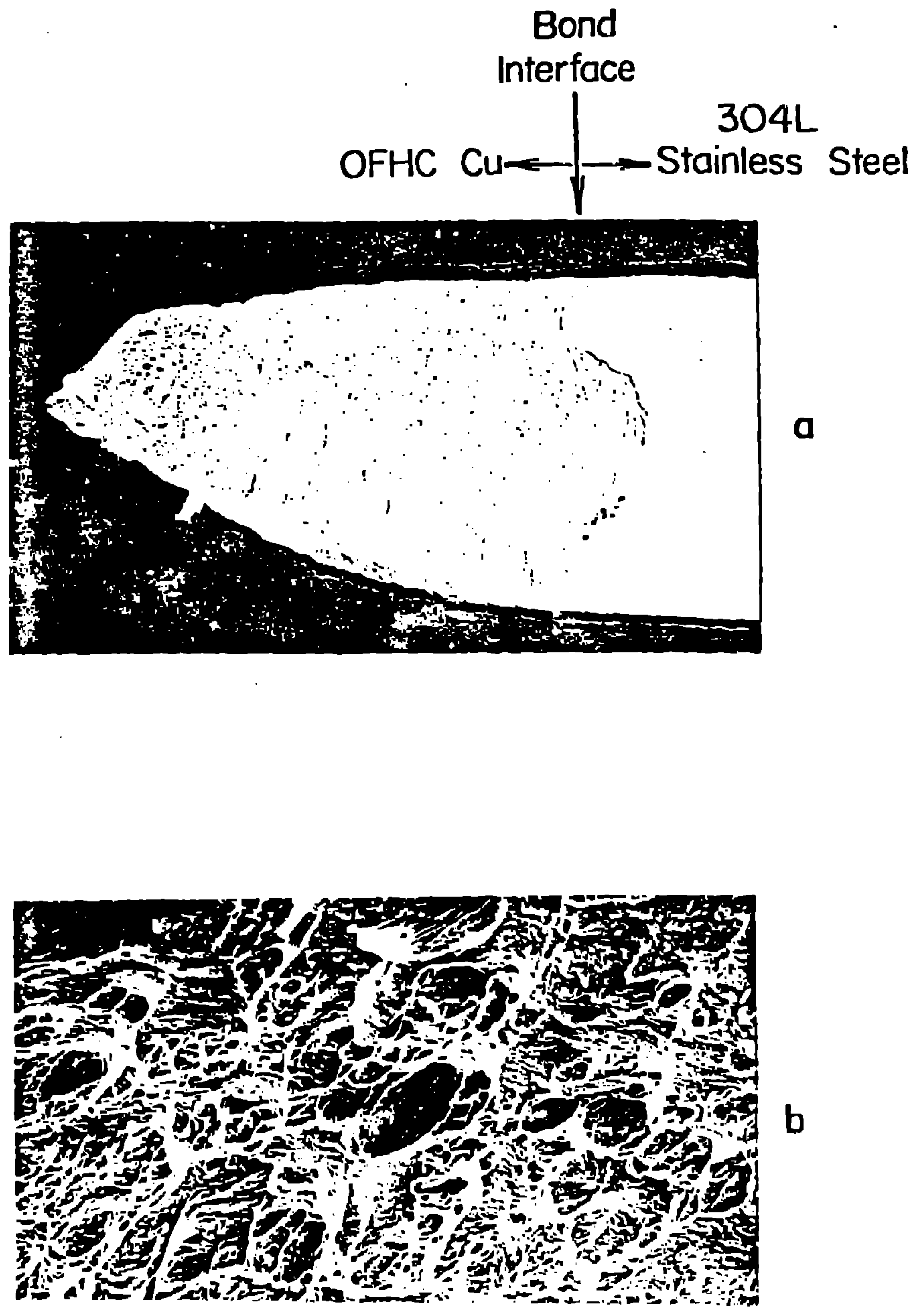



Fig. 5

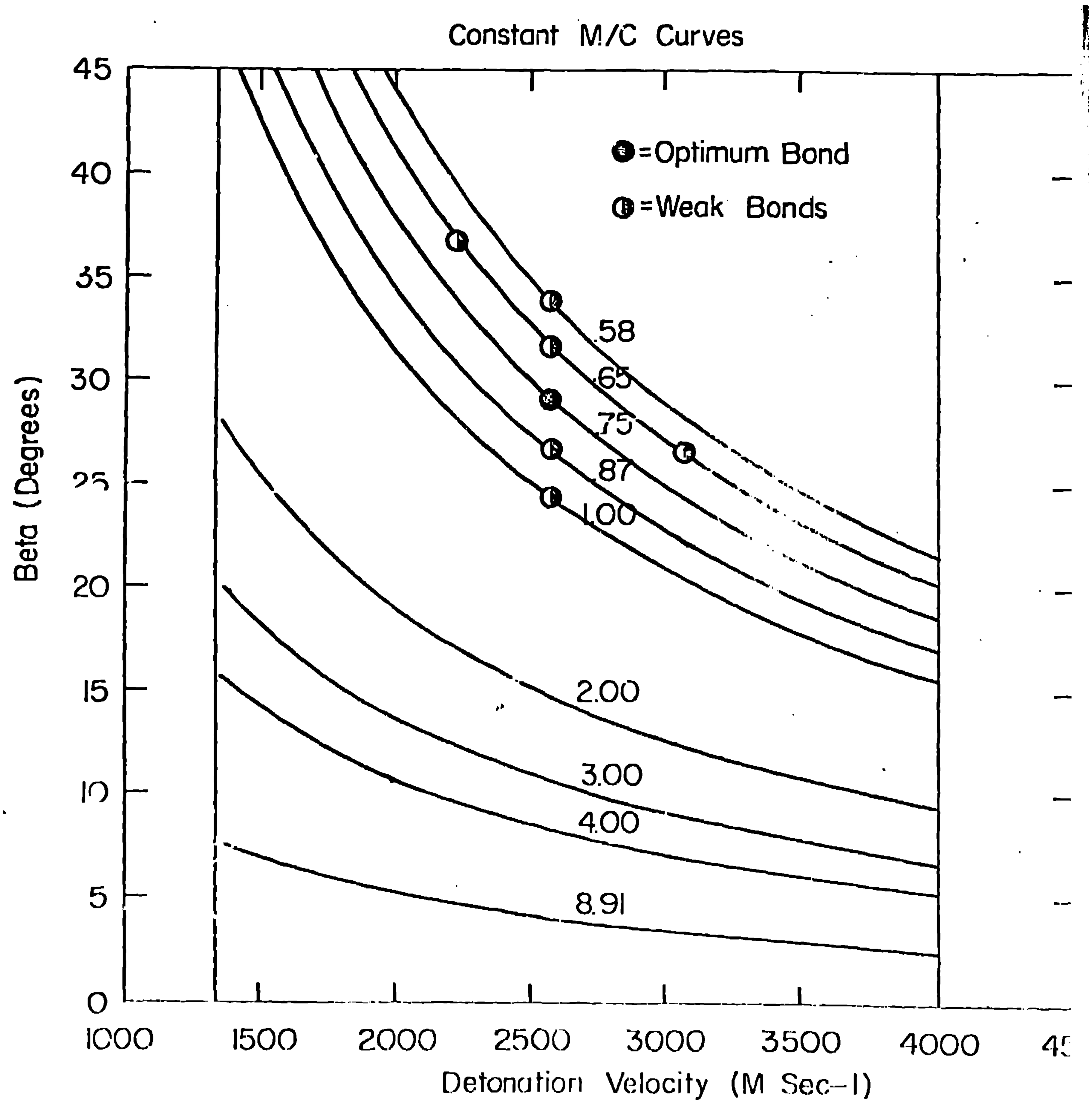
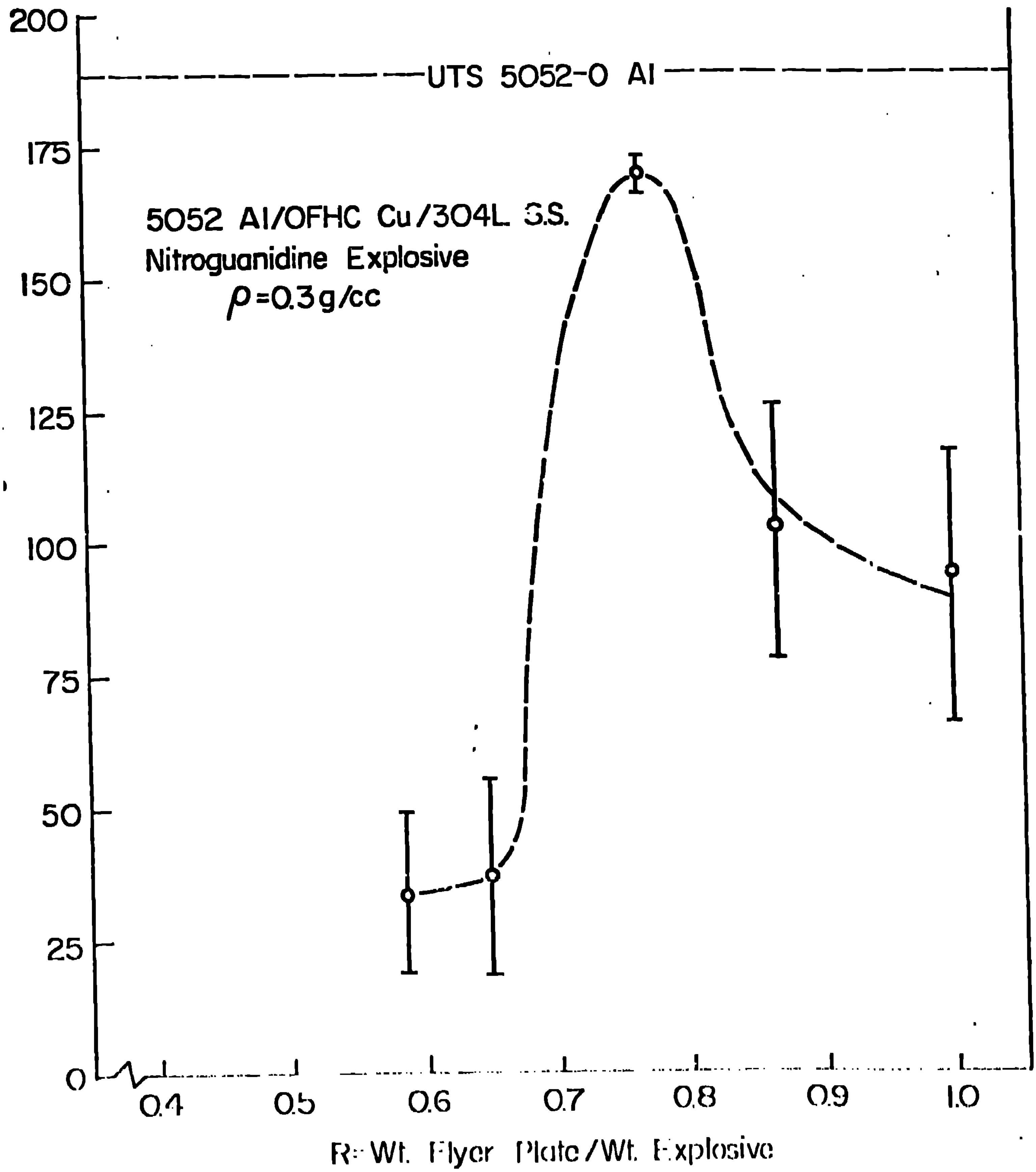

Constant M/C Curves
= Optimum Bond
= Weak Bonds
.58
.65
.75
.87
1.00
2.00
3.00
4.00
8.91
Beta (Degrees)
45
40
35
30
25
20
15
10
5
0
1000
1500
2000
2500
3000
3500
4000
Detonation Velocity (M Sec-1)

Fig. 6



200
175
150
125
100
75
50
25
0
UTS 5052-0 Al
5052 Al/OFHC Cu/304L S.S.
Nitroguanidine Explosive
ρ=0.3g/cc
0.4
0.5
0.6
0.7
0.8
0.9
1.0
R= Wt. Flyer Plate/Wt. Explosive


Fig. 7

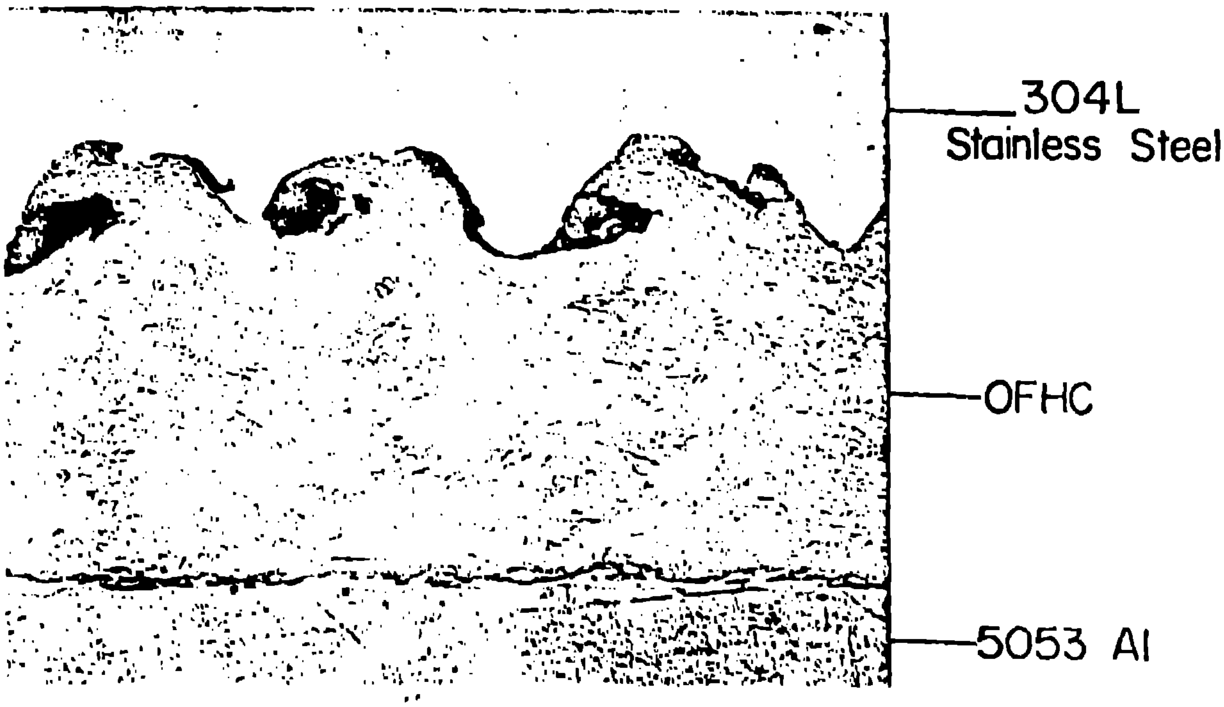



Fig. 8

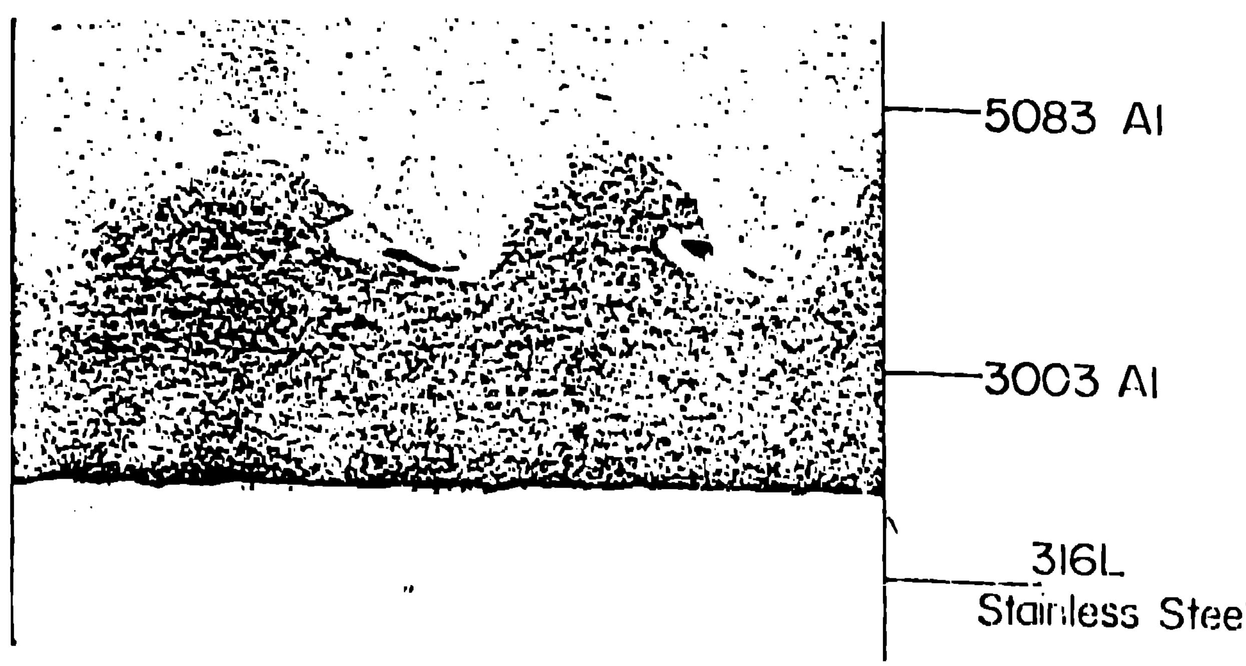



Fig 9

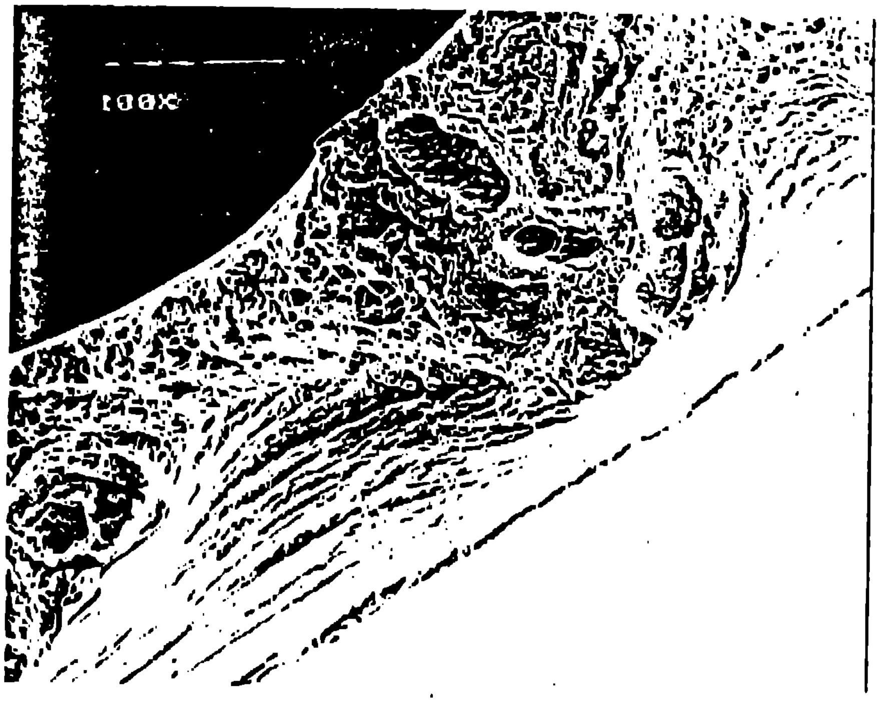




Fig. 1(c)