

NOBELCLAD TECHNICAL BULLETIN NT 200

**EXPLOSION BONDING PROCESS**

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**INTRODUCTION**

The explosion bonding process, also known as "cladding by the explosion welding process", is a technically based industrial welding process. As any other welding process, it complies with well understood, reliable principles. The process uses an explosive detonation as the energy source to produce a metallurgical bond between metal components. It can be used to join virtually any metals combination, both those that are metallurgically compatible and those that are known as non-weldable by conventional processes. Furthermore, this process can clad one or more layers onto one or both faces of a base metal, with the potential for each to be a different metal type or alloy.

Due to its use of explosive energy, the process occurs extremely fast; unlike conventional welding processes, parameters cannot be fine-tuned during the bonding operation. The bonded product quality is assured through selection of proper process parameters, which can be well controlled. These include material surface preparation, plate separation distance prior to bonding, and explosive load, velocity, and detonation energy. Selection of parameters is based upon the mechanical properties, mass, and acoustic velocity of each component metal being bonded. Optimum bonding parameters, which result in consistent product quality, have been established for most metals combinations. Parameters for other systems can be determined by calculation using established formulas.

The explosion cladding process was discovered in the late 1950's. By the end of the 1960s the process had been industrialized worldwide. During the near forty years of industrial application, the process has been continuously refined. Nobelclad and other experienced manufacturers have codified the technology and the method of determining bonding parameters. In comparison to the 1960s, today manufacturers can produce much larger plates, up to 30 square meters, and have mastered the more difficult metals combinations including cladding zirconium onto stainless steel.

## TERMINOLOGY

As with other welding processes, the explosion cladding process applies special terminology to many of the process variables.

The Cladding Metal (also called the cladder) is the plate, which is in contact with the explosive. It is typically the thinner component.

The Base Metal is the plate onto which the cladding metal is being bonded.

The Standoff Distance is the separation distance between the cladding metal and the base metal when fixtured parallel to each other prior to the bonding operation.

The Assembly Operation is the process in which the metals are fixtured into the proper positions for bonding, including setting standoff distance and explosive load.

The Bonding Operation is the period in which the explosive detonation occurs and in which the actual bonding occurs.

## PRINCIPLE

**Preparation** The first step of the cladding operation is the preparation of the two surfaces that are to be bonded together. These surfaces are ground or polished to achieve a uniform surface finish with a roughness Ra of 3  $\mu\text{m}$  (140RMS) or below, dependent upon the metals combination and thicknesses .

**Assembly:** The cladding plate is positioned parallel to and above the base plate, at a standoff distance which has been predetermined for the specific metals combination being bonded. This distance is selected to assure that the cladding plate collides with the base plate after accelerating to a specific collision velocity. The standoff distance typically varies from 0.5 to 4 times the cladder sheet thickness dependent upon the choice of impact parameters as described below. The limited tolerance in collision velocity results in a similar tolerance control of the standoff distance.



The standoff distance is controlled by support spacers at the plate edges and internally as needed. Internal standoff

devices are designed to be consumed by the jet, which is discussed below.

An explosive containment frame is placed around the edges of the cladding metal plate. The height of the frame is set to contain a specific amount of explosive providing a specific energy release per unit area.

**Bonding Operation:** The explosive composition and type is selected to yield a specific energy release and a specific detonation rate (the speed at which the detonation front travels across the explosive layer). The detonation rate must be subsonic to the acoustic velocities of the metals.

The explosive, which is generally granular, is uniformly distributed on the cladding plate surface filling the containment frame. It is ignited at a predetermined point on the plate surface using a high velocity explosive booster. The detonation travels away from the initiation point and across the plate surface at the specified detonation rate. The gas expansion of the explosive detonation accelerates the cladding plate across the standoff gap resulting in an angular collision at the specified collision velocity. The resultant impact creates very high-localized pressures at the collision point.

These pressures travel away from the collision point at the acoustic velocity of the metals. Since the collision is moving forward at a subsonic rate, pressures are created at the immediately approaching adjacent surfaces, which are sufficient to spall a thin layer of metal from each surface and eject it away in a jet. The surface contaminants, oxides and impurities are stripped away in the jet. At the collision point, the newly created clean metal surfaces impact at high pressures of several GPa (Figure 2). Although there is much heat generated in the explosive detonation, there is no time for heat transfer to the metals. The result is an ideal metal-metal bond without melting or diffusion.

**Impact parameters** The proper impact parameters for a specific metal combination are dependent upon the metal types, thicknesses, and mechanical properties. Selection of the proper parameters is critical to assure a strong, high quality, ductile bond. The impact conditions are associated by the equation:

$$V_p = 2 V_c \sin (\beta / 2)$$

Since the plates are parallel, the impact point velocity,  $V_c$ , is equal to the detonation velocity  $V_d$ .

Explosive detonation velocity,  $V_d$ , (2000 to 3500 m/s) is an independent variable selected to achieve required impact conditions.

Standoff Distance is an independent variable selected to achieve required impact conditions.

The impact angle  $\beta$  is a dependent variable, controlled by  $V_d$  and the standoff distance. It is typically 5 to 25°.



The plate collision velocity at the impact point,  $V_p$ , is typically in the 250 to 500 m/s range, with the specific value being dependent upon metal types, their physical and mechanical properties and chemical compatibility.

**The shooting parameters** The independent variables in the above equation, explosive detonation rate and standoff distance, are two major shooting parameters. These are selected to achieve the desired impact parameters. The explosive type and amount per sq-m is selected to achieve the necessary detonation energy and detonation velocity.



In combination with this, the plate separation distance is selected to achieve the collision velocity. These values are calculated for each metal combination using established formulas. Cladding metal thickness and mechanical properties of both metals are critical factors in these calculations. Most manufacturers have these calculations computerized.

- The amount of explosive per sq-meter C, is a function of the explosive energy E, the R ratio (unit area weight of explosive divided by unit are weight of cladding metal), the physical and mechanical properties of the metals.

$$V_p = f(E,R)$$

- The standoff distance, as well as the above parameters controls the specific plate velocity at the collision point.

- C and e typically vary with cladding metal thickness as shown in Figure 4.



**Process Variables:** Table 1 lists the process variables and indicates those that are essential and non-essential parameters of the cladding process.

Field	Variable	Essential	Non Essential
<b>Base metal</b>	Type and grade	X	
	Thickness	X	
	Heat Treat Condition	X	
<b>Cladder metal</b>	Type and grade	X	
	Thickness	X	
	Heat Treat Condition	X	
<b>Global</b>	Plate surface area		X

<b>dimensions</b>	Thickness ratio (Clad:Base)	X	
	Length and Width		X
<b>Cladding</b>	Stand-off distance	X	
	Explosive, weight/sq-m	X	
	Explosive type and composition	X	
<b>Operation</b>	Surfaces preparation	X	
<b>Variables</b>	Ignition kind and point		X
	Spacers device types		X
	Total weight of explosive		X
	Explosive Detonation rate	X	
	Explosive Confinement	X	

**Table I:** Explosion Cladding process Variables

**Practical Manufacturing Considerations:** The tolerances for explosive detonation rate and explosive energy are highly controlled for two reasons: 1) for many metals combinations the detonation rate window for bonding is small, 2) Non-uniformity in the explosion front can result in the jet front converging which causes nonbonding and damage. The explosives must comply with very strict standards for uniformity of detonation energy and detonation velocity. Proper understanding of the explosive manufacturing parameters and quality control processes is mandatory for consistent, reliable cladding.

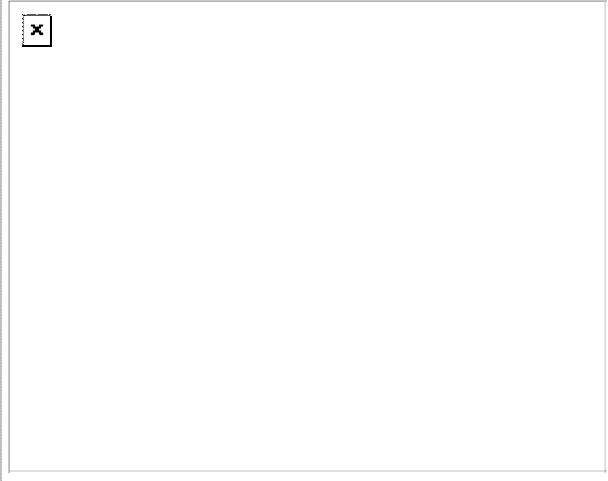
Since out-of-flatness of the cladding and base plates results in standoff variations, flatness requirements of component metals for cladding are typically much tighter than standard commercial tolerances.

**Interface** The interface generally exhibits wavy bond morphology (Figure 5). The wavelength  $\lambda$  and the height  $h$  of the waves depend on the impact parameters. The angle  $\beta$  and the thickness  $e$  of the cladding plate directly determine the wavelength  $\lambda$ .

$\lambda = k e \sin^2 (\beta / 2)$   $k$  is a constant which varies with

metals types and properties.

Thus, the wavelength can be controlled through impact parameters to achieve specific bond features as needed.

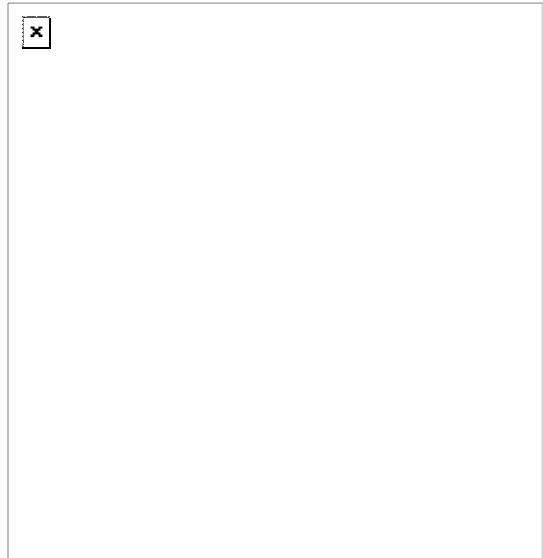


The wave shape is perfectly symmetric for metals with the same density and becomes increasingly asymmetric as the density differences increase. At excessive detonation rates, the vortex of the wave can exhibit localized melting due to adiabatic heating.

From the metallurgical perspective, the bond of an explosive clad plate is a direct interface between grains of the two different metal types.

There is no diffusion as a result of the low temperatures of bonding. Metallurgically, the bond is very similar to a high-energy grain boundary, Figure 6. Due to the cold deformation of bond wave formation there is a slight increase in hardness in the bond area.

**Limitations:** Explosive cladding deforms the metals at very high rates ( $10^4$  up to  $10^5$   $\text{sec}^{-1}$ ). The metals must be ductile enough to undergo this deformation without cracking. Limits usually accepted are a minimum elongation of 15 % and a notch toughness value above 30 J at bonding temperature. Most common engineering metals meet these criteria and are readily bondable.



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Cladding metal	Shear Strength (MPa) *	Shear Strength (MPa) **
Stainless steel	210	520
Nickel alloys	210	470
Cu-Ni alloys	140	285
Cu-Al alloys	140	400
Titanium Gr. 1	140	290
Zirconium 702	140	240
* Mini. Guaranteed by NOBELCLAD NC 501 specification.		
** According to NOBELCLAD tests.		
<b>Table II : Shear Strength of explosion bonding plates</b>		

**Performance:** The strength of the interface is usually greater than the strength of the weaker component metal. Shear testing or bend testing typically measures Bond strength. Bond integrity is normally measured using an ultrasonic test. Tests are performed to international standards. Typical shear strengths and minimum guaranteed values are shown in Table II.

Extensive tests over the past 40 years have shown that the process has slight effect on the mechanical properties of the base metal. These results have led to establishing additional specification requirements for the purchasing the metal that is to be bonded. Thus at the final step of production operations, including heat treatments if needed, the base metal complies with the customer's required specifications.

INDUSTRIALISATION

Cladding metal	Base Metal (ASTM)
DUPLEX	Rolling CSteel
SSteel 300	A 516
SSteel 400	A 387
Copper and alloys	Forged CSteel
Aluminum and alloys	A 266, A 350
Nickel and alloys	A 182
Titanium gr.1,7,12, etc.	Forged or Rolled SSteel 300
Zirconium gr. 702	
Tantalum	
<b>Table III : Main combinations done by explosive bonding</b>	

The explosion cladding process is commonly used for flat plates. The process can also be used for the manufacture of concentrically bonded tubes and pipes. In tube cladding, the explosive can be placed inside the bore, or on the outside of the outer tube, dependent upon diameters, wall thicknesses and other factors. The process is not suitable for cladding of complex contoured surfaces. When shaped products are required, such as heads, the clad is produced as flat plate and formed into the required product configuration after bonding.

Table III shows the wide range of combinations that can be done with explosion bonding

The cladding global dimensions are typically limited only by the availability of flat component metal sheet or plate and transport constraints. Maximum plate size may also be limited by explosive detonation limits, such as noise and environmental constraints. Rarely is size limited by cladding know-how.

The following maximum plate sizes can typically be produced:

Length 12,000 mm

Width 5,000 mm

Base thickness 500 mm

Cladding thickness 25 mm

Surface 35 m<sup>2</sup>

Annex I shows an example of a manufacture control chart. As shown, Nobelclad uses bar codes to track process operations and to optimize scheduling and work flow.

## FABRICATION

Clad metal can be readily formed and welded as needed to construct process equipment. However, it is not the aim of this paper address clad metal fabrication process. Many equipment fabricators worldwide have extensive expertise and know how in this area. Head and shell forming and welding of clad plates is well known by fabricators specializing in clad. For additional information, have a look at Nobelclad technical bulletins or Nobelclad web site <http://www.nobelclad.com/>.