# INVESTIGATION PROPERTIES OF EXPLOSIVE WELDED JOINTS BETWEEN STRUCTURAL STEEL AND HIGH ALLOYED MATERIALS

Prof. Dr Cvetkovski. S. PhD.[1]
Faculty of Technology and Metallurgy – Ss. Cyril and Methodius University, Skopje Republic of Macedonia [1]
sveto@tmf.ukim.edu.mk

***Abstract:***
*In this research work are presented results of investigation properties of explosive welded joints (bondings) between structural steel and high alloyed materials. As base material was used SA 516 Gr 70 structural steel, while AISI 316L austenitic stainless and nickel base alloy Inconel 825 were used as cladding materials.*
*Performed investigation can be divided as investigation of plates for welding before explosive welding and investigations of welded joints after performed welding. Chemical, mechanical (tensile testing, shear testing, hardness measurement and impact toughness) and microstructural investigations were performed of base metal plates. Welded joints were investigated after heat treatment of cut pieces from welded plates and chemical treatment of bended specimens in acid solution.*
*Obtained results from testing were compared with the standard requirement. Generally, obtained results correspond pretty well with standard requirement.*

**Keywords**: EXPLOSIVE WELDING, BONDING, CLADING MATERIAL, SA 516 Gr 70, AISI 316, INCONEL 825, HEAT TREATMENT, COROSSION

## 1. Introduction

Unlike other forms of welding such as arc welding (which was developed in the late 19th century), explosion welding was developed relatively recently, in the decades after World War II. Its origins, however, go back to World War I, when it was observed that pieces of shrapnel sticking to armor plating were not only embedding themselves, but were actually being welded to the metal. Since the extreme heat involved in other forms of welding did not play a role, it was concluded that the phenomenon was caused by the explosive forces acting on the shrapnel. These results were later confirmed in laboratory tests and, not long afterwards, the process was patented and put to use [1-4].
In 1962, DuPont applied for a patent on the explosion welding process, which was granted on 1964.
Explosion welding (EXW) is a solid state (solid-phase) process where welding is accomplished by accelerating one of the components at extremely high velocity through the use of chemical explosives. This process is most commonly utilized to clad carbon steel plate with a thin layer of corrosion resistant material (e.g., stainless steel, nickel alloy, titanium, or zirconium). Due to the nature of this process, producible geometries are very limited. They must be simple. Typical geometries produced include plates, tubing and tube sheets [5,6].
Explosion welding can produce a bond between two metals that can not necessarily be welded by conventional means. The process does not melt either metal, instead plasticizing the surfaces of both metals, causing them to come into intimate contact sufficient to create a weld. This is a similar principle to other non-fusion welding techniques, such as friction welding. Large areas can be bonded extremely quickly and the weld itself is very clean, due to the fact that the surface material of both metals is violently expelled during the reaction [7].
A disadvantage of this method is that extensive knowledge of explosives is needed before the procedure may be attempted safely. Regulations for the use of high explosives may require special licensing Technology [8,9].
It has been found to be possible to weld together combinations of metals, which are impossible, by other means.
Dissimilar metal explosion bonded joints are applied anywhere a designer needs to make a high-quality transition between metals. Typical uses include ultra-high vacuum joints between aluminum, copper and stainless steel, corrosion resistant claddings on mild steel substrates, and alloy aluminum joined to low-expansion rate metals for electronic packages. When an explosive is detonated on the surface of a metal, a high pressure pulse is generated. This pulse propels the metal at a very high rate of speed. If this piece of metal collides at an angle with another piece of metal, welding may occur. For welding to occur, a jetting action is required at the collision interface. This jet is the product of the surfaces of the two pieces of metals colliding. This cleans the metals and allows to pure metallic surfaces to join under extremely high pressure. The metals do not commingle, they are atomically bonded. Due to this fact, any metal may be welded to any metal (i.e.- copper to steel; titanium to stainless). Typical impact pressures are millions of psi.
Surface atoms of two joining metals must come in the intimate contact to achieve metallic bond [10,11].
Explosion welding joins metals together by using a powerful shock wave. This creates enough pressure between two metals to cause surface flow and cohesion. It is often used to weld large sheets together [12].
The basic mechanism of explosion welding is based on molecular bonding, as a result of high velocity impact. The high velocities are promoted by carefully detonated explosives.
Basic idea in this work is to check the quality of explosive welded bonds between structural steel and high alloyed cladding material trough very complex investigations. In such way will be confirmed preliminary prescribed explosive welding technology

## 2. Material and experimental

For experimental explosive welding were used plates of SA 516 Gr 70 structural steel as a base material with thickness of 40 mm. As a clad material was used plates of INCONEL 825 alloy and AISI 316L stainless steel with thickness of 4 mm in both cases. Chemical composition of the plates is given in the table 1

***Table 1*** *Chemical composition of base and clad material used for explosive welding*

| Comp. % | SA 516 Gr 70 | INCONEL 825 | AISI 316 |
|---|---|---|---|
| C | 0.15 | 0.006 | 0.014 |
| Si | 0.37 | 0.24 | 0.5 |
| Mn | 1.4 | 0.7 | 1.25 |
| P | 0.01 | 0.02 | 0.03 |
| S | 0.003 | 0.005 | 0.005 |
| Al | 0.02 | 0.1 | 0.008 |
| Cr | 0.04 | 23.1 | 17.1 |
| Cu | 0.2 | 2.4 | 0.4 |
| Ni | 0.17 | 38.6 | 10.4 |
| Mo | 0.01 | 2.5 | 1.5 |
| Ti | 0,03 | 0.8 | 0.02 |
| Co | 0.05 | 0.15 | 0.21 |

Mechanical properties of base metal SA 516 Gr 70 are shown in the table 2, and in table 3 can be seen measured hardness values (HRB) of base and clad plates.

***Table 2** Mechanical properties of base metal*

| Reh, MPa | Rm, MPa | A, % | KV (-45 $^0$C), J |
|---|---|---|---|
| 388 | 522 | 38 | 189 |

***Table 3** Measured hardness values of base and clade plates*

| | SA 516 Gr 70 | INCONEL 825 | AISI 316 |
|---|---|---|---|
| HRB | 75 | 89 | 100 |

For determination of grain size of base metal structural steel SA 516 Gr 70 were prepared metallographic specimens with investigated surface perpendicular for rolling direction Standard metallographic preparation was performed. It means that after grinding at different papers and polishing with diamond powder, chemical etching of specimen with Nital was done. For determination of grain size was used software for analysis of photography's VideoTest 5.1 (standard ASME E 1382). Microstructure of base metal is presented in the figure 1a and grain size distribution is shown in the figure 1b. The coarsest grains are with size 7.7 and the most represented grains are the grains with size 10.3. Microstructure of the base metal is ferritic-perlitic.

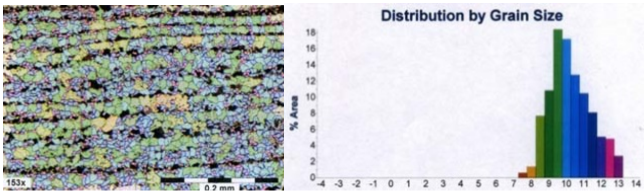


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***Figure 1** (a and b) Microstructure of base metal and grain size distribution*

Plates from base and clad material were prepared for explosive welding. Two types of plates with different dimensions were prepared:

**Plate 1**

1520x1520x40+4

Base material SA 516 Gr 70, thickness of 40 mm

Clad material INCONEL 825, thickness of 4mm

**Plate 2**

1650x1650x40+4

Base material SA 516 Gr 70, thickness of 40 mm

Clad material AISI 316L, thickness of 4mm

After preparation the plate's explosive welded at the military polygon. Explosive welding could be of two types. The oblique and parallel configuration, the oblique configuration is shown in figure 2a, this method come into play when the size of plate is thin and small, but when the plate is large then parallel method is taken as shown in figure 2b. This method was performed in our case.

In parallel method the plates to be welded are clean and polish very gently so as to form the good welding, in this process the base plate are keep at the ground in which the flyer plate is placed at top of it by the predefine distance called stand-off distance, the design of the stand-off should be able to bear and handle the load of flyer plate and explosive, above this buffer sheet is kept at the surface of flyer plate ,so as to protect the top surface from damage due to the shock impact of the explosive. Now the prepared explosive placed in a box structure design at the perimeter of the flyer plate is placed at the top of the flyer plate.

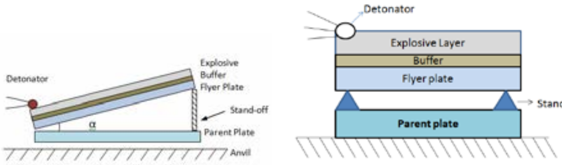


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***Figure 2** (a and b)*

Experimentally welded plates were brought for investigation in the material testing laboratory.

The first step of investigation was ultrasonic testing of the plates (bonding). Ultrasonic device USN 52R Krautkamer with SEB4 probe (frequency 4MHz) was used for testing. Nonwelded areas or unallowed defects were not detected.

From the experimentally welded plates were cut pieces, perpendicular to the rolling direction for heat treatment in order to relax residual welding stresses. The cut pieces were put in the furnace previously heated to temperature of 425$^0$C after that the furnace temperature was increased until 610℃ ±10℃. Heating rate was 100℃/1h. After reaching the necessary temperature, material was kept inside the furnace 170 min. After that controlled cooling to the temperature of 425℃ with the cooling rate of 100℃/1h was performed. Finally the pieces were taken off from the furnaces and cooled in the calm air.

From the heat treated pieces were machined specimens for bend testing Dimension of specimens are the following 300x30x full thickness. Full thickness means thickness of base metal and clad metal (44 mm). The view of the specimens after bending test is given in the figure 3. All specimen fulfilled standard requirement. It means that cracks on the stretched side of the specimens were not fount after bending to 180$^0$.

***Figure 3** Bend specimens after testing*

Round specimens (ϕ12.7mm) were prepared for tensile testing of the heat treated pieces too. These specimens were machined from the base metal i.e. SA 516 Gr 70 A. Tensile testing was performed on tensile machine INSTRON 600LX. Tested specimens are presented at figure 4 and obtained results are given in the table 4.


*Figure 4 Tensile specimen after testing*

***Table 4** Mechanical properties of base metal after explosive welding and the heat treatment*

| | Reh | Rm | A% |
|---|---|---|---|
| Value | 375 | 504 | 36 |

Tensile testing's or trough thickness testing in order to determine contraction of base metal in direction of Z axis was performed too. Round specimens ϕ6.35 were tested on tensile machine AVERY DCJ 7109 (50 tons). Results of contraction tastings are given in the table 5. Tested specimen can be seen in the figure 5

***Table 5** Contraction of base metal in the z direction*

| No. of meas. | 1 | 2 | 3 | Average |
|---|---|---|---|---|
| Z(%) | 72.6 | 67.74 | 69.54 | 70.8 |


*Figure 5 Contraction testing spesimens*

Charpy testing was performed for determination the base metal impact toughness. The results are presented in the Table 6 These measurements were performed at temperature of -45℃.

***Table 6*** *Impact toughness testing*

| No. of meas. | 1 | 2 | 3 | Average |
|---|---|---|---|---|
| KVL-$45^0$C,J | 162 | 149 | 175 | 162 |

In the table 7 are presented results of hardness measurement of the vase metal and clad material.

***Table 7*** *Hardness measurement of clad plates after explosive welding and heat treatment*

| No. of meas. (HRB) | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| INCONEL 825 | 95 | 94 | 94 | 94 |
| AISI 316 | 106 | 105 | 104 | 105 |

Shear test of explosive welded joints was performed according ASTM A264 Specimens. Preparation of specimen is presented given if figure 5. Specimens from the plate 1 and 2 were prepared and obtained values for shear strength are given in the tables. Minimal value prescribed with the standard is 200 MPa. The view of specimen before and after testing is given in the figure 6.

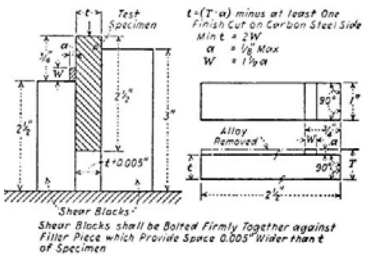


***Figure 6*** *Preparation of specimens for shear test*

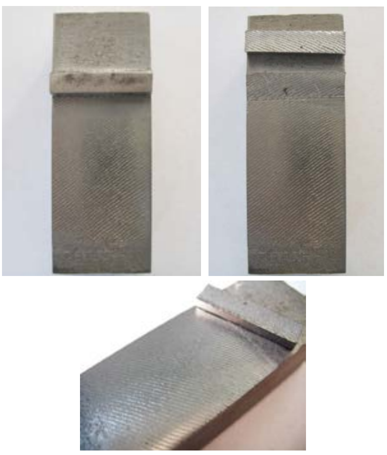

***Figure 6*** *Specimen for shear test before and after testing*

Results from shear test are given in the table 8.

***Table 8*** *Results of shear test of different joints*

| No. of meas. Shear strength | 1 | 2 | 3 | Average |
|---|---|---|---|---|
| INCONEL 825 | 305 | 298 | 300 | 301 |
| AISI 316L | 282 | 311 | 299 | 297 |

Corrosion resistance of explosive welded joint was tested according to ASTM A262 – E. Acid solution of copper sulphate was prepared. 100 g CuSO4 ( $CuSO_45H_2O$ ) were saluted in 700 ml distillated water. After that 100 ml sulphuric acid were added. Finally all this content was diluted in 1000 ml distilled water. So the solution contains 5 mas' % $CuSO_4$ and 16 ma's %$H_2SO_4$.

Machined specimens with dimension 20x80x4 were treated in the prepared solution. After that the probes are immersed in the acid solution at room temperature. Testing time was measured starting from the moment when solution and specimens inside start to boil. The specimens stay in boiled solution 15 hours. They were cleaned from the residual copper after they were taken off from the solution. Cleaned specimens after chemical treatment were bent until the angle of $180^0$ with the diameter of thorn with of 4 mm. After that stretched side of the bent probes was photographed with magnification of x20 and obtained photos were compared with the referent figure 7 from the standard. Figure 7a concerns to passing specimen and figure 7b to the failing specimen. In the figure 8 are shown are presented tested specimens. Figure 8a is specimen of INCONEL 825 and figure 8b to specimen of AISI 316.

Metallographic pictures of the explosive welding interface are given in the figure 9. These figures concern to specimens of INCONEL 825 and AISI 316L Typical wave nature of the interlayer is visible in both cases.

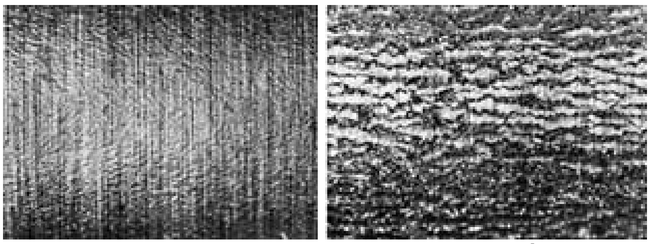

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***Figure 7*** *Referent photos of the stretched side of the bend specimens*
a. good b. failing

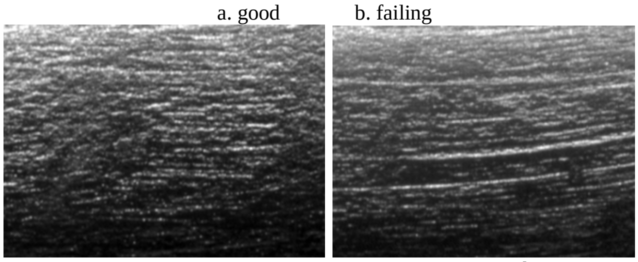

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***Figure 8*** *Photos of stretched side after bending a, INCONEL 825 b AISI 316L*

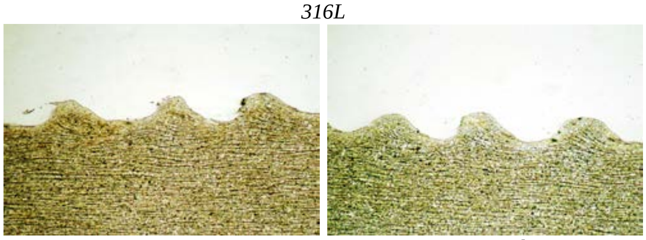

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***Figure 9*** *Microstructure of explosive welded bonds (interface)*

### *4. Discussion*

Preliminary investigation of base and clad plates intended for explosive welding confirm that their chemical composition and mechanical property fulfill standard requirement explosive welding was performed according preliminary given technology. Complex investigations of the welded plates were performed. Results of investigations confirmed that quality of the experimentally welded plates is at very high level because all results satisfy standard requirement. It means that prescribed explosive welding technology can be implemented for regular welding.

### *5. Conclusion*

Performed investigation confirmed that preliminary given explosive welding parameters completely fulfilled quality requirement of the explosive welded plates. So, preliminary given welding technology can be used for regular production.

### *6. Literature*

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[2] ASTM A262 - 15 Standard Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels

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