Production of Steel-Light Metal Compounds with Explosive Metal Cladding

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Abstract

Explosive Metal Cladding is a High Speed Welding Process using the energy of an explosive to bond different metals and alloys in a 2-dimensinal areal configuration. Parameters influencing the cladding process are discussed and the potentials of the method are presented. Microscopic properties of a Cu-Al and a Steel-Ti transition zone are studied in detail to get a better knowledge of the principle mechanisms included in the bond creation. A perspective for future applications of explosive cladding in different industries like automotive and aerospace is given.

Keywords

Bonding, Titanium, Explosive Metal Cladding

1 Introduction

New applications of explosive metal cladding in the automotive and aerospace industry are thought after. Especially the possibility to create 2-dimensional areal substance-to-substance bonds between different metals and alloys is an attractive opportunity that allows the creation of light-weight compounds. As all different forgeable materials could be bond together, composites consisting of Aluminium-Steel, Titanium-Steel and Aluminium-Titanium are easily created. Even composites with Magnesium like Magnesium-Steel, Magnesium-Aluminium or Magnesium-Titanium are imaginable.

While the process of metal cladding is known since the 1960s a satisfying explanation of the bonding mechanism is still pending. A better knowledge of the processes in the transition zone and the created structures and phases is needed to further establish the method and increase the acceptance in the engineering community.

2 Explosive Metal Cladding Process Parameters

2.1 Basic Principle of the Method

Explosive Metal Cladding is a high speed welding process similar to pressure welding. In the basic setup (cmp. Fig. 1) a layer of explosive is distributed atop of a metal sheet – the clad material – which is placed at a certain stand-off from the base material to which it should be bound. When the explosive is ignited, the chemical energy is transferred to the kinetic energy of the clad material or flyer plate. The flyer plate hits the base plate at the collision point creating a material jet, if the cladding parameters are chosen correctly. This material jet cleans the surfaces of both binding partners from unwanted surface deposits like metal oxides. The two metal partners are forced close together forming the bond while a very strong plastic deformation of the interfaces is created at the transition zone.

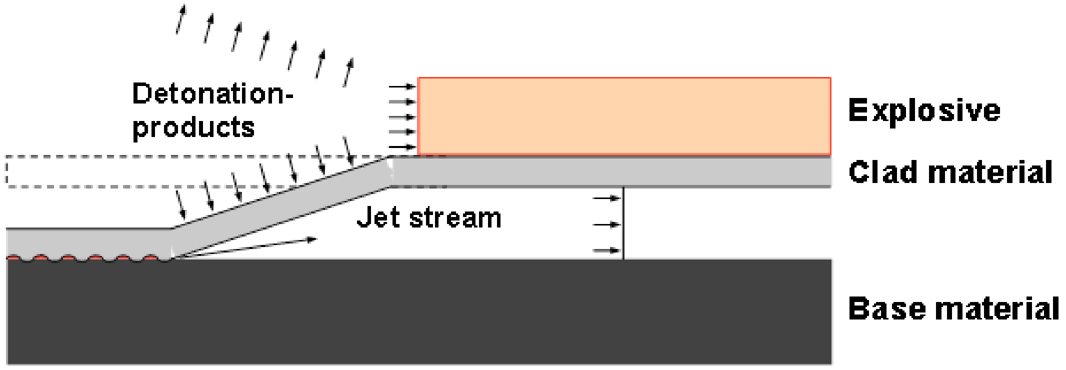


***Figure 1**: The detonating explosive accelerates the Clad material (flyer plate) to the Base Material creating a Jet Stream at the Collision Point that cleans the surfaces of the bonding partners; the kinetic energy binds the two partners together resulting in a plastic deformation of the metals in the transition zone*

In a plan parallel setup like the one shown in Fig. 1 the collision point velocity v_{coll} is equal to the detonation velocity v_d. As the formation of a shock wave inside on of the cladding partners would immediately result in the creation of cracks, this has to be avoided under all circumstances. The detonation velocity v_d must therefore be smaller than the velocity of sound of the metallic partners. To achieve this, specific cladding explosives are used, based on Ammonium Nitrate Fuel Oil (ANFO) explosives adapted to create very low detonation velocities in the range of 1800 – 3000 m/s.

2.2 Cladding Parameters

For the determination of the flyer plate velocity v_{fly} the Gurney Equation (Eq. 1) could be used [1]. In an open sandwich configuration like the one shown in Fig. 1 the flyer velocity is:

$$v_{flyer} = \sqrt{2E_G} \cdot \left(\frac{3}{1 + 5\frac{M}{C} + 4\left(\frac{M}{C}\right)^2} \right)^{\frac{1}{2}} \qquad (1)$$

Here M determines the mass of the flyer plate per unit area and C the explosive charge per unit area. As the Gurney Energy E_G is a constant of the explosive it could be easily deduced from Eq. 1 that a linear relationship between flyer plate thickness and explosive mass used for the cladding process should exist if the flyer plate velocity has to be kept constant.

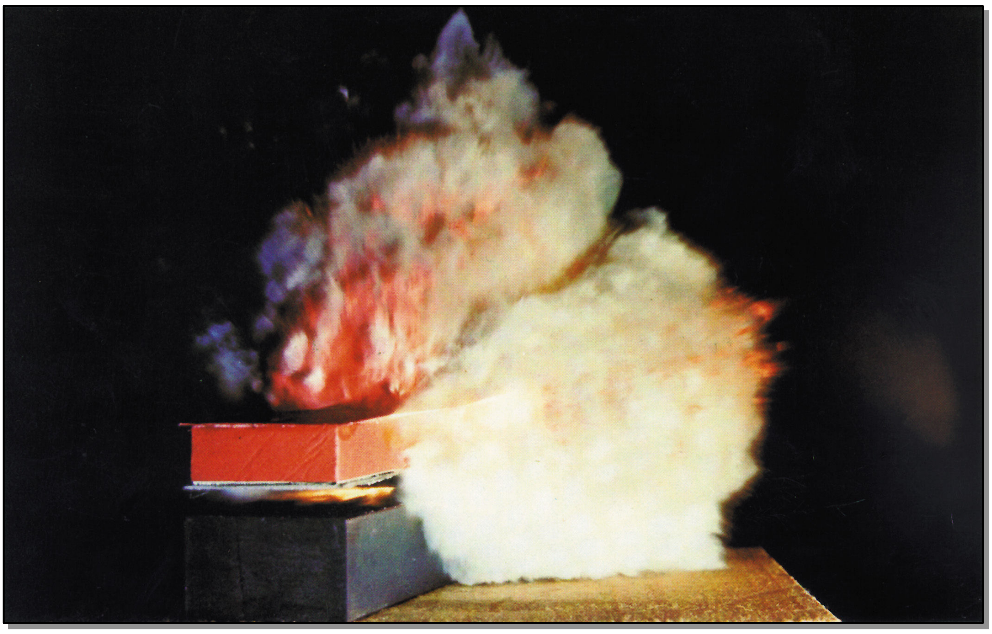


***Figure 2**: Argon Flash photograph of the detonation during explosive metal cladding*

For most explosives the Gurney velocity v_G is related to the detonation velocity v_D of the explosive [2]:

$$v_G = \sqrt{2E_G} \approx \frac{v_d}{2.97} \qquad (2)$$

Unfortunately this relation is not valid for ANFO explosives and especially cladding explosives don't follow this relation that has been deduced for High Energy (HE) explosives used in military applications.

The Gurney velocity v_G has therefore to be determined for each explosive used individually. Flash X-ray pictures could be used to do this.

2.3 Temperature in the gas gap

Combining metals with explosives, besides the impressive energy release due to the detonation, is a relative cold process. The temperatures created in the gas gap between the metal partners could be approximated, if the Mach number M_0 of the shock wave travelling through the gas is known [3].

$$M_0 = \frac{v_{Shock}}{c} \tag{3}$$

To calculate the Mach number M_0 the velocity of sound c of the gas (cmp. Eq. 4) and the shock velocity v_{Shock} (cmp. Eq. 5) have to be known. The velocity of sound depends on the adiabatic coefficient γ, the gas temperature T_0 of the unshocked gas and the molar mass μ_{mol} of the gas:

$$c = \sqrt{\frac{\gamma R T_0}{\mu_{mol}}} \tag{4}$$

The shock velocity v_{Shock} of the gas can be calculated from the Shock Hugoniot, which for most gases is given by Eq. 5 [1]:

$$v_{Shock} = 0.899 + 0.939 \cdot u \tag{5}$$

Here the particle velocity u in the gas is given by the collision point velocity v_{coll}. The temperature in the gas T_1 after the shock is given by Eq. 6 where the parameter μ^2 depends on the adiabatic coefficient γ of the gas (Eq. 7).

$$T_1 = T_0 \cdot \frac{\left(1+\mu^2\right) \cdot M_0^2 - \mu^2 + \mu^2\left(\left(1+\mu^2\right) \cdot M_0^2 - \mu^2\right)^2}{\left(1+\mu^2\right) \cdot M_0^2} \tag{6}$$

$$\mu^2 = \frac{\gamma - 1}{\gamma + 1} \tag{7}$$

For a typical situation with a collision point velocity of v_{coll}=2000 m/s with air as the gas between the plates and an initial temperature of T_0=300°K the gas temperature in the shock front would be T_1=4000°K. As could be seen in Eq. 3 – 7 the type of gas between the plates has a strong influence on the shock temperature T_1. If Argon would be used instead of air the shock temperature would be T_1=7250°K. For Helium the shock temperature would be reduced to T_1=970°K.

As the shock front travels very fast, the time to heat up the metal surfaces is very short and only a small zone of approximate 100 µm could be influenced through increased temperatures.

From these considerations it becomes obvious that a close study of the metal-metal interface depending on the cladding parameters like explosive amount detonated and gas in gap between the plates is necessary to prove the quality of the bond for high sophisticated applications.

2.4 General Properties of the explosive bond

The reasons to use claded metal composites are manifold. First there is the lower material costs compared with high-alloyed solid plates. In addition a combination of the properties of the binding partners could be desirable. Mechanical properties, electrical conductivity, thermal conductivity and corrosion resistance are potentially altered due to the material combination

A broad spectrum of different metal combinations (cmp. Tab. 1) is commonly bond by explosive cladding today. Nearly all forgeable metal alloys could be bond with this method creating a substance-to-substance bond. The bond is 2-dimensional and allows a further machining of the compound with standard technologies like rolling, drilling, turning, milling or welding of unmixed metals.

Base Material	**Clad Material**
Carbon Steels for Vessels	Austenitic steels
Micro-alloyed steels	High-strength steels
High-strength steels	Al + Al alloys
Austenitic steels	Cu + Cu alloys
Al + Al alloys	Ni + Ni alloys
Cu + Cu alloys	Titanium, Ta, Zr
Ni + Ni alloys	Silver
	Mo

***Table 1**: List of possible clad combinations commonly used today*

The quality of the bond is checked with destructive and non-destructive material testing. Ultrasonic testing is used to guarantee a homogenous binding quality over the complete claded area, with side bend tests, bend tests according to ASTM and shear strength tests the quality of the bond is ensured (cmp. Tab. 2). Penetration tests and Corrosion tests are further commonly used methods.

Clad Material	Base Material	Measured Shear Strength [MPa]
Stainless Steel	Carbon Steel	310-580
Nickel / Ni-Base	Carbon Steel	300-410
Copper	Carbon Steel	170-230
CuNi30Fe	Carbon Steel	265-390
Titanium Grade 1	Carbon Steel	200-480
Zirkonium 700	Carbon Steel	200-360
Tantalum	Carbon Steel	200-250
Aluminium	Carbon Steel	70-120
Aluminium	Copper	70-120
Titanium	Copper	220-280

***Table 2**: Measured Shear Strength for different material combinations*

3 Microscopic Properties of the Binding Zone Between the Metal Partners

A closer study of the interface with Scanning Electron Mircrogaphs using advanced technologies like EDAX and EBSD has been performed to better characterise the nature of the bond created.

3.1 Cu-Al Transition Zone

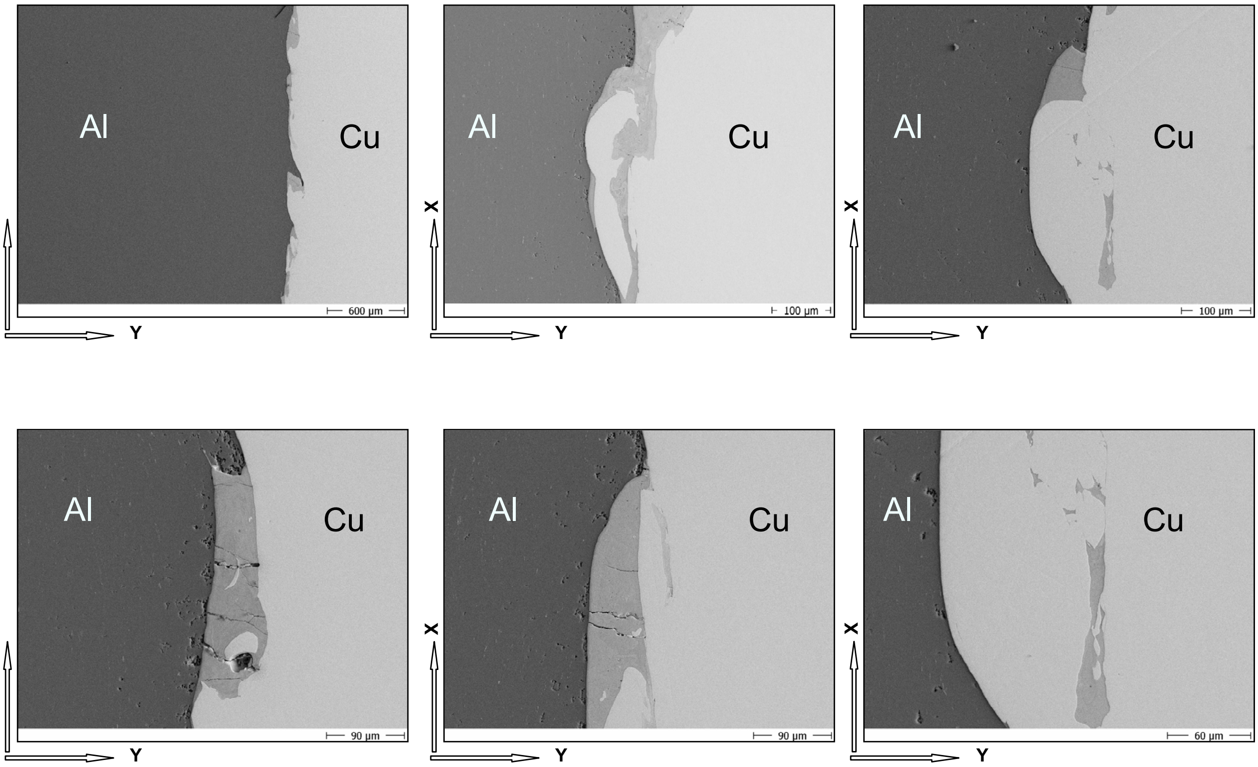
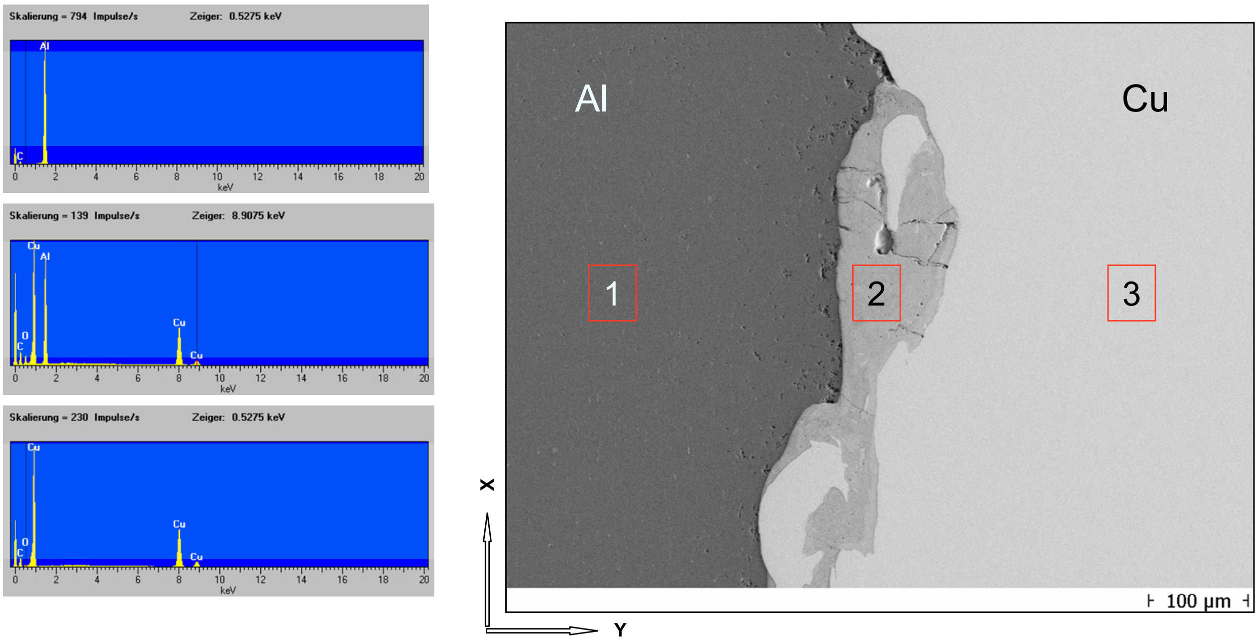


***Figure 3**: SEM of the transition zone for an Aluminium Cupper interface*

The Aluminium-Cupper Interface (Fig. 3) shows a smooth transition line and only minor, microscopic defects could be found. Most cavities were completely enclosed by pure material. In single location the occurrence of a new phase was observed. A characterisation of this phase with EDAX (Fig. 4) showed an Al-Cu compound. A statistical rating of the likelihood for the occurrence of these phases is still pending. In addition the influence of the cladding parameters on the structure of the interface is the subject of ongoing research.



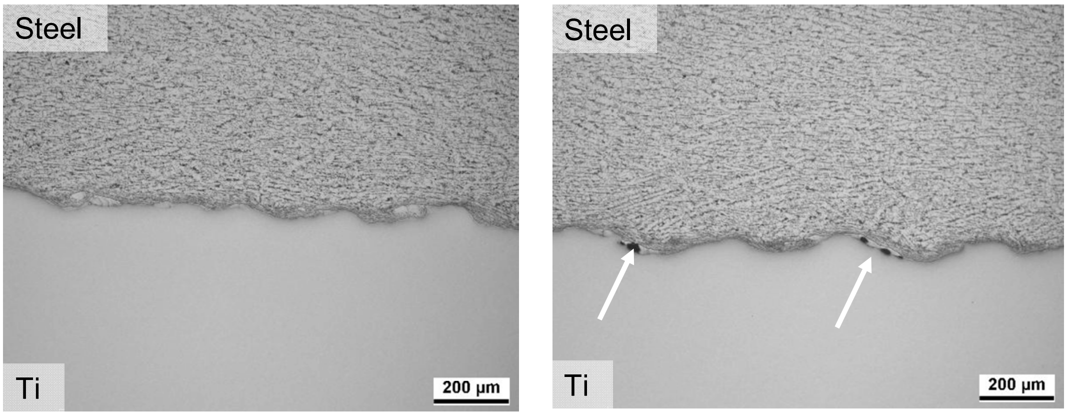
Position	Al	Cu	O
1	99.15	0.04	0.81
2	20.59	76.38	3.33
3	0.09	99.32	0.59

Positions of EDX measurements

Figure 4: *EDAX characterisation of the metal phases in the transition zone. In position 2 an Al-Cu compound is found.*

3.2 Steel-Titanium

The Steel-Titanium Interface forms a characteristic wave shaped structure (cmp. Fig. 5). At some locations of the Interface minor defects could be found. Like in the Al-Cu case a statistical interpretation of these effects is still pending. As no continuous defect zone was found the quality of the bond is not influenced by these holes.



excellent interface

defects located at the interface

Figure 5: *Steel-Titanium Interface with characteristic wave shaped structure. Wave length* λ*=250 µm, Amplitude 50 µm. In single locations minor defects could be localised at the interface of the metals.*

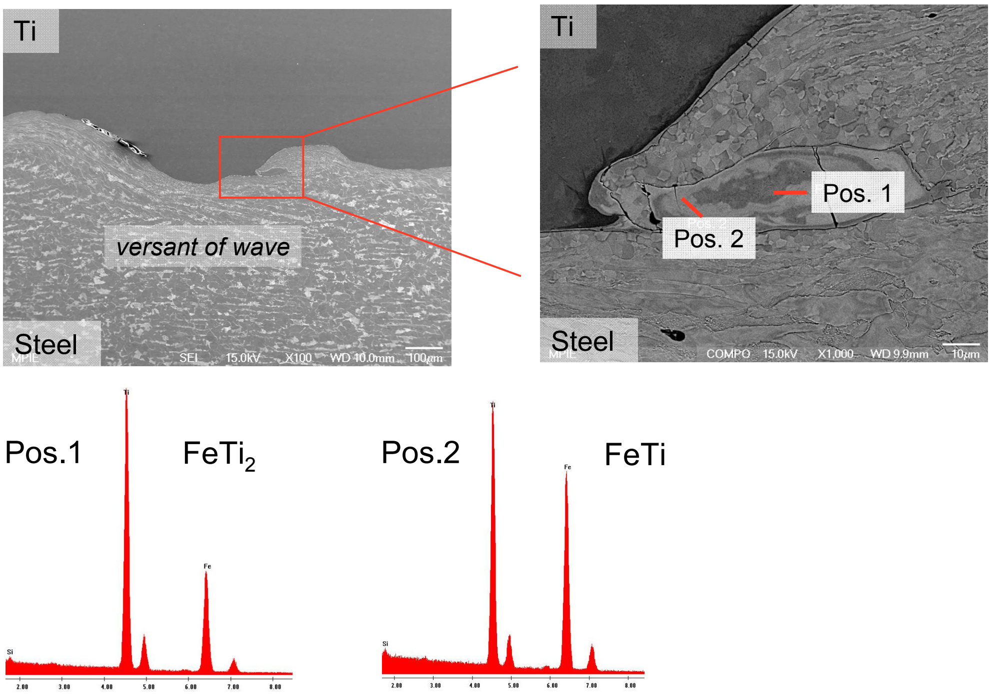


Figure 6: *Phase characterisation in the versant of a broken wave of a Titanium-Steel interface. Compounds with 2 different chemical compositions according to FeTi and* $FeTi_2$ *were found.*

A closer study of the versant of a broken wave showed the occurrence of a new phase as an inclusion of the wave peak (Fig. 6). A chemical characterisation of this zone showed two different chemical compositions of the compounds according to FeTi and $FeTi_2$.

Here also a better understanding of the binding mechanism is the subject of ongoing research.

4 Industrial applications of explosive metal claded sheets

A number of well established companies – like DYNAenergetics – offer explosive metal claded products on the market. The dimensions of single plates produced could be up to 4x7 m².

***Figure 6**: Preparation of a plate sandwich for cladding in the underground mine DYNAenergetics uses. The ANFO explosive is homogenously distributed with an Aluminium lath to guarantee a homogenous layer thickness.*

Claded sheets are used today in power plants, for applications in the chemical and petrochemical industry, for construction purposes, in environmental applications, for desalination plants, in electronics and electrical applications, for electrolysis electrodes, in ship building and for medical applications.

Especially the fact that metal combinations that are difficult or impossible to bond by other means and a metallic continuity is formed are attractive for other applications like in the automotive and the aerospace industry. Light weight metals like Titanium, Aluminium and even Magnesium can be bond to other metallic partners like Steel or to each others.

5 Conclusions

The method of explosive metal cladding, which is known since the 1960s, is a well established technology in certain industries today. On the opposite it is not a standard engineering tool in our days and in certain industries the advantages of the technology are not utilized. In this paper the effect of process parameters on the cladding results and the benefits of the technology are emphasized. To increase the acceptance of explosive metal cladding a research program to better characterise the metal-metal interface has been started. First results of the Al-Cu and the Ti-Steel interface are very promising and prove the good quality of the bond. Further improvements are likely to be achieved by adjustment of process parameters.

References

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