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EXPLOSIVE CLADDING OF TITANIUM AND ALUMINIUM ALLOYS ON THE EXAMPLE OF Ti6Al4V-AA2519 JOINTS

WYBUCHOWE PLATEROWANIE STOPÓW TYTANU I ALUMINIUM NA PRZYKŁADZIE POŁĄCZENIA Ti6Al4V-AA2519

Explosive cladding is currently one of the basic technologies of joining metals and their alloys. It enables manufacturing of the widest range of joints and in many cases there is no alternative solution. An example of such materials are clads that include light metals such as titanium and aluminum. ach new material combination requires an appropriate adaptation of the technology by choosing adequate explosives and tuning other cladding parameters. Technology enabling explosive cladding of Ti6Al4V titanium alloy and aluminum AA2519 was developed. The clads were tested by means of destructive and nondestructive testing, analyzing integrity, strength and quality of the obtained joint.
Keywords: explosive cladding, detonation velocity, Ti6Al4V-AA2519 clad.

Platerowanie wybuchowe jest obecnie jedną z podstawowych technologii łączenia metali i ich stopów. Pozwala ona na wytwarzanie najszerszej gamy połączeń i w wielu przypadkach nie ma alternatywy. Przykładem takich materiałów są platery z udziałem metali lekkich, jak: tytan, aluminium. Każda nowa kombinacja materiałowa wymaga odpowiedniej adaptacji technologii poprzez dobór właściwych materiałów wybuchowych i pozostałych parametrów spajania. Opracowano technologię wybuchowego łączenia stopów tytanu Ti6Al4V i aluminium AA2519. Platery przebadano przeprowadzając testy nieniszczące i niszczące, oceniając spójność, wytrzymałość i jakość uzyskanego połączenia.

1. Introduction

The explosion cladding process is known for many years and widely used. It is used among others to decorate objects, increase solderability, decrease friction [1], protect against corrosion [2], hardening surfaces etc. The most common cladding method is hot rolling, but adding layers of one metal onto another can also be performed in other processes such as: extruding [3,4,5], drawing and in explosive technology. Explosive cladding [6,7] is a technology giving a wide range of possibilities of joining different types of metals and their alloys, including intermetallic combinations of materials with largely different melting temperatures, forming and mechanical properties. An example of such combination is AA2519 aluminum alloy and Ti6Al4V titanium alloy. Both of those materials show increased chemical activity by means of interacting with each other. This tendency is especially visible during explosive cladding, where temperature and pressure values are extreme in the point of contact of both colliding plates. Despite that the duration time of the process can be counted in microseconds, the appearing plasticized or melted area of both metals contributes to creation of various intermetallic compounds. Not to be omitted also the structural changes taking place in the crystal network of both metals, which influence their level of strengthening and mechanical properties. All these factors are a consequence of direct influence of the detonation wave generated by explosives on the metals.

2. Selection and assessment of the tested explosive materials

The chemical composition of the explosives (EX) and its used quantity have a key influence on the explosive cladding process and the quality of the resulting joint by appropriate thermodynamics of the EX chemical reaction [8]. The applied explosive materials should meet the following: provide an appropriate level of initiation sensitivity, stable flow of the detonation process, sufficient energetic expense and low manufacturing costs. Previous experience shows that joining the selected material pairs, taking into consideration the properties of the joined metals, will require carrying the process out within the low range of the bonding parameters. Such conditions are obtained for EX with detonation velocities in range from 1800 to 2500 m/s. In case of a need of manufacturing multilayer joints, this velocity can be even higher.

The main assumption of the design process of new explosive mixtures was its orientation towards the necessity

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of manufacturing on the basis of ammonium nitrate. It is a common ingredient of industrial explosives due to its low price in comparison to classical explosive materials such as TNT and hexogen. Safety reasons, aspect of ecological production and usage of such material, suggest the need of eliminating nitrocompounds and nitroesters from its composition. All these factors point to a necessity of analyzing the capabilities of mainly using ANFO explosives, whose main ingredients are: ammonium nitrate and carbohydrate fuel. Explosive materials of this type are generally characterized by good usage parameters and low mechanical impulses sensitivity, which make them safe in application. Their explosive properties are placed in a wide range of usage parameters, such as detonation velocity or the ability to perform work. Selecting an appropriate composition of the explosive material and its physical state, requires performing a series of detonation velocity measurements during fire ground trials. The assessment of other parameters of the detonation wave, influencing the process of explosive cladding, such as: detonation pressure, chemical reaction time of the EX enables for example the electromagnetic method. Yet the final verification of the obtained results always takes place basing on the assessment of the manufactured sample from intermetallic joints.

For appropriate explosive material selection a series of eleven sample explosive mixtures were prepared. Their signing and chemical compositions are presented in table number 1.

The composition contained granulated and milled ammonium nitrate. Diesel fuel was used as the fuel component. Energetic expense tuning of particular mixtures was performed by addition of inert materials such as sodium chloride and silica. For the chosen mixtures an assessment of friction and impact resistance was performed, which confirmed the possibility of their safe application in industrial practice.

For each mixture, a series of detonation velocity measurements in fire ground conditions was performed with differentiated load heights. The size of tested loads ranged from 500 x 1000 mm to 600 x 1500 mm was chosen in a way that would make certain of the stable detonation flow, similar to the one present while performing explosive cladding of sample plates. For measurement purposes a multichannel optical meter was used that enabled measurement on five consecutive bases. The measurement method was presented on Figure 1.

Averaged measurement data for manufactured mixtures are presented in Table 2. The obtained results fully cover the selected range of detonation velocities and are between 1820 m/s and 3044 m/s.

TABLE 1

Chemical compositions of the tested explosive mixtures

No	EX signing	Chemical composition [% mass]				
		Milled ammonium nitrate	Ammonium nitrate granulated/milled 1:1	Carbonhydrate fuel	Natrium chloride	Silica
1.	Saletrol 1	0	95	5	0	0
2.	Saletrol 2	0	76	4	20	0
3.	Saletrol 3	0	76	4	0	20
4.	Saletrol 4	0	78.4	1.6	20	0
5.	Saletrol 5	0	79.2	0.8	20	0
6.	Saletrol 6	0	79.2	0.8	0	20
7.	Saletrol 7	76	0	4	20	0
8.	Saletrol 8	76	0	4	0	20
9.	Saletrol 9	79.2	0	0.8	20	0
10.	Saletrol 10	79.2	0	0.8	0	20
11.	Saletrol 11	69.3	0	0.7	0	30

TABLE 2

Outline of averaged results of detonation velocity measurements for the tested EX compositions. The value x determines the amount of measurement repetitions.

EX signing	**Detonation velocity D[m/s] for load height H[mm] D/H**						
	30	40	50	60	70	80	100
Saletrol 1	2539/3	-	-	-	-	-	-
Saletrol 2	2048/3	2126/3	2235/3	-	-	-	3044/3
Saletrol 3	-	2053/3	2172/3	2415/3	-	-	-
Saletrol 4	-	2280/4	-	2480/3	-	-	-
Saletrol 5	1826/4	-	1953/3	2206/3	2366/3	2574/3	2716/3
Saletrol 6	-	-	1922/3	-	-	-	-
Saletrol 7	2033/3	2339/3	2349/3	-	-	-	-
Saletrol 8	1994/3	-	2283/3	-	-	-	-
Saletrol 9	1854/3	2000/4	2052/3	2398/3	-	2454/2	-
Saletrol 10	1820/4	-	1942/3	-	-	-	-
Saletrol 11	-	-	-	-	2140/3	2380/3	2581/3

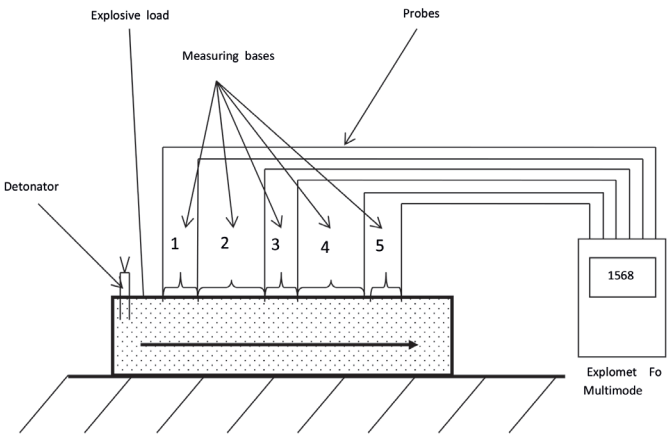

Fig. 1. Detonation velocity measurement setup

In order to compare the detonation wave parameters of selected EX compositions the electromagnetic method was used [9,10,11]. Its principle is based on measuring the electromotor induction force E, which is generated in the electric conductor of length l, that travels in constant magnetic field with induction B. Schematic of such measuring setup and its geometrical appearance is presented in Figure 2.

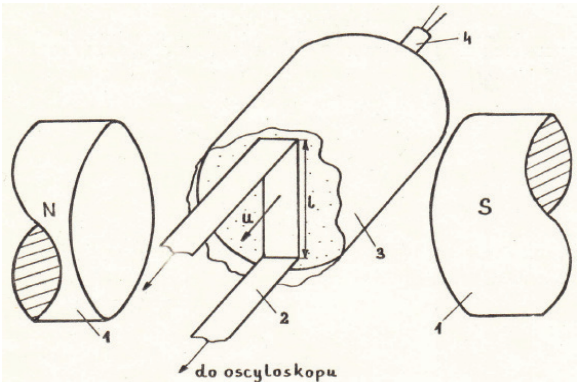

Fig. 2. Detonation wave of EX parameter measurement using the electromagnetic principle, 1 - electromagnet poles, 2 - sensor, 3 - EX load, 4 - electric detonator

As a sensor a thin aluminum foil is used, which is placed inside the explosive load. Its front surface, after it has been reached by the detonation wave, begins to move together with the detonation products with the same velocity as their mass velocity U. The generated voltage is then outputted to an oscilloscope, whose value is determined by the following equation:

$$\mathbf{E = B \times U \times l,} \qquad (2,1)$$

where:
E – Induction electromotoric force, B – electromagnetic field induction, U – mass velocity of the front surface, I – conductor length. A sample measurement oscillogram is depicted in the Figure 3.

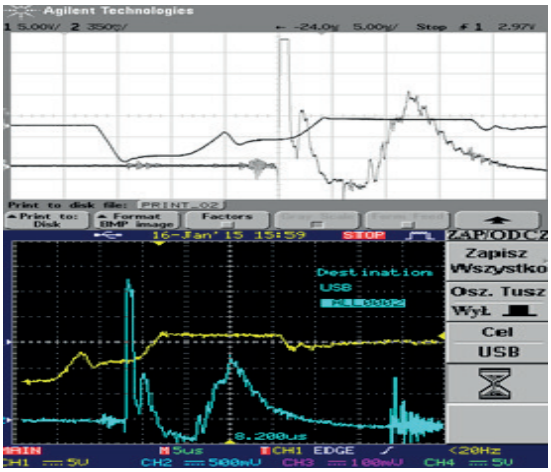

Fig. 3. Oscillogram readout for EX of type saletrol (95% ammonium nitrate, 5% diesel fuel)

Not delving into the theoretical details of the described method it can be said that the measurement basing on the measured mass velocity U enables to approximate the basic parameters of the detonation wave such as: detonation pressure and the chemical reaction time of the explosive in a so called chemical peak. These parameters have a direct impact on the ability to perform work by the explosive in an explosive cladding setup. The purpose of the measurement was not to quantitatively determine the parameters of the detonation wave, but only to perform its comparative assessment for selected explosive test mixtures which differed in content of inertial material and fuel. The obtained results showed that using the described method to test explosive materials based on ammonium nitrate with low detonation velocities, especially characterized by lowered amount of fuel and heightened amount of inertial material gave results of little precision. The resulting oscillograms are hard to interpret. Their profile considerably differs from what is observed in stronger explosive materials. The performed comparative analysis showed only that for an explosive with balanced oxygen level, increase the amount of inertial material, with decrease the detonation pressure and widens the chemical peak. Additional raising of the oxygen balance of such mixture, by lowering the amount of fuel, reduces the detonation pressure even more. It also shortens the chemical reaction time of the explosive in the effect area of the detonation wave. An influence of the inert material type on the shape of the chemical peak can also be observed. Its size is a little bigger for sodium chloride and smaller for silica. The observed differences should have an influence on the explosive cladding process and be helpful during interpretation of the obtained results.

3. Explosive cladding samples

The explosive cladding process [14,15] was conducted by using the horizontal setup in three variations as depicted in Figure 4. These were the following:

a) direct Ti6Al4V and AAl2519 sheet cladding without using an interlayer,
b) simultaneous cladding using a high plasticity metallic interlayer as a separate Al (EN AW-1050) thin sheet or

Ti Gr. 2 or a rolled on one side of the AA2519 aluminium alloy 0,3 to 0,5 mm layer of EN AW-1050.

c) multilayer cladding performed in a single shot (simultaneously) using an additional flyer plate and using AA2519 plates double-sided cladded with thin Al layer by means of rolling.

For cladding test purposes 3, 5 and 10 mm plates were used, composing setups 3 mm + 3 mm (series "3"), 5 mm + 5 mm (series "5"), 10 mm + 10 mm (series "10") and multilayer setups 5x3 mm and 7x3 mm (series "3M") in described earlier cladding setups). Each sample plate was cladded on a 20 mm thick steel anvil, which was to minimalize the deformation of the obtained clads. The manufactured cladded plates were produced using aluminum and titanium plates in formats 330 x 500 mm and 500 x 500 mm.

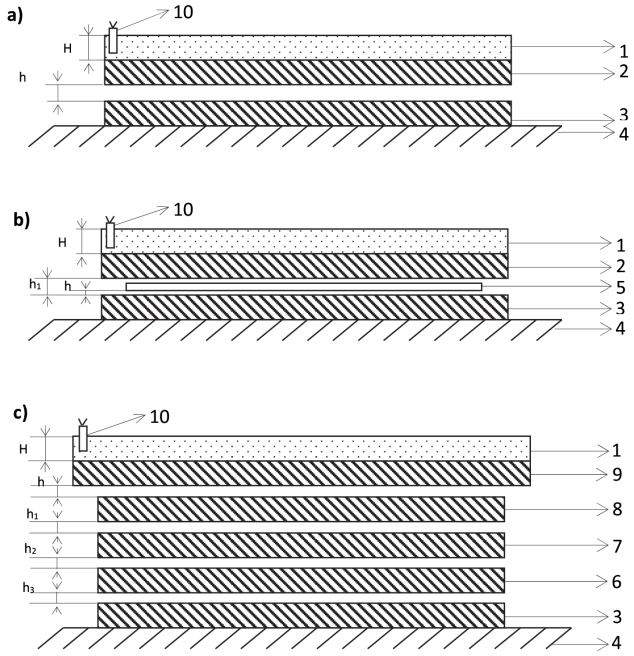

Fig. 4. Explosive cladding setup: a) direct cladding, b) cladding with interlayer, c) multilayer cladding, where: H - EX load height, h,h1,h2,h3 - clad plate propelling distances, 1 - explosive material, 2 - cladding plate, 3 - base plate, 4 - ground/anvil, 5 - interlayer, 6,7,8 - consecutive cladding plates, 9 - clad plate, 10 - electric detonator

Fig. 5. Batch of manufactured plate samples

In each case the cladding process was performed with measuring the detonation velocity. A series of test plates was manufactured, testing different joining parameters. Subject to alterations were the type and amount of the used EX and the propelling distance of the flyer plate. All double-layer clads were manufactured by laying the aluminum sheet onto the titanium sheet, whereas for five and seven layer setups, the external layers were titanium sheets.

4. Sample plate testing

One of the sample plate batches are shown in figure nr 5. Sample plates were subject to a series of tests, which enabled to assess the quality of the obtained joint and the correctness of the chosen cladding parameters from further processing point of view. These comprised of the following:

a) ultrasonic joint integrity and titanium and aluminum layer integrity testing,
b) peel strength testing of the manufactured bond,
c) titanium – aluminum joint microstructure assessment in order to analyze the amount of intermetallic layers,
d) assessment of hardening of the selected sample plates after cladding and straightening.

The cladding process efficiency was determined by calculating the percentage participation of the nominal joined area in the initial setup area that was subject to cladding. This indicator in context of the manufactured sample plates was as in the ranges defined below:

- Series „3" plates from 50 to 80%,
- Series „3M" plates from 36 to 59%,
- Series „5" plates from 64 to 75%,
- Series „10" plates from 35 to 81%.

The significant dispersion of the calculated ranges is a consequence of applying varying parameters of the performed cladding operations and relatively small areas of the cladded surfaces. Performing cladding with optimized joining parameters and larger sheet sizes with full certainty would result in significant rising of performance of the process.

All sample plates were subject to mechanical strength tests of the joint, by means of peel tests. The method of performed tests is presented in figure 6.

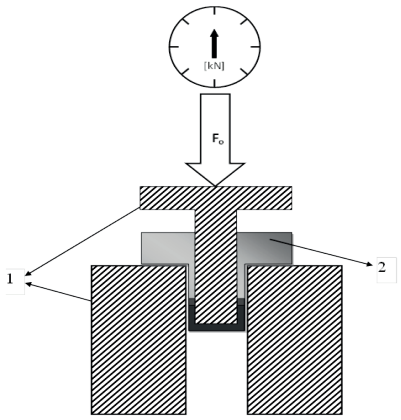

Fig. 6. Method of performing peel strength test, where: 1 - tooling elements, 2 – tested sample

The measured peel strength values could be placed in the following ranges:

- for series „3” sample plates from no bonding to 168 MPa,
- for series „3M” sample plates from 132 to 143 MPa,
- for series „5” sample plates from no bonding to 234 MPa,
- for series „10” sample plates from no bonding to 240 MPa.

All samples acquired from plates cladded directly with no additional soft metallic interlayer severed in the Al/Ti joint. This shows that the material was highly strengthened in the bond zone and has small susceptibility to deformation, despite the noted high levels of mechanical endurance. Joints of the highest quality were destroyed in the plastic layer of the Al (EN AW-1050) or Ti Gr. 2 interlayer. The obtained in these cases endurance values often exceeded the tensile endurance values of these metal due to the strengthening process taking place during cladding. The tests were performed on clads that were not subject to heat treatment.

Microstructure tests of the joint was conducted in the XJL-17AT metalographic microscope and the Neoscope II JCM-6000 electron microscope. Assesed were the Ti6Al4V-AA2519, Ti6Al4V-EN AW-1050 and Ti Gr. 2-AA2519 joints which were considered the most important as it is for the endurance of the joint because of the possibility of appearance of various types of intermetallic Ti-Al compound layers. As a joint quality assessment criteria the equivalent melted zone thickness parameter (RGP) was used. The methodology of calculating the RGP on the example of a wavy joint is presented in figure 7.

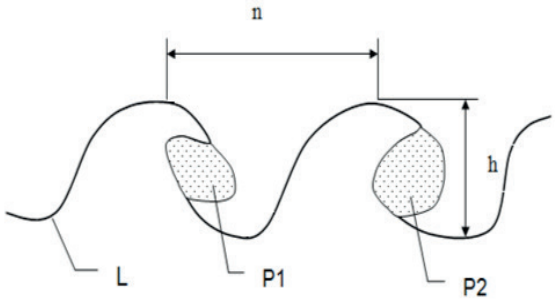

Fig. 7. Schematic wavy joint, formed duing explosive welding, where: n - wave length, h - wave height, P1,P2 - melted zone areas, L - bond area length

Basing on the calculated data, the RGP parameter can be defined as below:

$$RGP = \frac{\sum_{i=1}^{n} P_i}{L} \tag{4,1}$$

where:

$\sum_{i=1}^{n} P_i$ – summed melted zone area on the tested bond line,

L – length of the tested bond line.

Microstructure and the characteristic of the bond was shown in figure 8. In most cases the obtained joints had a flat interface.

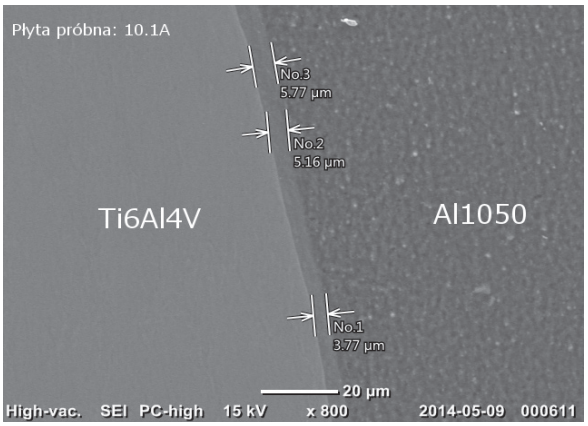

Fig. 8. Microstructure and bond characteristic of sample plate number 10.1A

Table 3 presents the collective manufacturing parameter breakdown and results of tests of selected sample plates for which the best results were obtained.

The explosive cladding process introduces stress into the structure of the bonded materials, which is caused by very strong squash, present strongly in the bond area and the influence of the detonation wave on the cladding material. This results in deformation of the cladded plates and creates a need of submitting them to straightening to enable further industrial processing. Application of stiff steel anvils during the cladding operation prevents the deformations. The straightening operation is usually done after applying appropriate heat treatment, which eliminates all or a majority of the introduced stress. At the current stage of the project the possibility of performing straightening on raw, not subjected to heat treatment was performed. In order to determine the effectiveness of such procedure, selected sample plates were subjected to stress level measurement using the trepanation method. Strength level tests of the obtained bimetals acknowledged a clear increase of stress in the clads structure with increase of the thickness

TABLE 3

Test results of selected sample plates

Sample plate number	EX	H [mm]	h_1 [mm]	h_2 [mm]	D [m/s]	R_o MPa	Fracture location	RGP [um]
3.10A	S2	30	2	10	2039	156	Al1050	1.6
3.17PL	S9	40	4.5	-	2027	155	Al1050	1.7
5.5A	S2	30	1.5	15	1982	185	Al1050	3.9
10.1A	S8	50	1.5	20	2254	182	Al1050	4.1
10.9PL	S9	50	15	-	1969	214	Al1050	7.2

of the joined metal sheets. Negative stresses from the AA2519 aluminium alloy side were observed and from the titanium side sheer stresses were found. The straightening operation affects stress values and their distribution. An unambiguous assessment of the final strengthening state of the manufactured plates after straightening was not obtained. This was most probably due to the fact that all clads were straightened on a hydraulic press, loading the material in a point-manner with changing pressure rate, which resulted in heterogeneity in the stress distribution of the processed material. The straightening process conducted in the next stages, performed on clads of bigger sizes, will be carried out on multi roll rollers that should eliminate the mentioned problems and enable to achieve more reliable results.

5. Analysis of the obtained results

As the conducted tests had shown, all bonding combinations of the AA2519 and Ti6Al4V alloy, directly as well as with the Al (EN AW-1050) or Ti Gr. 2 interlayer are possible to be manufactured. Direct bonds are characterized by high mechanical strength, yet their main drawback is low plasticity in the bond zone and its susceptibility to cracking during straightening. The final area of the preserved bond in this case after straightening can be reduced even up to 50% relative to the initial area. This phenomenon increases with the thickness growth of the bonded plates. Application of heat treatment cannot always bring the wanted effect due to the possibility of forming brittle intermetallic phases between both alloying materials. The direct bonding variant should be noted as an unfavorable one.

Application of a high plasticity metallic interlayer from EN AW-1050 and Ti Gr. 2 was tested for sample plates from series „3" and „5". In both scenarios a high quality bond was achieved, yet it was noted that application of Ti Gr. 2 requires more precision in keeping the geometrical parameters of the cladding setup than in the aluminum interlayer version. Deviation from the planned parameters, caused by the increased curvature of the plate can result in no bonding. This fact can have a significant meaning during manufacturing clads of bigger format. A significant observation is also the considerably higher sample plate temperature, manufactured in the same conditions, but differing only in terms of the used interlayer. While performing bonding in the same conditions of a 5+1+5mm setup with an Al (sample 5.5A) interlayer a temperature increase of the clad of 33 Celsius degrees was observed. Whereas in a 5+0.8+5 setup with a Ti Gr. 2 interlayer (sample plate 5.5T) the temperature increased of 47 Celsius degrees. Considering the specific heat of the cladded materials it can easily be calculated that the sample plate with the Al interlayer had accumulated about 150kJ of heat energy, whereas with the Ti Gr. 2 interlayer about 200 kJ. As the collision energy of the clad plate in both cases was the same, it can be noted that the clad with the aluminum interlayer absorbs by means of plastic deformation much more energy than the clad with a titanium interlayer. Sample plates manufactured using an aluminum interlayer should show an increased ability to accumulate energy during ballistic endurance tests against projectiles not causing puncture of the plate. Another argument for using the aluminum interlayer is its price which is about 10 times lower than the price of titanium. Taking all the mentioned points into consideration, it should be taken that the most effective solution would be manufacturing plates with the Al (EN AW-1050) interlayer.

Performing cladding with the use of the Al interlayer was tested in two setups. The first one was based on using a separate aluminum sheet which was used to join AA2519 and Ti6Al4V sheets in a single shot. In the second scenario AA2519 aluminium alloy which was one or two-sided clad by rolling with a thin layer of EN AW-1050 alloy was used. Usage of the clad AA2519 plates significantly eases the explosive bonding process. This setup was tested for clad plates from series „3" and „10" in a two plate setup as well as a series of 5 and 7 clad layers was manufactured. The high quality of plates manufactured with this version of selected bonding parameters were confirmed by mechanical tests and metallographic assessment.

From all sample plates manufactured in different bonding scenarios five were chosen as those which bonding parameters were selected as optimal. Bonding parameters of these samples are presented in table 3. In the next stage of the carried out research project, these parameters will be optimized for the needs of manufacturing clads of bigger formats.

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