

Investigation on the Corrosion Resistance of Al-Steel Laminated Composite

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Abstract

In this study corrosion behavior of the laminated metal steel-aluminum composite was investigated. The composite was obtained via explosion welding at various welding conditions. The impact of explosion welding parameters as well as time of exposure to close to marine environment was determined. The corrosion deterioration of the composite starts at the interface between metals and proceeds in Al.

Keywords: steel, aluminum, clad metal, corrosion, laminated composite

1 Introduction

Corrosion resistance properties of laminated metal steel/Al composites are of a great importance in many industrial applications such as shipbuilding, nuclear industry [1, 6]. Previous studies reported that the degree of corrosion deterioration of the composite in seawater depends on the explosion welding parameters, the condition of welded surfaces and structural heterogeneity [3]. The first corrosion impact is usually observed at the interface between bonded metals [7].

Although previous studies reported results on the corrosion resistance of steel/aluminum joints in salt water [2, 7], there is still little knowledge on the evolution of corrosion deterioration of Al-steel composites during their long-term interaction with humid air.

The most common method of steel-Al joints fabrication is explosion welding (EW). Usually the EW process is described by several parameters, however the energy spent on metal plastic deformation W_2 can be applied to distinguish between various explosion welding conditions [5].

The aim of the present study was to investigate the behavior of laminated steel-Al composite under corrosion impact.

2 Materials and Methods

In this study explosion welding was employed to join steel with aluminum. Chemical composition of applied materials is presented in the table 1.

Table 1: Chemical composition of the materials used in this study

Material	Chemical composition, wt. %					
Aluminum	Al, >99.3	Si, <0.3	Cu, <0.05	Ti, <0.15	Fe, <0.3	Zn, <0.1
Steel	Fe, 97	C, 0.2	Si, 0.2	Mn, 0.5	Cr, <0.3	Cu, <0.3

Table 2 shows EW regimes used in this study. Each regime corresponds to the W_2 range and the amount of molten zones formed at the interface between metals during EW.

Table 2: Explosion welding regimes used in this study

Structure type	I	II	III	IV
$W_2, MJ/m^2$	1.1-1.4	1.4-1.6	1.6-1.8	1.8-21
Molten zone relative length, %	0	2-5	15-25	65-75

The specimen were exposed to immersion in salt water according to the 1 minute cycle: first the specimen were immersed in salt water for 10 seconds

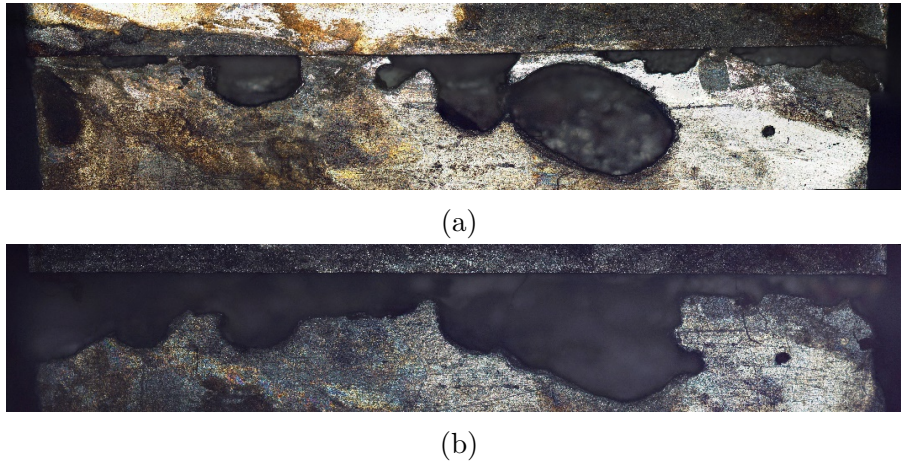


Figure 1: Optical image of Al/steel interface after (a) 15 and (b) 90 days of immersion tests ($W_2 = 1.8 - 2.1 MJ/m^2$)

and subsequently dried in the air for 50 seconds. The immersion tests were carried out for 90 days. Every 15 days the specimen were examined using metallographic analysis and weight loss investigations, which were conducted with 0.1 gr accuracy.

Olympus BX-62 optical microscope was used to carry out metallographic investigations of the surface of corroded materials and to measure depth of corrosion losses. SEM Versa-3D equipped with an EDS were applied to perform chemical and surface analysis of materials.

3 Results and Discussion

Steel Al joints, subjected to marine conditions, undergo galvanic corrosion, which leads to Al deterioration.

Metallographic investigations revealed the origins of corrosion to be molten zones, which formed during EW. The subsequent materials deterioration proceeds into adjacent to steel Al. After 15 days of exposure the specimen obtained at highest values of W_2 had the mean value of depth of corrosion losses of 0.7 mm. The losses were observed mainly in molten zones (fig. 1a) After 45 days of immersion the mean depth of corrosion losses was 1.2 mm. The evolution of the mean depth of corrosion losses value is presented on figure 2b.

After 90 days of tests 100% of the steel/Al interface was covered with corrosion products (fig. 1b). The relative length of corroded steel-Al interface was higher for larger values of W_2 during the first 45 days of tests (fig. 2a). Subsequent corrosion deterioration does not depend on the EW conditions due to complete erosion of the molten zones formed during EW and proceeds mostly into Al layer.

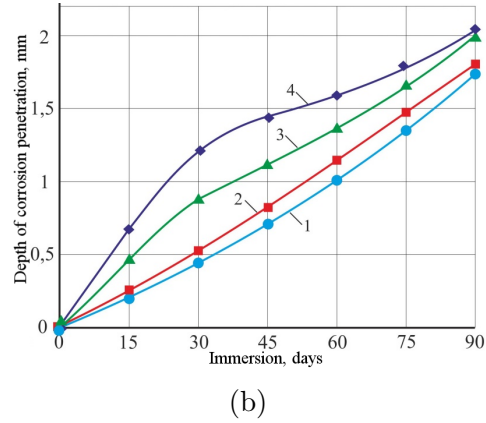
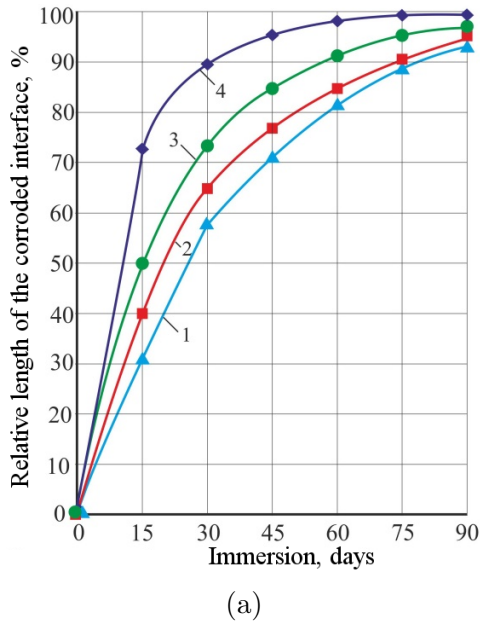


Figure 2: Relative length of the corroded interface (a) and the depth of corrosion penetration (b) with respect to immersion time (W_2 : 1 – 1.1-1.4MJ/m²; 2 – 1.4-1.6MJ/m²; 3 – 1.6-1.8MJ/m²; 4 – 1.8-2.1MJ/m²)

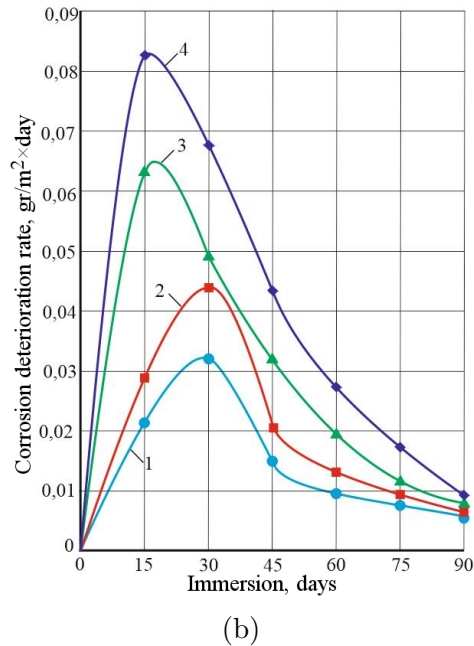
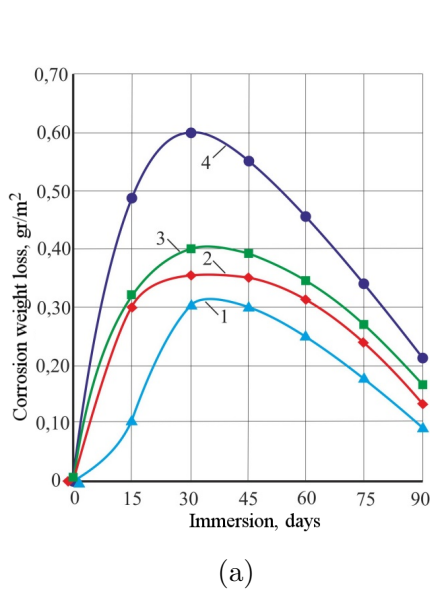


Figure 3: Corrosion weight loss (a) and corrosion deterioration rate (b) with respect to immersion time (W_2 : 1 – 1.1-1.4MJ/m²; 2 – 1.4-1.6MJ/m²; 3 – 1.6-1.8MJ/m²; 4 – 1.8-2.1MJ/m²)

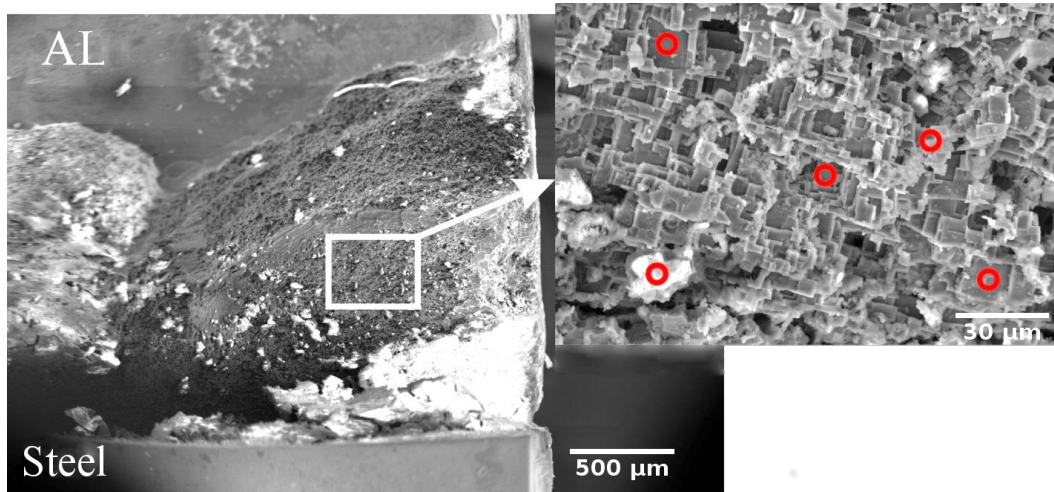


Figure 4: SEM image of the explosion welded Al/steel interface after 90 days of immersion tests ($W_2 = 1.8 - 2.1 MJ/m^2$)

Corrosion both penetrates into the material and proceeds over its surface. The corrosion penetration rate decreases with the immersion time. According to the study [4] the corrosion penetration rate is given by:

$$K = \frac{\Delta m}{\tau}, \quad (1)$$

where τ - denotes time of exposure to corrosion environment, Δm - denotes the weight loss and is given by:

$$\Delta m = \frac{m_0 - m_1}{S}, \quad (2)$$

where m_0 - specimen mass before corrosion impact, m_1 - specimen mass after corrosion impact and after corrosion products removal, S - specimen surface area.

During the galvanic corrosion of steel/Al bimetal, Al experiences the weight loss, however the corrosion products sediment on steel, which is confirmed by visual inspection - steel did not corrode during the experiments. Thus the thin layer on steel tends to counteract the weight loss of Al, however the specimen mass was decreasing during the experiment.

The corrosion weight loss depends both on the EW conditions and the exposure time (fig. 3a). The weight loss maximum was observed after 30-45 days of immersion when the growth rate of mean relative corroded interface length value reduced. Such behavior is apparently promoted by large amount of corrosion products, sedimented on steel. The increase in W_2 from 1.1 to 2.1 MJ/m^2 leads to the acceleration of the weight loss process.

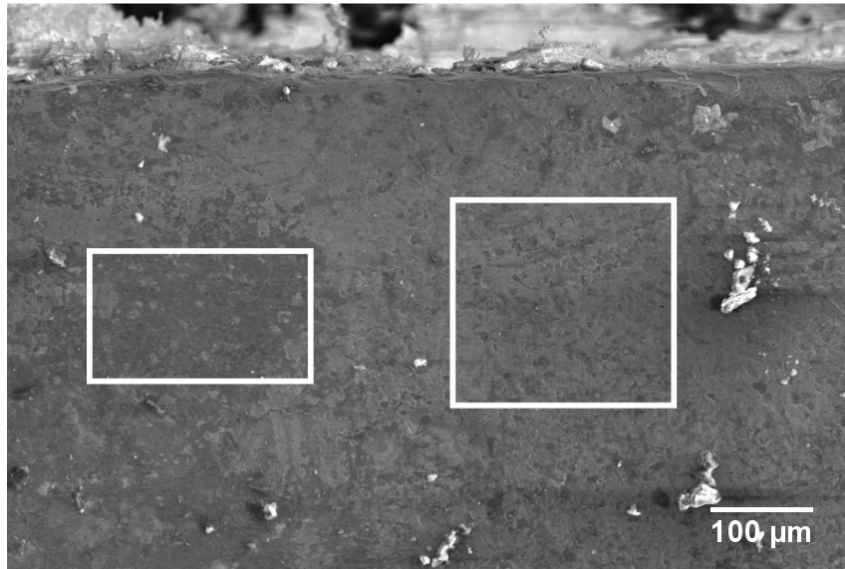


Figure 5: SEM image of steel after 90 days of immersion tests ($W_2 = 1.8 - 2.1 MJ/m^2$)

The maximum value of corrosion rate was observed on the 30th day of experiment to be $0.08 \text{ gr}/m^2$ at $W_2 = 1.8 - 2.1 MJ/m^2$ (fig. 3b). On the 90th day of immersion tests corrosion rate dropped down to $0.01 \text{ gr}/m^2$ for all observed values of W_2 .

Chemical composition of steel and Al surface was examined on the 90th day of immersion. The Al surface contained 1-2% of total area inclusions which had 2-3% Na, 3-4% Cl, 29-30% O and 64-65% Al. The remaining area was covered by oxide layer (96-97% Al, 3-4% O) (fig. 4).

The layer covering steel had two types of coatings, which were visually identified as light and dark regions (fig. 5) with 33-34% and 66-67% of total steel area respectively.

Dark regions were composed of 89-91% Fe, 7.2-8.3% O and small fragments of Na, Al and Cl (table 3). The elements sedimented on steel as a result of cathode process. Due to more active cathode process, light regions contained more Oxygen (23.5-24.1%) as well as Na, Al and Cl elements. The presence of such regions can be explained by surface chemical heterogeneity, which is typical for ordinary quality steels.

4 Conclusion

1. Long interaction of Al/steel bimetal with marine environment leads to corrosion at the interface between metals. Lowest corrosion resistance is typical for regions with large amount of molten zones. EW parameters

Table 3: Chemical composition of the steel layer coating after 90 days of immersion tests.

Element	O,%	Na, %	Al,%	Cl,%	Fe,%
Dark region	7.2-8.3	0.4-0.5	0.97-1.15	0.4-0.5	89.0-91.0
Light region	23.5-24.1	1.12-2.4	5.81-6.10	0.97-1.2	66.2-68.6

have a strong influence on the corrosion of Al/steel bimetal.

2. The corrosion deterioration is mainly promoted by anode process on Al layer. The corrosion rate and the depth of corrosion penetration can reach $0.08 \text{ gr}/\text{m}^2$, and the corrosion products can cover the whole interface of the bimetal.
3. The anode process on Al coincides with the cathode process on steel, which causes the sedimentation of corrosion products (6% Al, 2.4% Na, 1.2% Cl and 24% O) on steel and thus its protection.

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References

- [1] K.R. Trethewey and G.T. Little, Explosion-bonded transition joints for structural applications, *Construction and Building Materials*, **3** (1989), no. 2, 64 - 72. [http://dx.doi.org/10.1016/S0950-0618\(89\)80002-9](http://dx.doi.org/10.1016/S0950-0618(89)80002-9)
- [2] S. Takehisa, T. Iizuka, Galvanic Corrosion Related to Steel/Aluminum Dissimilar Joining Tailored Blank, *Key Engineering Materials*, **611 - 612** (2014), 1460 - 1467. <http://dx.doi.org/10.4028/www.scientific.net/kem.611-612.1460>
- [3] D.V. Pronichev, L.M. Gurevich, Yu.P. Trykov, S.P. Pisarev, M.D. Trunov and V.M. Yastrebov, Issledovanija korrozionnoi stoikosti bimetalla AD1-ST3, *Izvestija VolgGTU*, **20** (2014), no. 23, 15 - 19.
- [4] Gardner S. Haynes, Laboratory corrosion tests and standards: a symposium by ASTM Committee G-1 on Corrosion of Metals, Bal Harbour, FL, 14-16 Nov. 1983. No. 866, ASTM International, (1985).
- [5] V.I. Lysak, S.V. Kuzmin, Lower boundary in metal explosive welding. Evolution of ideas, *Journal of Materials Processing Technology*, **212** (2012), no. 1, 150 - 156. <http://dx.doi.org/10.1016/j.jmatprotec.2011.08.017>

- [6] Yu.P. Trykov, L.M. Gurevich, V.G. Shmorgun, Sloistye kompozity na osnove alyuminiya i yego splavov, Metalurgisdat, Moscow, 2004.
- [7] M. Czechowski, Stress corrosion cracking of explosion welded steel-aluminum joints, *Materials and Corrosion*, **55** (2004), no. 6, 464 - 467. <http://dx.doi.org/10.1002/maco.200303771>

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