The influence of the post-weld heat treatment on the microstructure of Mangalloy – carbon steel clad-plate obtained by explosive welding

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Abstract

This paper aimed to investigate the influence of post-weld heat treatment on the microstructure of the Mangalloy – carbon steel (C45) bimetal joint. The materials have been successfully bonded through the method of explosive welding by using ammonal explosive containing 3 % aluminum powder. The obtained bimetal joint was subjected to two different types of post-weld heat treatments: stress-relief annealing (620 °C/90 min) and normalizing (910 °C/30 min). To investigate the influence of the heat treatment on their microstructure, the joints have been subjected to light and scanning electron microscope observations, as well as the microhardness analysis. It has been reported that stress-relief annealing caused the formation of carbides in the Mangalloy layer on the grain boundaries and joint line. At the same time, normalizing resulted in the recrystallization of Mangalloy and the dissolution of cementite together with the formation of ferrite-pearlite microstructure in the C45 steel layer.

K e y   w o r d s: explosive welding, ammonal, heat treatment, steel, Mangalloy, microstructure

1. Introduction

The modern industry requires new materials and technologies to limit the abrasive wear of components operating in an extreme environment [1–3]. Wear resistance of materials can be improved in many ways, including chemical heat treatment, coating, cladding, and cold working (e.g., shot peening) [1, 4–7]. The obtained modification of material surface should provide good wear resistance, as well as coherency with the base material and low economic cost of the process [5, 8, 9]. One of the most promising technologies, which combines low cost and excellent properties of the product, is the explosive welding technique [10–12]. In this process, the energy released during detonation of the high explosive is used to accelerate one metal plate into another, and as a result, the high-velocity collision of metal plates occurs, which allows us to form a metallic bond between them [11, 13, 14]. This technology allows producing a bimetallic clad-plate consisting of load-bearer, inexpensive material (e.g., carbon steel) and cladding material which provides a specific resistance for corrosion or wear [11]. Explosive welding is widely used for the production of corrosion-resistant equipment for the chemical industry (e.g., heat exchangers, pressure vessels) [10, 13]. The important aspect of this process is a significant strain hardening in the bimetallic joint zone, which causes problems in the forming process of the clad-plate. For this reason, the clad-plate after explosive welding process is subjected to the heat treatment to reduce strain hardening and to eliminate the residual stress in the joint zone [11, 12, 15]. In this research, the investigated clad-plate consists of steel C45 (base material) and Mangalloy (cladding material). This system has the potential to limit the abrasive wear of some of the components in the mining industry and heavy machinery through the use of Mangalloy. This alloy has

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Table 1. Chemical composition of the materials to be joined

% mass	C	Mn	Si	P	S	Cr	Fe
Mangalloy	1.26	12.1	0.3	0.1	0.32	0.8	Base
Steel C45	C	Mn	Si	Cr	Ni	Cu	Fe
	0.46	0.6	0.35	0.2	0.24	0.2	Base

Table 2. The welding parameters used in this study

Flyer plate thickness	Stand-off distance	Explosive layer thickness	Detonation velocity
3 mm	3 mm	30 mm	2280 m s^{-1}

excellent resistance to wear and is used as a material for components in which extreme anti-abrasion properties are required, such as railroads, crusher jaws, and treads of caterpillar vehicles [16, 17]. The important aspect of the explosive welding technique is knowledge about microstructure changes in the joint line during heat treatment. Depending on the properties of welded materials, there is a possibility of new phase formation (including intermetallic compounds) due to diffusion changes in the joint subjected to annealing process [13, 15]. Significant plastic deformation in the joint area also can drastically reduce the amount of energy needed for heat-activated phenomena in welded materials, e.g., precipitation processes, recrystallization [13, 18–20]. These phenomena can decrease the strength of the joint and cause the risk of failure during heat treatment and forming at the manufacturing stage of a specific component [11, 13]. In this research, authors performed the explosive welding process of Mangalloy and C45 steel and subjected the obtained joint to two types of post-weld heat treatment: stress-relief annealing (620 °C/90 min) and normalizing (910 °C/30 min) in order to establish the influence of the heat treatments on the microstructure of the joint.

2. Experimental material and procedure

In this investigation, the materials used for the manufacturing of bimetal clad-plate were a 5 mm thick plate of steel C45 and a 3 mm thick sheet of Mangalloy (X120Mn12). The dimensions of the plates were equal to 80×100 mm^2. The surfaces to be joined have been polished and cleaned with acetone directly before welding. The chemical compositions of the materials are presented in Table 1.

The explosive material used in the process was ammonal consisting of 97 % ammonium nitrate and 3 % aluminum flake powder. The measured density of the
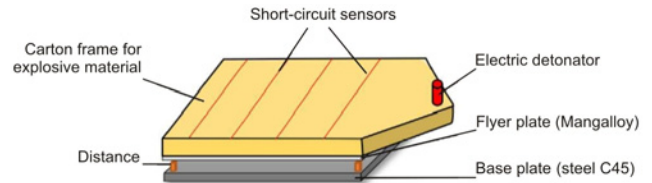

Fig. 1. The scheme of the used explosive welding system.

prepared ammonal was equal to 0.97 g cm^{-3}. To perform the welding process, the system with a parallel arrangement of plates was produced (Fig. 1).

The stand-off distance between plates was equal to 3 mm. Like an anvil, the 100 mm thickness steel block was used. The 30 mm high carton frame localized on the flyer plate was equipped with short circuit sensors to determine the detonation velocity of ammonal directly during the welding process. The distance between used sensors was equal to 20 mm. The initial, triangle part of the frame with placed electric detonator was developed for obtaining a flat detonation wave, as well as to eliminate the influence of detonator on the measurement of ammonal detonation velocity. The selection of the explosive and stand-off distance was based on the experience of authors in explosive welding techniques. The measured detonation velocity was equal to 2280 ± 30 m s^{-1}, which in the case of a parallel explosive welding system also represents the welding velocity. The welding parameters are presented in Table 2.

The obtained clad-plate was cut into three series of samples to analyze the influence of the post-weld heat treatment on the microstructure of the joint. The first sample was investigated in the as-welded state; the second sample was subjected to heat treatment of stress relief annealing (at 620 °C for 90 min), and the third sample was subjected to the normalizing (at 910 °C for 30 min). The designation of the samples is presented in Table 3.

Table 3. Designation of the investigated samples

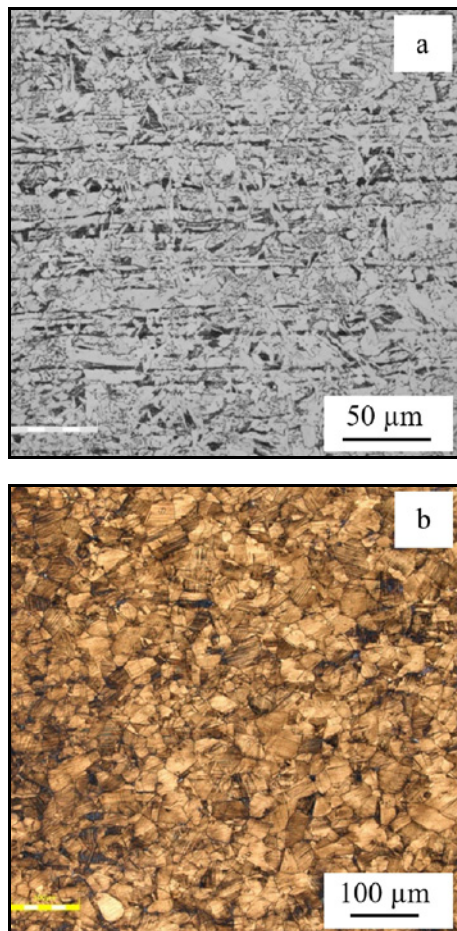| Sample	Description
A3 EXW	Sample in the as-welded state
A3 HTR	Sample subjected to the post-weld stress relief annealing (at 620 °C for 90 min)
A3 HTN	Sample subjected to the post-weld normalizing (at 910 °C for 30 min)

Fig. 2. Microstructure of materials in the as-received state: (a) steel C45; (b) Mangalloy.

Fig. 3. The microstructure of the joint in sample A3 EXW: (a) light microscopy image; (b) scanning electron microscopy image.

To perform the microstructure analysis, the samples were subjected to a metallographic preparation. The cut samples were mounted in resin, ground with the abrasive paper of 80, 320, 600, 1200, and 2400 gradations and polished using the diamond paste of 1 μm gradation. To reveal the microstructure of the joint, a 2 % nital etchant with an etching time of 5–10 s was used. The microstructure of the samples was investigated using light microscope OLYMPUS LEXT OLS 4100 and scanning electron microscope (SEM) Jeol JSM 6610 equipped with energy-dispersive x-ray spectroscopy (EDS) and back-scattered electron (BSE) detector. To establish the strain hardening of the joint zone in the analyzed samples, the Vickers microhardness test was performed with the loading of 100 g.
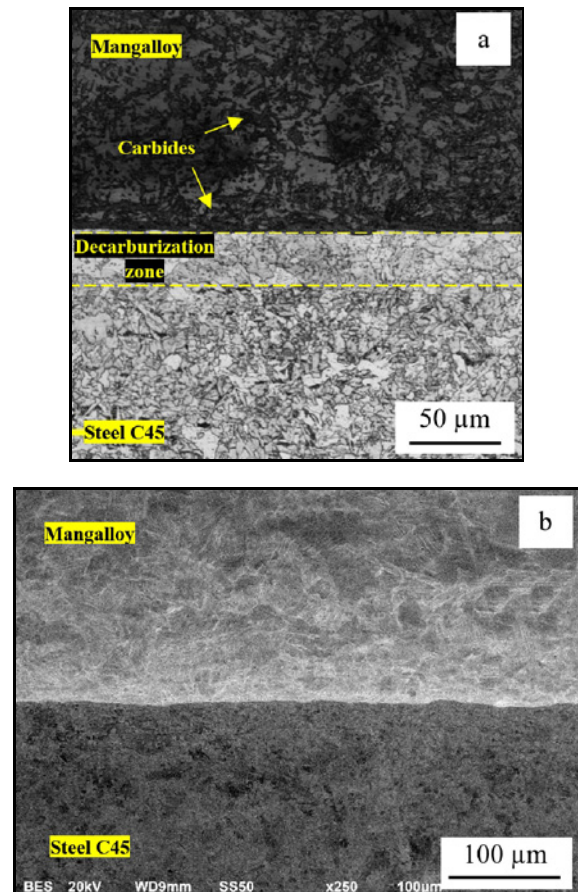
3. Results and discussion

In the first part of the investigation, the light microscopy observations of the base materials were performed. The microstructures of steel C45 (Fig. 2a) and Mangalloy (Fig. 2b) in the as-received state are presented in Fig. 2. Steel C45 microstructure consists of ferrite, pearlite bands, and fine dispersion of spheroid cementite. Mangalloy has an austenite microstructure characterized by the occurrence of twins. The micro-
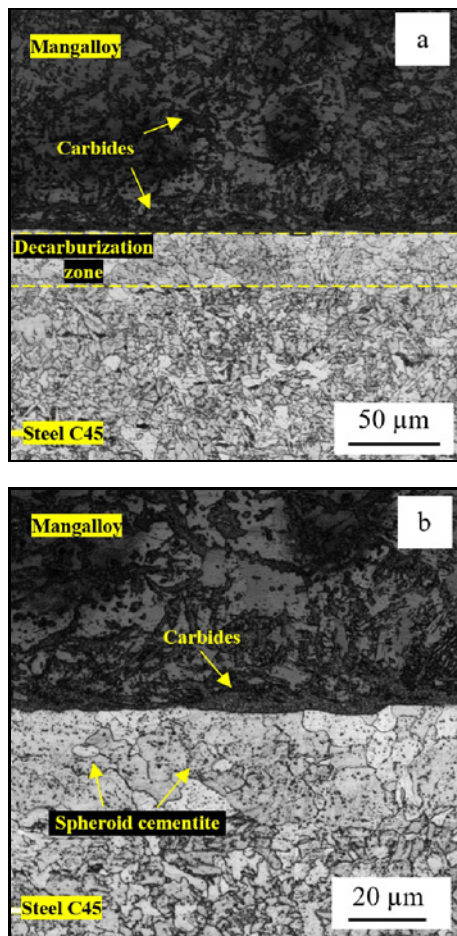
Fig. 4. The microstructure of the joint in sample A3 HTR: (a) joint line with decarburization zone; (b) spheroid cementite in decarburization zone.
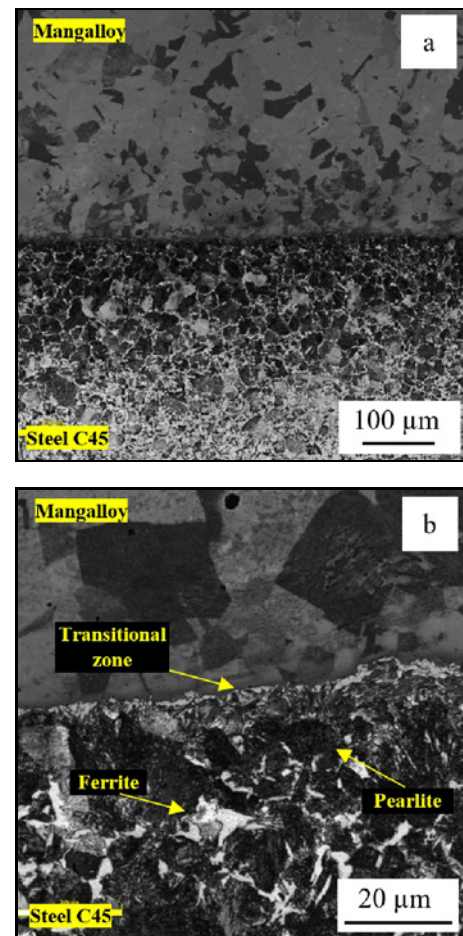

Fig. 5. The microstructure of the joint in sample A3 HTN: (a) ferrite-pearlite microstructure of C45 steel close to the joint line; (b) transitional zone at the weld interface.

hardness of base materials was measured with registered values of 154.3 ± 4.2 HV0.1 for steel C45 and 220.2 ± 3.6 HV0.1 for Mangalloy.

The explosive welding process resulted in the formation of high-quality joint free of any imperfections such as voids, cracks, and delamination (Fig. 3a). It had been reported that in the joint line area, grains of joined materials underwent noticeable plastic deformation. The obtained joint has a flat geometry with the occurrence of single waves what indicates the low value of collision and welding velocity during the bonding process, which can be observed on the SEM image (Fig. 3b). Another investigation concerned with explosive welding of high manganese steel to carbon steel reports that a wavy joint interface can be obtained using a detonation velocity of $3200 \, \mathrm{m \, s^{-1}}$ [21]. However, the presence of joint imperfections in the form of cracks in Mangalloy and the occurrence of melted zones at the joint line was noticed [21].

Heat treatment in the form of stress-relief annealing at 620 °C for 90 min caused the series of changes

in the joint line area. As it can be observed (Fig. 4a), the performed annealing process resulted in the formation of carbide precipitates at the grain boundaries of Mangalloy. A worth noting phenomenon is a high concentration of carbides on the joint line (Fig. 4b). At the same time, the presence of a pearlite-free decarburization zone in C45 steel indicates the diffusion of carbon from C45 steel into Mangalloy due to performed heat treatment, which promotes the formation of carbides localized on the joint line. The width of the pearlite-free zone is about 30 μm. The only high-carbon concentration residue is the spheroid cementite (Fig. 4b). Additionally, the significant grain growth of steel C45 has been reported in the decarburization zone of the A3 HTR sample. Steel C45 grains localized on the joint line do not have a deformation texture, and their size is about 15–20 μm.

Normalizing in 910 °C for 30 min led to the complete recrystallization of Mangalloy with the occurrence of fine grains close to the joint line (Fig. 5a). In the case of C45 steel performed annealing resulted in

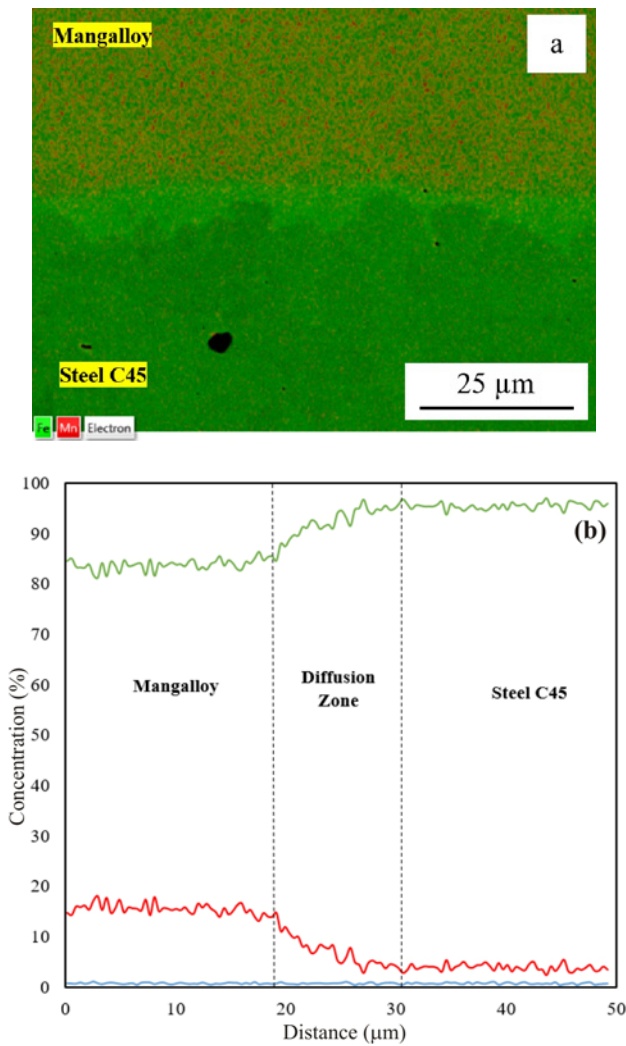Fig. 7. The results of microhardness analysis.

Fig. 6. The microstructure of the joint in sample A3 HTN:
(a) distribution of alloying elements in the joint zone;
(b) results of the line scan analysis (white marker): iron
(green), manganese (red), carbon (blue).

the formation of ferrite-pearlite microstructure. This change in microstructure relates to the dissolution of spheroid cementite due to annealing temperature and as a consequence, increasing carbon concentration in the solution. Recrystallization of C45 steel grains combined with the dissolution of cementite formed new pearlite grains at a distance of about 200 μm from the joint line (Fig. 5a). It is a well-known fact that the higher degree of plastic deformation, the lower energy is necessary to initiate and complete heat-activated phenomena (e.g., recrystallization) and for this reason the noticed changes in C45 microstructure took place in the joint zone, where the highest plastic deformation occurs during the welding process. Additionally, it has been reported that the transitional zone at the joint line consists of ultrafine grains (Fig. 5b).

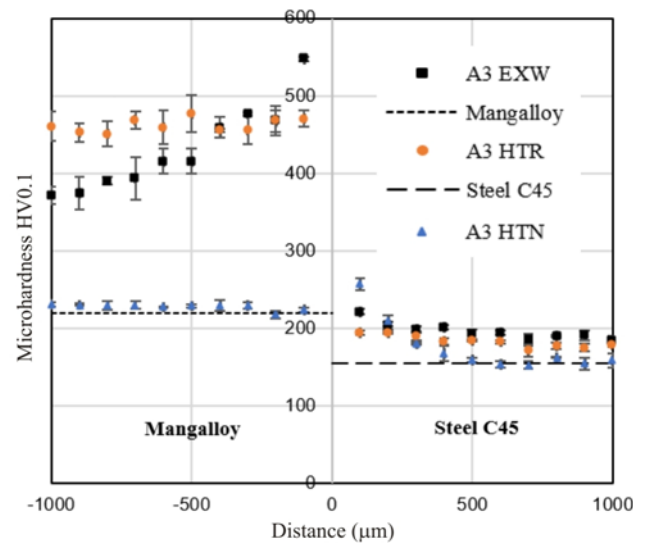Scanning electron microscopy analysis, including

distribution of alloying elements (Fig. 6a) and line scan through joint line (Fig. 6b), indicates the diffusional character of the transitional zone (Fig. 5b). Based on the lines scan results, it is possible to estimate the width of the diffusion zone as about 10 μm.

The observed joint zone microstructure in all samples finds their reflection in the results of microhardness analysis (Fig. 7). In case of the joint in the as-welded state, there is the increase in microhardness in the joint zone; it has been reported that the most significant hardening, about 470 HV0.1 (increase from 220 HV0.1 to 690 HV0.1) is related to Mangalloy which high strain hardening rate is caused by deformation twinning. The effect of the collision on Mangalloy hardness is noteworthy even in 1000 μm from the joint line. A similar level of Mangalloy microhardness at the joint line (725 HV0.1) has been reported in the investigation in which 3200 m s^{-1} detonation velocity was used [21].

Although the explosive hardening of Mangalloy is used in the industry, the obtained level of hardening is significantly lower [22]. This can be explained by the higher value of pressure during the collision of metal plates accelerated by detonation than in the case of the direct affecting metal plate by detonating explosive material [23]. For steel C45, the observed hardening in the joint zone does not have such a drastic increase (an increase from 154 HV0.1 to 265 HV0.1). Although stress relief annealing slightly decreases hardness of both materials in the area closest to the weld interface and equalizes the strain hardening of steel C45, it also causes the formation of carbides in Mangalloy (Fig. 4a) which results in the high value of hardness (about 470 HV0.1) uniformly distributed in the joint zone. Clad-plate subjected to normalizing heat treatment undergoes noticeable softening. Mangalloy re-

crystallization decreases the hardness of clad material to its pre-welded state (about 220 HV0.1) without the formation of carbides due to the shorter time of the annealing. Also, at the distance of 400 μm from the joint line, the microhardness of base material has returned to its pre-welded state (about 154 HV0.1).The only reported fluctuation in the distribution of welded materials microhardness is related to the dissolution of cementite with the formation of pearlite grains in the steel C45 layer, mostly noticeable at a distance 200 μm from the joint line (Fig. 5b). This phenomenon causes an increase of microhardness in this area due to the formation of ferrite-pearlite microstructure, which does not allow to obtain a pre-weld microhardness value of base material.

4. Conclusions

Mangalloy and steel C45 are possible to join by explosive welding technique using ammonal explosive with detonation velocity about 2300 m s^{-1}. A high-velocity collision during explosive welding process resulted in strain hardening of both joined materials, especially Mangalloy with the reported increase from 220 HV0.1 to 690 HV0.1 close to the joint line. Heat treatment in the form of stress relief annealing (620 °C/90 min) led to the formation of carbide precipitates at the grain boundaries of Mangalloy, and additionally, it formed pearlite-free decarburization zone at 30 μm from the joint line having recrystallized 15–20 μm sized grains. The presence of carbides severely affected the hardness of cladding material by uniform increase to a value of 470 HV0.1 in the joint area. Normalizing (910 °C/30 min) resulted in complete recrystallization of Mangalloy microstructure and decrease hardness value to its pre-weld state. At the same time, the dissolution of cementite in steel C45 led to significant changes in the microstructure of this material, caused the formation of pearlite grains and increased its hardness close to the joint zone.

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