

Microstructure and residual stress analysis of explosion cladded Inconel 625 and ASME SA516-70 carbon steel bimetal plates

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Abstract. In the present work the explosion welded joint produced between an Inconel 625 alloy and ASTM A516-70 carbon steel plates was investigated. After welding, the cladded plates were submitted to stress relief annealing at 600 °C for 3 h. The cross section of the cladded plates was examined in both as welded and heat treated conditions by optical microscopy and scanning electron microscopy. The hardness profile across the cladded interface was measured and the residual stress state created as a consequence of the explosion welding process was determined by X-ray diffraction. The experimental results showed that the Inconel 625 alloy adhered well to the ASTM SA516-70 steel, demonstrating the viability of the explosion cladding process for producing bimetal plates of the mentioned alloys. In the as welded condition, metallography analysis indicated severe plastic deformation close to the cladded interface and a wavy morphology characteristic of high bond strength. Elevated tensile residual stresses were created as a result of the welding process and considerable stress relaxation was attained by application of the proposed heat treatment.

1. Introduction

In many engineering applications, structural materials require a combination of mechanical strength and corrosion resistance. While many grades of carbon steel offer adequate mechanical properties within a reasonable price, corrosion resistance requires the application of stainless steels, nickel or titanium alloys and often implies an increase in production costs. Because corrosion is essentially a surface phenomenon, an alternative to the application of bulk corrosion resistant materials is the use of composite metals produced by cladding processes, whereby the corrosion resistant material is joined with a less expensive base material thus combining low cost with adequate properties [1].

Explosion welding is an important solid state cladding technique which allows the fabrication of multi-layered cladded plates with large contact area where conventional fusion welding methods are impractical [2, 3]. The clad metal is accelerated towards a base plate by the energy released from the detonation of an explosive. Upon impact, plastic deformation of the metal surfaces causes hydrodynamic flow in the form of a high velocity jet that sweeps away impurities and oxides from both metal surfaces assisting the establishment of a strong metallurgical bond [4]. The bond between both metals involves intense plastic deformation at the interface, which commonly assumes a wavy morphology as a consequence [5, 6].

In the explosion welding of dissimilar materials, intense plastic deformation at the interface, as well as differences in elastic and thermal properties among the different base materials, may introduce elevated residual stresses in the welded joint. Welding induced residual stresses may

cause e.g. dimensional instability during cutting or machining operations. For this reason, a number of recent investigations have been carried out with the objective of quantifying explosion welding residual stresses [7-11] as well as to establish appropriate stress relaxation treatments [12-14].

The objective of the present work was to investigate the microstructure and residual stresses formed as a consequence of the explosion welding process applied for the production of ASME SA516-70 carbon steel and Inconel 625 alloy composite plates. The cladded plates produced by explosion welding were also submitted to stress relief annealing. Inconel is a corrosion resistant Ni based superalloy with outstanding mechanical properties over a wide temperature range [15]. However, despite its excellent properties, high production costs have limited its individual application [16]. In turn, ASME SA516-70 is a carbon steel currently used in welded pressure vessel applications. Evaluation of residual stresses in Inconel/steel claddings is relevant given the recent increase in Inconel applications in offshore and seawater applications [17].

2. Experimental Procedure

Materials. Plates of ASME SA516-70 carbon steel and Inconel 625 Ni alloy were explosion welded in parallel configuration. Prior to welding, both plates were inspected for surface defects and ground in order to increase contact area and assist the bonding process. The cladded plate was produced in parallel configuration with the SA516-70 steel being the base plate and the Inconel 625 alloy being the flyer plate. The final dimensions of the welded plates were 762x330x31.6 mm. The welding procedures were carried out by Dynamic Materials Corporation (US).

Stress relief heat treatment. Post weld heat treatment for stress relief was carried out in a conventional furnace (with no controlled atmosphere) at 600°C for 3 h. After annealing, the samples were removed from the furnace and air-cooled. The temperature was selected in order to minimize microstructure modifications (e. g. grain growth, phase transformations) of both materials.

Microstructure analysis. Samples for microstructure analysis were prepared by applying mechanical grinding with 80 to 1200 grit SiC grinding paper followed by polishing in 6 and 3 μm diamond suspensions. Etching of the Inconel 625 alloy was accomplished by employing a 4HCl:1HNO₃ solution while a 2% Nital solution was used for etching the SA516-70 carbon steel. Observation of the microstructure was performed by applying Optical Microscopy (OM), Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray spectroscopy (EDX).

Microhardness measurements. Vickers microhardness (HV) measurements were performed across the cladded interface with a 100 gf load (HV0.1) and a 15 s holding time. In total, three microhardness profiles were measured and the average values were determined. The first hardness measurement of each profile began 0.05mm beneath the Inconel alloy surface and subsequent measurements were performed in 0.2mm steps. The hardness of the original base materials before application of the welding procedure was also determined.

Residual stress analysis. Residual stress analysis was performed by applying X-ray Diffraction (XRD) on a 60x60x20 mm piece which was removed from the original welded joint. The $\sin^2\psi$ method [18] was used with equally spaced ψ intervals between 0 and 71.57°. The measurements were performed by focusing the X-ray beam on the center of the Inconel 625 alloy side of the cladded plate and the reflections from the Ni (220) and (311) lattice planes were selected for residual stress calculation. The elastic constants for each reflection were determined by applying the Hill model and the residual stresses were computed for each lattice plane individually. The final residual stress values were obtained by averaging the reflection specific values.

3. Results and Discussion

Microstructure. The microstructure of the cladded interface of the Inconel alloy in the as welded condition is presented in Fig. 1. The microstructure of the Inconel 625 base material is composed of equiaxed grains. At a distance of approximately 40-50 μm from the interface, the microstructure changes significantly and becomes difficult to resolve by OM. This probably occurs due to extensive plastic deformation caused by the explosion welding process. The microstructure of the SA516-70 base material, which is presented in Fig. 2, consists of fine equiaxed ferrite grains and pearlite colonies. The cladded interface exhibits the wavy morphology which is typical of explosion cladding. Such morphology is considered to be indicative of a strong bond due to the increase in contact area between materials (the presence of undulations does not, however, appear to be a necessary precondition for high bond strength, e.g. [19]). The average wave amplitude and period were, respectively, 50 and 500 μm . The microstructure of the SA516-70 steel also changes significantly as the distance to the interface decreases, as seen in Fig. 2. The ferrite and pearlite grains become elongated close to the interface and follow its wavy structure. The grain formation denotes a complex plastic flow.

The microstructure of the cladded interface after heat treatment at 600 $^{\circ}\text{C}$ for 3 h is presented in Fig 3. Significant microstructural changes occurred near interface as a result of the annealing process. The grain structure is now equiaxed and no longer oriented parallel to the wavy interface. This indicates that recrystallization occurred with the heat treatment due to the accumulated strain energy in the vicinities of the cladded interface.

The cladded interface after heat treatment was further studied by SEM and EDX and the results are presented in Fig. 4 (the position of the EDX line scan is indicated by the dotted line). An arrow indicates the existence of an intermediate zone transitioning between the SA516-70 and Inconel 625 base materials. In other points along the interface, the transition between the two different alloys is instead sharp. The chemical composition profile indicates that the transition zone has an intermediate chemical composition relative to the SA516-70 and Inconel 625 base materials, particularly in regard to the concentration of Fe, Cr, Ni and Mo. In the SA516-70 base material EDX reveals negligible amounts of Ni and Cr, and an average Fe concentration of

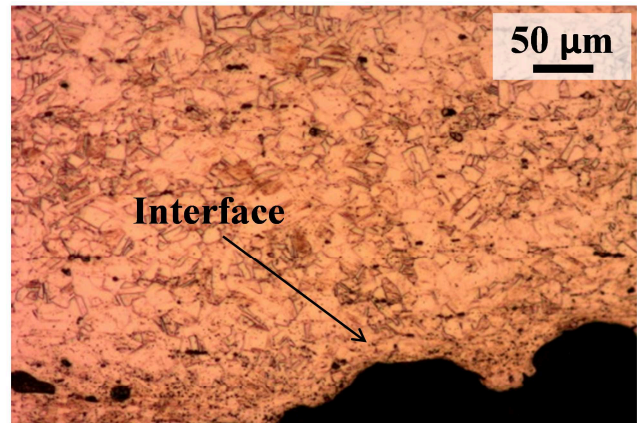


Figure 1: Optical micrograph from the as cladded Inconel 625 alloy

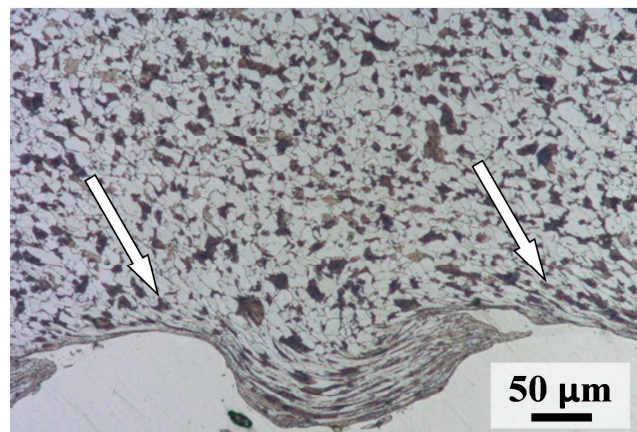


Figure 2: Microstructure of the ASME SA516-70 steel at the cladded interface

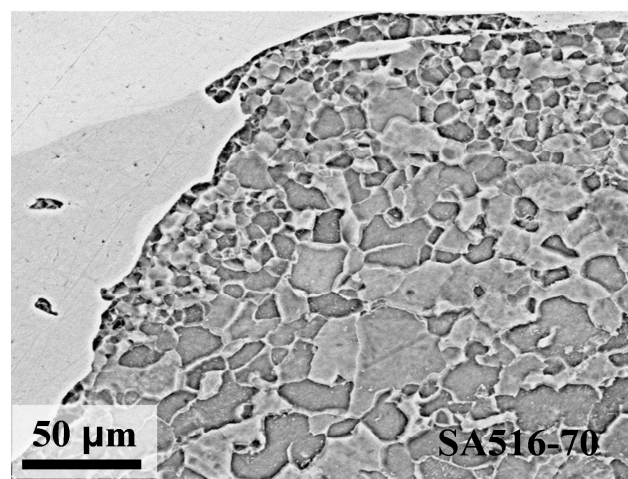


Figure 3: Microstructure of the cladded interface after heat treatment at 600 $^{\circ}\text{C}$ for 3 h.

approximately 95%. In the intermediate region, Fe, Cr and Ni average concentrations are, respectively, 16, 19 and 53%, whereas in the Inconel 625 base material the average Cr and Ni concentrations are 13 and 60% with negligible amounts of Fe. This variation in chemical composition appears to indicate that the particle highlighted in Fig. 4 was formed by melting and mixing near the cladding interface, during the explosion welding process [20, 21].

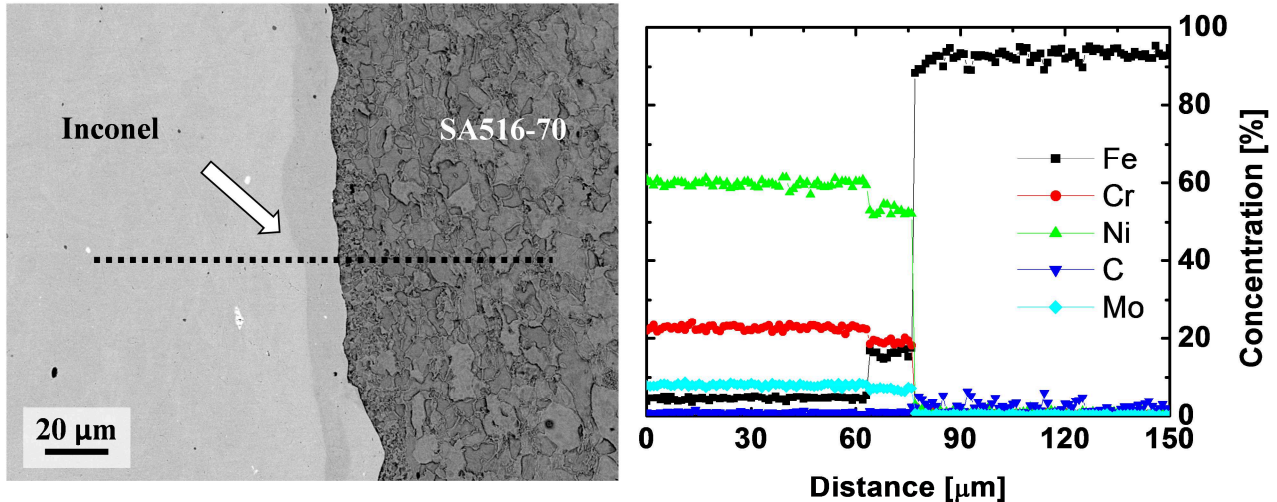


Figure 4: SEM micrograph of the cladded interface and variation of chemical composition.

Microhardness. Vickers microhardness measurements were performed across the cladded interface and the results are presented in Fig. 5. Two plots are presented, corresponding to microhardness line profiles taken from materials in both the as welded and heat treated conditions. The hardness values of the base materials prior to the welding process, indicated by dashed lines, were 196 and 234HV for the SA516-70 steel and Inconel 625 alloy, respectively. The maximum hardness value in the as welded condition (560HV) occurs at the bond interface on the Inconel 625 alloy side of the joint with a significant increase in comparison to the base material prior to welding. After heat treatment, the maximum hardness is also observed directly on the interface (654 HV). It is unexpected that the after annealing hardness values have increased relative to the as welded condition. The hardness measurements in the vicinities of the cladded interface ought to be taken critically, however, because of the heterogeneous distribution of localized melted zones variations in grain size and chemical composition. Overall the hardness variation exhibited in Fig. 5 can be attributed to strain hardening caused by intense plastic deformation at the collision zone and refinement of the grain structure since these were the two distinctive features present in the interface microstructure (Figs. 1-3).

Residual stress analysis. Residual stress analysis was performed on the Inconel 625 side of the welded joints by measuring the distances of the Ni (222) and (311) lattice planes. The results are presented in Fig. 6 in terms of the variation of the average Ni FCC structure lattice parameter with respect to $\sin^2\psi$. The average residual stress for the as welded condition calculated from the slope of the linear fit of the $\sin^2\psi$ plots was 455 ± 30 MPa. The residual stress associated with welding of dissimilar materials is often connected to differences in Coefficient of Thermal Expansion (CTE),

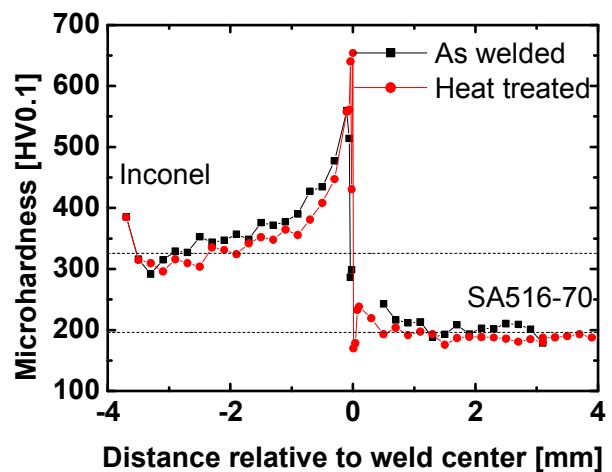


Figure 5: Vickers microhardness measured across the cladded interface.

or elastic properties among the base materials. Since Inconel 625 and carbon steel have similar elastic modulus, residual stresses should be influenced by the thermal cycle common to welding procedures with contributions from the CTE mismatch among the welded materials. The heat treatment applied brought about a significant relaxation of the residual stress field on the Inconel alloy side of the clad plate, as shown also in Fig. 6. The residual stress value observed on the Inconel 625 side of the clad plate was of 14 ± 20 MPa. In spite of the fact that hardness values remained high after heat treatment (Fig. 5), apparently sufficient recovery occurred in the base material to allow for near complete elimination of residual stresses.

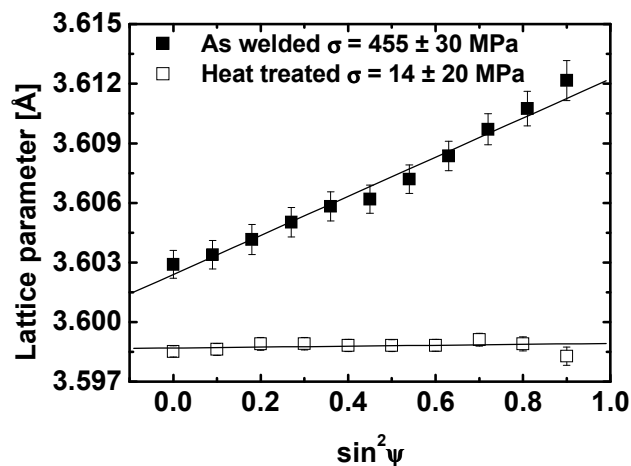


Figure 6: Results of the residual stress analysis performed on the Inconel 625 side of the clad plates in as welded and heat treated conditions.

4. Conclusions

The explosion welding process was applied to clad Inconel 625 Ni alloy to ASME SA516-70 carbon steel. Microstructure analysis revealed intense plastic deformation close to the clad interface and modification of the grain structure morphology, equiaxed in the base material and elongated in the welding direction close to the interface. Overall, the interface exhibited the wavy morphology which is characteristic of elevated bond strength in explosion welds. The hardness profile across the welded joint was influenced by strain-hardening taking place during the welding process. Residual stress analysis performed on the Inconel side of the clad plate revealed the presence of tensile stresses of 455 ± 30 MPa. The heat treatment process applied effectively relaxed the residual stress field in the welded materials.

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