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Bimetallic shape memory alloy composites produced by explosion welding: Structure and martensitic transformation

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ABSTRACT

The aim of the present work was a study of the influence of explosion welding on the grain structure, chemical composition, phase composition and phase transitions in bimetallic shape memory composites containing the TiNi shape memory alloy as an active layer and one of four alloys having different abilities to react with TiNi alloys as passive layer. Stainless steel was chosen as a non-reacted material, TiNi alloy was used as the alloy with close chemical composition, and Ti6Al4 V alloy and copper beryllium (C17200) alloy were chosen as materials which might react with TiNi alloy to form new phases. The results of the study showed that variations in the grain structure and properties of the layers in the bimetal composite depended on the ability of the alloys used for the production of these composites to react with TiNi alloys. If the alloys did not react with TiNi alloy, as in the case of stainless steel, the explosion welding resulted in significant plastic deformation of the layers. This led to a change in the grain morphology, a deep decrease in transformation temperatures and a suppression of the martensitic transformation (a decrease in the volume fraction undergoing phase transformation). In this case, annealing at high temperatures had to be used for recovery of the grain structure and properties of the composite before application. If the alloys were able to react with TiNi alloy to form the intermediate phases, for instance Ti6Al4 V alloy, the explosion energy was then expended for the formation of the intermediate layer and the plastic deformation of the basic layers was small. This composite retained the parameters of the martensitic transformation and grain structure and should be subjected to annealing at low temperature to decrease the internal stresses appeared during welding.

1. Introduction

Shape memory alloys are used for many applications due to their ability to recover large unelastic strain on heating (the shape memory effect) or unloading (pseudoelasticity), their generation of high recovery stress and the performance of a large useful work. All the observed phenomena are caused by the thermoelastic martensitic transformation that occurs in the alloys. The most applicable shape memory material is TiNi alloy because the value of the recovery strain is about 10%, the recovery stress is about 800–1000 MPa and the value of the useful work is about 10 MJ/m^3. It allows one to use the TiNi-based alloys in medicine and in engineering for actuators, sensors and heat engines.

However, Lester et al. (2015) showed that the shape memory alloy composites demonstrated better shape memory alloy properties and might be used for designing new constructions for complex application in techniques. Shape memory alloys may be used as a filler to make the composite more flexible or as matrix than contains another filler to make the composite stronger. For instance, Simpson and Boller (2008) used Kevlar reinforced by TiNi wire to design flexible wings. At the same time, Yu et al. (2016) reinforced the TiNi matrix by Nb thin wires and it allowed them to increase in strength of the composite. Among different types of composites, the planar shape memory composite seems to be more useful as a body for the thermomechanical actuator because this composite includes the shape memory alloy as an active layer and the elastic alloy as a passive layer. Belyaev et al. (2010b, 2014) showed that the co-existence of active and passive layers in one composite results

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in the “TiNi-steel” and “TiNi-TiNi” composites becoming able to demonstrate recoverable strain on cooling and heating through the temperature range of the martensitic transformations. Irzhak et al. (2010a, 2014) found the same phenomenon in “TiNi-Pt” and “TiNi—Magnetic shape memory alloy” composites.

There are some types of planar composite production, however, two of which are widely used: deposition of one layer to the other or welding. Irzhak et al. (2010b) found that a very thin shape memory composite (dozen of microns) might be produced using the first method. The welding allows a thick composite to be fabricated however, Eijk et al. (2003) and Gugel and Theisen (2009) showed that heating of the samples during plasma or laser welding led to the formation of thick heat-assisted zones where the microstructure differed from the structure of the material far from the joints. As a result, the mechanical and functional properties of the composites were degraded and the lifetime of the material decreased. Nevertheless, there is one type of welding that does not result in the formation of a heat-assisted zone due to its short action time – this is explosion welding. Zimmerly and Inal (1994) showed that this type of the joining might be used for the production of TiNi–steel composite. Prummer and Stockel (2001) found that a variation in explosion velocity allowed one to control the joint process and to obtain the composite with straight or wave joint. Xing et al. (2006) showed that explosion welding might be used to fabricate the “TiNi–TiNi” composite where TiNi layer had different chemical composition. Belyaev et al. (2010a) found that, the TiNi layer was subjected to a large plastic deformation during explosion welding due to the high impact energy that led to suppression of the martensitic transformation. Belyaev et al. (2010c) demonstrated that post-explosion heat treatment of bimetal composite was needed to recover the ability of the TiNi layer to undergo the phase transformation and to demonstrate the shape memory effects.

Therefore, the analysis of the published data allows one to conclude that explosion welding may be successfully used for production of planar TiNi-based shape memory composite. Despite the “TiNi-steel” and “TiNi–TiNi” composites were fabricated by this method there is no any reason why the TiNi alloy cannot be connected to other materials using explosion welding. At the same time, it is known that the impact during explosion welding influences the structure of the layer via plastic deformation and variation in chemical composition in the joint vicinity. Findik (2011) showed that this effect depended on the chemical composition and the mechanical properties of the alloys used for welding. The mechanical properties of the alloys (especially their plasticity) influence the process of joining. The lower the dislocation yield stress, the better the joining of the alloys during explosion welding. For instance, it is known that joining of TiNi alloy to other TiNi or steel by explosion welding is better if the TiNi alloy is in the austenite state than the same alloy is in martensite state. This is due to TiNi alloy in the austenite state is characterized by lower dislocation yield stress than in the martensite state.

The chemical composition of the alloys influences the possibility of new phase formation in the joining area during the impact. For instance, Eijk et al. (2003) showed that Ti_2Ni and TiC precipitates formed during plasma welding of TiNi and TiNi alloys or TiNi and steel. However, these phases do not appear during explosion welding due to short impact duration is not enough for precipitation formation. Hence it may be concluded that the TiNi alloy and stainless steel are not able to undergo the reaction during explosion welding. The joining of the TiNi alloy and the TiNi alloy with different chemical composition should not be accompanying by the precipitate formation due to a difference in chemical composition is small and it is not enough for precipitation of Ti-rich or Ni-rich particles. Thus, it may be assumed that TiNi can not react to the other TiNi during explosion welding. As the explosion energy is not spent to formation of new phases then, all this energy goes to the plastic deformation of the layers. It is confirmed by Belyaev et al. (2010a) and 2014 showed that TiNi layers in TiNi-steel and TiNi–TiNi composites were subjected to a huge plastic deformation and it led to a deep suppression of martensitic transformations.

At the same time, if the TiNi alloy is welded to alloys containing components which may react to Ti or Ni, then new phases may appear during explosion welding. In this case, one part of the explosion energy is spent to the formation of new structure and the other part of explosion energy goes to the plastic deformation of the layers. One may expect that in such composites a suppression of the martensitic transformations in TiNi layer should be less and these composite may be able to demonstrate the recoverable strain variation just after explosion welding. Therefore, it is necessary to join the TiNi alloys with the alloys containing the chemical elements which may react to Ti and Ni elements of TiNi layer and to form new phases and solutions. From this point of view, it should be the alloys containing the Ti and Cu elements because these elements dissolve in TiNi alloy and may form different intermetallic phases. At the same time, these alloys should demonstrate good elastic properties needed for ability of composite to demonstrate the recoverable strain variation in future. The better candidates are the Ti6Al4 V alloy and copper beryllium (C17200) alloy however, there is no any information about the joining of TiNi alloys and these alloys by explosion welding. Thus, the first aim of the present work is to produce the “$Ti_{50}Ni_{50}$–Ti6Al4V” and “$Ti_{50}Ni_{50}$–C17200” composites by explosion welding. The second aim was to study the structure and martensitic transformation in four composites: “$Ti_{49.4}Ni_{50.6}$–AISI 304”, “$Ti_{50}Ni_{50}$–$Ti_{49.3}Ni_{50.7}$”, “$Ti_{50}Ni_{50}$–Ti6Al4V” and “$Ti_{50}Ni_{50}$–C17200” to clarify the influence of the intermetallics formation during the explosion welding on the structure and martensitic transformation in TiNi layer connected to materials having different abilities to react with TiNi alloys.

2. Experimental details

Equiatomic Ti—50.0 at.% Ni alloy and Ti—50.6 at.% Ni alloy were used as the shape memory alloy layers and four different alloys—stainless steel (AISI 304), Ti—50.7 at.% Ni, Ti-based alloy (Ti6Al4 V) and copper-beryllium alloy (C17200) were used as passive elastic layers. The $Ti_{49.3}Ni_{50.7}$ layer was used as the passive elastic layer because this alloy was able to demonstrate the pseudoelasticity effect that was characterized by a recovery of large unelastic strain. Stainless steel is chosen as the non-reacted material, TiNi alloy is used as the material with close chemical composition and Ti6Al4 V alloy and copper beryllium (C17200) alloy are chosen as materials which may react with TiNi alloy to form new phases.

The following composites “$Ti_{49.4}Ni_{50.6}$–AISI 304”, “$Ti_{50}Ni_{50}$–$Ti_{49.3}Ni_{50.7}$”, “$Ti_{50}Ni_{50}$–Ti6Al4V” and “$Ti_{50}Ni_{50}$–C17200” were produced by explosion welding. The TiNi plate was covered by the ammonite + 30% NaCl layer and located with an angle of 12° to the basic plate of passive layer which horizontally located. After detonation of the explosive, the TiNi plate collided with the passive elastic layer plate and the connection between them took place. The detonation velocity was 2150 m/s. The flyer plate velocity was estimated as shown in Findik (2011) and it was equal to 450 m/s. The explosion welding was carried out at room temperature. Before explosion welding, the length of the composite was 100 mm, the width was 50 mm and the thickness was as given in Table 1. After explosion the thickness of the composites as well as the ratio of the TiNi layer thickness to the total thickness of the composites are given in Table 1.

The microstructure of the composite cross-section as well as the martensitic transformation that occurred in the composites