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Functional properties of bimetal composite of “stainless steel – TiNi alloy” produced by explosion welding

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Abstract

The functional properties of “TiNi–stainless steel” bimetal composite produced by explosion welding were studied. The influence of the ratio of the TiNi layer thickness to the total thickness of the sample as well as the influence of preliminary deformation on the recoverable strain and a temperature of shape memory effect were studied. It was found that the best combination of strain variation observed in repeated thermal cycles was demonstrated by the bimetal sample in which the thickness of the TiNi layer was 64% of the thickness of the sample. The preliminary deformation resulted in an increase in stress stored in the sample and led to an increase in recoverable strain.

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Keywords: “TiNi – stainless steel” bimetal composite; explosion welding; recoverable strain

1. Introduction

One claimed application of shape memory alloys is actuators, which may produce some action on cooling and heating at the temperature range of martensitic transformation. Actuators of repeated action may be developed on the base of bimetal composite where one component possesses a shape memory effect and the other has good elastic properties (bias component). Ordinary TiNi alloy is connected to other alloys by laser or plasma welding. However the strength and functional properties of these objects are not so good due to the formation of precipitates such as TiFe₂, TiFe, TiC, and Ti₃Ni₄ in the heat-assisted zone [1-2]. Meanwhile Prummer and Stockel in [3] showed that the bimetal composite of “TiNi alloy–stainless steel” may be produced by another type of joining: explosion welding. S. Belyaev et al. [4] found that the formation of brittle intermetallics and non-metallics particles was not observed in “TiNi–stainless steel” composite produced by explosion welding. Moreover it was shown that the width of the mixture zone between the steel layer and the TiNi one was very narrow and did not exceed 6 μm. It was found that a

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martensitic transformation in the TiNi component of bimetal composite was strongly depressed by plastic deformation imparted to the TiNi alloy during an impact with a steel plate. Belyaev et al. [4] found that the kinetics of a phase transition may be restored by subsequent annealing of the composite.

However for application of bimetal composite it is very important to study not only the kinetics of martensitic transformation but also the functional properties. It is known that the behaviour of actuators depends on the relation between the ability of the bias element to accumulate an elastic energy and the ability of the shape memory alloy to recover a strain. Thus, in the case of actuators created on the base of bimetal plate, the properties of the actuator should depend on the ratio of the thickness of the TiNi layer to that of the steel one. However the ability of the sample to accumulate stress is determined not only by the thickness of the steel layer but also by the level of preliminary strain of the bimetal composite. Because a preliminary strain of the sample results in a higher strain recovery on heating, it induces a higher stress to accumulate in the composite on subsequent heating. One may make the assumption that the high level of stress stored in the sample may lead to the higher level of recoverable strain observed in subsequent thermal cycles of the sample. Thus, a goal of the paper is to study the influence of the thickness of TiNi and steel layers and the value for preliminary deformation on the functional properties of “TiNi–stainless steel” bimetal composite produced by explosion welding

2. Experimental procedure

A Ti-51 at.% Ni plate with a thickness of 1.68 mm and an AISI 304 stainless steel plate with a thickness of 0.98 mm were used for preparing a bimetal composite by explosion welding. Explosion welding was carried out according to the scheme published in [4]. After explosion, the thickness of the bimetal composite was 2.33 mm, the thickness of the TiNi layer was 1.56 mm, and the thickness of the steel layer was 0.77 mm and martensitic transformations were partially depressed (see Fig.1). The bimetal composites were annealed at 600 °C for 2 hours. A study of the martensitic transformation was carried out on cooling and heating the samples in a Mettler Toledo 822° Differential Scanning Calorimeter over the temperature range of 100 to –100 °C with a heating/cooling rate of 10 °C/min. The DSC data showed that after this heat treatment the bimetal composite underwent a martensitic transformation from the cubic B2 phase to the monoclinic B19' phase at temperatures of $M_s = 6$ °C and $M_f = -17$ °C and the reverse B19' → B2 transformation at temperatures of $A_s = 8$ °C and $A_f = 26$ °C (see Fig.1).

The samples with a length of 50 mm and a width of 7 mm for mechanical tests were cut by electro-discharge machine from bimetal composite plate. To study the functional properties of bimetal composite, the samples were deformed (TiNi is in tension) at a temperature of –170 °C by three point bending methods and unloaded. After this, the unloaded samples were heated up to 150 °C to study the shape memory effect and were then subjected to ten thermal cycles at a temperature range of 150 to –170 °C to investigate the recoverable strain and the temperatures of

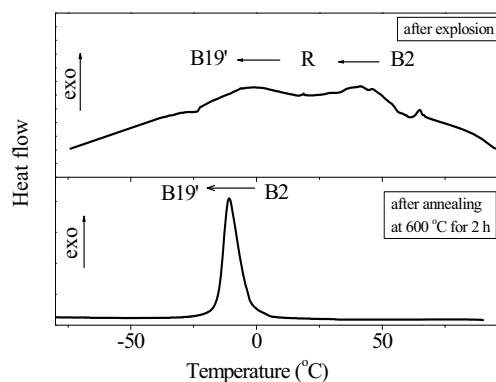


Fig. 1 Calorimetric curves obtained on cooling and heating of bimetal composite “TiNi – stainless steel” after explosion welding; and after annealing at 600 °C for 2 hours.

strain variation. The strain was estimated in outer fiber.

3. Results and discussion

To study the influence of the TiNi layer thickness on the functional properties of bimetal composite, samples

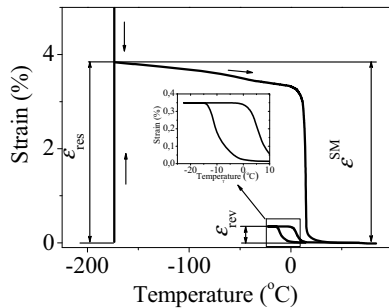


Fig. 2 Strain vs temperature dependence obtained on heating and subsequent thermal cycling the TiNi sample deformed up to 5% at temperature of -170 °C.

with different ratios of the thickness of the TiNi layer to the total thickness of the sample (from 0 to 100%) were deformed by up to 5%, then heated up to 150 °C, and thermal cycled at the temperature range of 150 to -170 °C. Figure 2 shows a strain vs temperature dependence obtained on heating and subsequent cycling of a TiNi sample after deformation of up to 5% at -170 °C. It is seen that the strain recovery takes place on heating at the temperature range of 11–15 °C and a perfect shape memory effect is observed. Moreover a two-way shape memory effect is found on subsequent cycling the sample at the temperature range of martensitic transformation. To study the influence of cycling on the value for a two-way shape memory effect, each sample was subjected to ten thermal cycles. The data obtained show that there are no changes in parameters (values and temperatures) of two-way shape memory effects on cycling virgin TiNi sample. The same strain vs temperature dependences were obtained for the

bimetal composites with different ratios of the TiNi layer thickness, and the values of residual strain (ϵ_{res}), shape memory effect (ϵ^{SM}), and two-way shape memory effect (ϵ_{rev}) were determined as shown in Figure 2. A recovery coefficient K estimated as a ratio of strain recovered on heating (ϵ^{SM}) to residual strain (ϵ_{res}) is used for characterization of the samples' strain recovery ability.

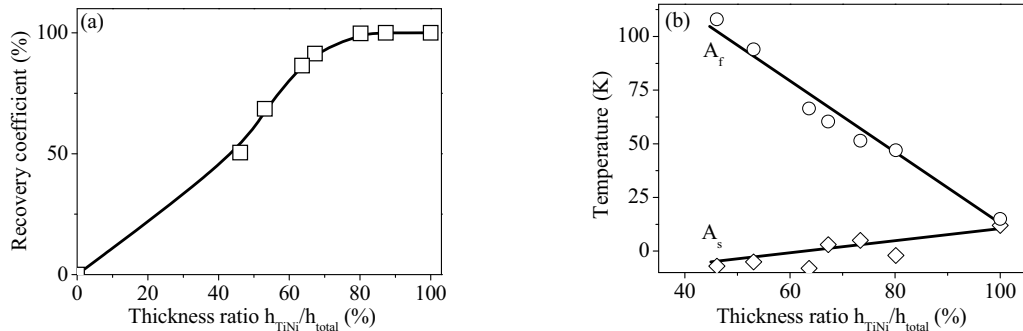


Fig. 3. Dependence of the recovery coefficient (a) and the temperatures of shape memory effect (b) on a ratio of thickness of the TiNi layer to the total thickness of the bimetal sample.

The dependence of the recovery coefficient on the relative thickness of the TiNi layer is presented in Figure 3a. It is found that a decrease in the TiNi layer thickness from 100% to 80% does not influence the recovery coefficient and results in an increase in the temperature interval of strain recovery (Figure 3b). However a decrease in relative TiNi layer thickness of less than 80% leads to a dramatic decrease in the recovery coefficient and huge widening of the temperature interval of A_f – A_s . So, on heating the bimetal sample with a TiNi layer thickness of 80%, a perfect shape memory effect is observed, while on heating a bimetal composite with a TiNi layer thickness of 46%, only 50% of the strain is recovered and the temperature interval of the shape memory effect increases from 43 °C to 115 °C. It is important to note that the increase in the temperature interval of strain recovery was first of all due to a strong increase in the finish temperature A_f , while the start temperature A_s decreases to a small extent. To understand this phenomenon let us describe a variation in stress–strain behaviour occurring in the TiNi layer and steel layer during deformation and heating. On loading the bimetal sample up to 5% the stress increases in the

sample from zero to some maximum value and decreases to zero on unloading according to stress–strain diagrams. On subsequent heating the TiNi layer undergoes a reverse martensitic transformation and strain recovery takes place, which results in a bending steel layer and a stress appearing in the sample. Thus, strain recovery in the bimetal composite begins at a condition of zero stress because the shape change has not started and the strain recovery finishes under a high opposite stress. The larger the thickness of the steel layer, the higher the stress that accumulates in the sample on heating. Thus, a temperature of A_s changed only slightly and a temperature of A_f increased dramatically according to the Clausius-Clapeyron relation. The appearance of high stress is the cause of the decrease in the recovery coefficient observed in the experiments (Figure 3 a). Thus, one may conclude that the best shape memory effects are observed in the bimetal samples with relative thicknesses of the TiNi layer of 80 % and higher.

For the application of bimetal composites as actuators, the most important parameter is the strain variation observed on subsequent repeated thermal cycles. For characterization of strain variation at thermal cycling the recoverable strain ϵ_{rev} will be taken into account. It is easy to suppose that if the thickness of the steel layer is very small, the strain variation on cycling is thus determined by the two-way shape memory effect only, and if the steel layer is very large then the strain variation is depressed. Hence an optimal ratio of the TiNi layer thickness to the total thickness of the bimetal sample must exist at which a good strain variation takes place on repeated thermal cycles. To prove this statement, dependences of the strain (ϵ_{rev}) observed during the first and tenth cycles on the relative thickness of the TiNi layer were studied. As expected, Figure 4 shows that a non-monotonic influence of the relative thickness of the TiNi layer on the recoverable strain observed in repeated thermal cycles exists. The maximum strain is found in the bimetal sample where the TiNi layer occupies about 65 % of the total thickness of the sample. The value ϵ_{rev} observed during the first cycle was 1.53 %, which is four times higher than the two-way shape memory effect found in the pure TiNi sample.

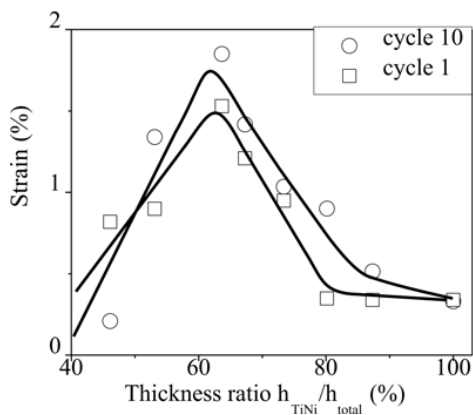


Fig. 4 Dependence of strain observed at the first thermal cycle and at the tenth cycled on ratio of TiNi layer thickness to the total thickness of the sample.

TiNi layer. Thus, the higher the strain recovery of the TiNi layer, the larger the deformation of the steel layer and the higher the stress stored in the bimetal composite. To increase the strain recovery of the TiNi layer, the sample must be preliminarily deformed up to higher level of strain. Hence the functional properties of the bimetal composite should depend on the preliminary deformation.

The influence of the preliminary deformation on the functional properties of the bimetal sample was studied. The bimetal samples with TiNi layer thicknesses of 64 % were deformed up to strain from 1 % to 10 % at a temperature of -170 °C, unloaded, heated up to 150 °C, and subjected to ten thermal cycles. The influence of residual strain on the value of the shape memory effect is presented in Figure 5a. As expected, an increase in the preliminary strain results in an increase in strain recovery. However an increase in recovery strain leads to increase in the values of stresses accumulated in the bimetal sample upon heating, as mentioned earlier. Thus, the higher the preliminary

Depending on the thicknesses of the TiNi layer and steel layer, repeated thermal cycling results in different influences on the value of strain. If the ratio of h_{TiNi}/h_{total} exceeds 50 % then an increase in the cycling number leads to an increase in the strain; this phenomenon is known as the training effect. For instance, in a bimetal composite with a TiNi layer thickness of 64 %, the value ϵ_{rev} increases from 1.5 % up to 1.85 % from the first thermal cycle to the tenth one. At the same time, cycling of the bimetal sample where the thickness of the steel layer exceeds the thickness of the TiNi layer results in a strong decrease in ϵ_{rev} . So, in the bimetal sample with a TiNi layer thickness of 46 %, 0.82 % of the strain is observed in the first thermal cycle and only 0.27 % in the tenth cycle.

Thus, the results of the study allow us to find the optimal geometrical sizes of the thickness of the TiNi layer and steel layer in bimetal composite that lead to observation of the best strain variation during repeated thermal cycles. This value for strain is determined by the stress accumulated in the bimetal sample on heating due to deformation of the steel layer by the

strain of the bimetal composite, the higher the stress that hinders the strain recovery. This is why the recovery coefficient decreases linearly. At the same time a high level of stresses accumulated in the sample must induce a higher value of the transformation plasticity effect on subsequent cooling, and as a result the value for recoverable

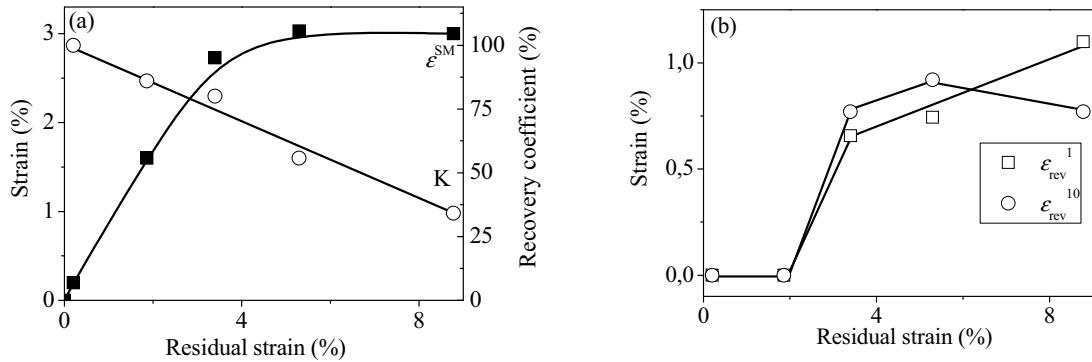


Fig. 5 Dependences of value of shape memory effect ϵ^{SM} and the recovery coefficient K (a) and strain observed on the first ϵ_{rev}^1 and tenth ϵ_{rev}^{10} thermal cycles (b) on residual strain ϵ_{res} of bimetal composite.

strain ϵ_{rev} observed during the first and other thermal cycles has to rise. This statement is proven by the results presented in Figure 5b. It is seen that the value of ϵ_{rev} observed during the first cycle increases with the rise in residual strain. It is important to note that the strain variation does not occur in the bimetal composite where the residual strain is less than 2%. Obviously in this case the value of stress stored in the sample is not enough for the initialization of the transformation plasticity and shape memory effect on thermal cycling. This is verified by a high value of the recovery coefficient because a low stress accumulated in the sample on heating results in a high ability of the composite for strain recovery. Meanwhile repeated thermal cycles influence the recoverable strain in a different way. If the value of residual strain is less than 7% then thermal cycling results in a rise in the recoverable strain, which is known as the training effect. At the same time if the value of residual strain is higher than 7% then a decrease in the recoverable strain is observed on cycling. This is because after a preliminary deformation up to a high strain, huge stresses appear in the sample on heating, and thus subsequent thermal cycling is realized under a high stress that results in degradation of the shape memory effects.

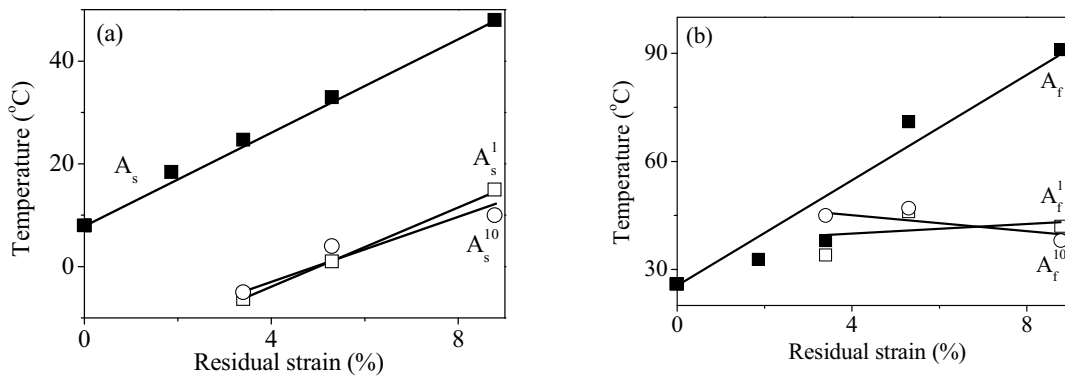


Fig. 6 Dependences of the start (a) and finish (b) temperatures of strain variation measured on heating after deformation (A_s , A_r) and during the first (A_s^1 , A_r^1) and the tenth (A_s^{10} , A_r^{10}) thermal cycles on the residual strain.

Besides the value for recoverable strain, the temperatures of strain recovery are also very important for bimetal composite applications. Figure 6 shows the influences of residual strain on the start and finish temperatures of strain recovery measured on heating after deformation (A_s , A_r) and during the first (A_s^1 , A_r^1) and the tenth (A_s^{10} , A_r^{10})

thermal cycles. It is found that a preliminary deformation increases the start temperatures (A_s , A_s^1 , A_s^{10}) and finish temperature A_f , and slightly changes the finish temperatures measured in the first (A_f^1) and the tenth (A_f^{10}) cycles. The increase in temperature A_s on preliminary deformation is due to the effect of martensite stabilization. According to Liu et al. [5], a preliminary deformation shifts the temperatures of the shape memory effect up to higher temperatures; however this is observed only on heating just after deformation and does not occur on subsequent thermal cycles. Figure 6 a shows that the value of temperature A_s is higher than the values of temperatures A_s^1 and A_s^{10} measured in the first and the tenth cycles. According to Liu et al., [5] a preliminary deformation shifts both temperatures A_s and A_f in the same manner; however in Figure 5b it can be seen that the A_f vs ϵ_{res} curve is non-linear and that the increase in temperature A_f is higher than that of temperature A_s (Figure 6a). So the maximum shift of temperature A_s is 40 °C whereas the shift in temperature A_f is 65 °C. The stronger dependence of temperature A_f on the residual strain is caused by two factors: a shift in temperature due to stabilization of martensite and a shift in temperature due to stress, stored in the sample during strain recovery, according to the Clausius–Clapeyron relation.

Thus, it is found the preliminary deformation influences the functional properties of the bimetal composite that allow us to manage the values of the shape memory effect and recoverable strain observed on cycling and the temperatures and temperature intervals of strain variations.

4. Conclusions

The results of the study show that the bimetal composite “TiNi–stainless steel” produced by explosion welding demonstrates a shape memory effect and recoverable strain variation on repeated thermal cycling. It is found that the recoverable strain in the bimetal composite exceeds the value for the two-way shape memory effect in TiNi alloy. This is due to the action of the elastic steel layer. The value for recoverable strain is controlled by the ratio of the TiNi layer thickness to the total thickness of the sample and by the value of the preliminary strain of the bimetal composite. The value of the recoverable strain may be changed by repeating thermal cycling in the bimetal samples with optimal geometrical sizes. It is concluded that the bimetal composite produced by explosion welding may be used as an element of an actuator of repeating action.

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