

## APPLICATION OF SHAPE MEMORY ALLOYS IN PIPELINE COUPLINGS FOR SHIPBUILDING

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### ABSTRACT

*The aim of the study is to analyse shape memory alloy (SMA) pipeline joints in limited space applications for all kinds of ships. Generally, the space available in various areas on ships is strictly limited and service works usually meet many obstacles. If we consider a pipeline, the flange joints always require a larger free space around the pipe than the pipe alone. A simultaneous problem can occur with the propeller shaft line coupling between bearings. SMA couplings require less space around the pipe and service should be easier, e.g., insulation fixing, painting and so on. SMA couplings last for a lifetime and there is no need for periodical seal replacement. Herein, some proposals among other unpublished data are discussed. There is a significant technological interest in the use of SMAs for applications not widely used yet. A wide variety of alloys present the shape memory effect and many generate an expressive restitution force considerable for commercial interests.*

**Keywords:** pipelines, couplings, shape memory alloys, shipbuilding, coupling durability

### INTRODUCTION

Shape memory alloys (SMA) constitute a group of metallic materials with the ability to recover a previously defined length or shape when subjected to an appropriate thermomechanical load. SMAs exhibit vastly different stress-strain behaviour in comparison to ordinary metals, as shown in Fig. 1.

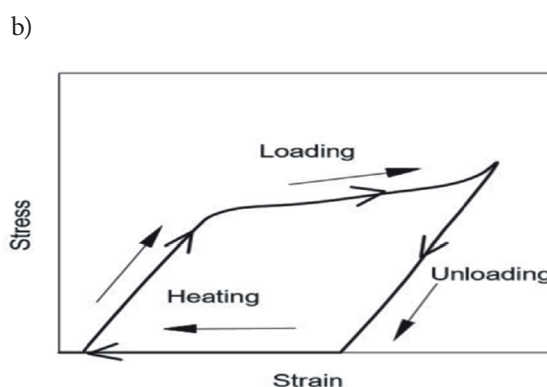
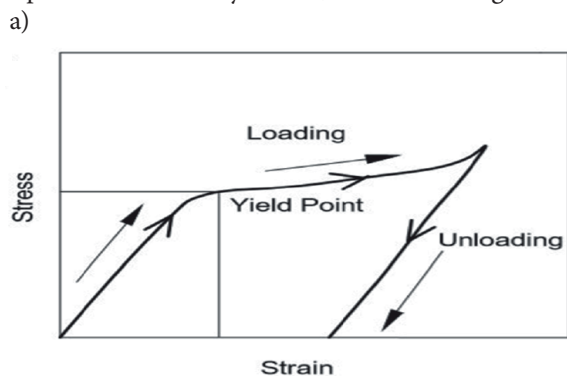


Fig. 1. Comparison of stress-strain behaviour of an ordinary metal (a) with permanent plastic deformation remaining after unloading and of a shaped memory alloy (b) with its original shape recoverable on heating [1]

When there is a limitation of shape recovery, these alloys promote high restitution forces. Because of these properties, there is significant technological interest in the use of SMAs for different applications. Although a relatively wide variety

of alloys present the shape memory effect, only those that can recover from a large amount of strain or generate an expressive restitution force are of commercial interest. In particular, alloys based on Ni-Ti and Cu, such as Cu-Zn-Al and Cu-Al-Ni, are especially important. SMAs based on Ni-Ti are most frequently used in commercial applications because they combine good mechanical properties with shape memory [1–5].

SMAs have found many technical applications, including in fluid sealing technology. They are ideally suited for stationary sealing conditions, for instance in static flange pipe joints, high-pressure hydraulic fittings, pipe and tube coupling systems, fasteners, connectors and clamps in a variety of applications. These materials are also utilised in dynamic sealing conditions, such as in lip radial oil seals, mechanical face seals, soft gland packing and magnetic fluid seals [5].

This article presents some constructional solutions of pipe couplings that make use of SMAs. These couplings are used, in addition, in hydraulic systems in aviation and shipbuilding, as well in oil and gas transportation pipelines. Applying metal alloys with the shape memory effect for sealing pipe couplings provides an opportunity for the significant simplification of their structure and ensures extremely durable and leak proof coupling.

## MECHANISM OF SHAPE MEMORY EFFECT IN SMAs

SMAs can return to a predetermined shape when heated. The shape memory effect is caused by the temperature dependent crystal structure. SMAs can exist in two different crystal structures (phases) known as martensite and austenite. Martensite has a monoclinic structure and is a relatively soft and easily deformed phase that exists at lower temperatures. Austenite has a high-temperature cubic structure and is the stronger phase of a SMA. When martensite is heated, it begins to change into austenite. The temperature at which this phenomenon starts is known as the austenite start temperature  $A_s$ . The temperature at which this phenomenon is completed is the austenite finish temperature  $A_f$ . When austenite is cooled, it begins to change into martensite. The temperature at which this phenomenon starts is the martensite start temperature  $M_s$ . The temperature at which martensite is again completely reverted is known as the martensite finish temperature  $M_f$ . When the SMA is below its phase transformation temperature, the material can be deformed into another shape with relatively little force. The new shape is retained provided that the material is kept

below its transformation temperature. When heated above this temperature, the material reverts to its parent structure, causing it to return to its original shape (Fig. 2). The shape memory effect is repeatable and can typically result in up to

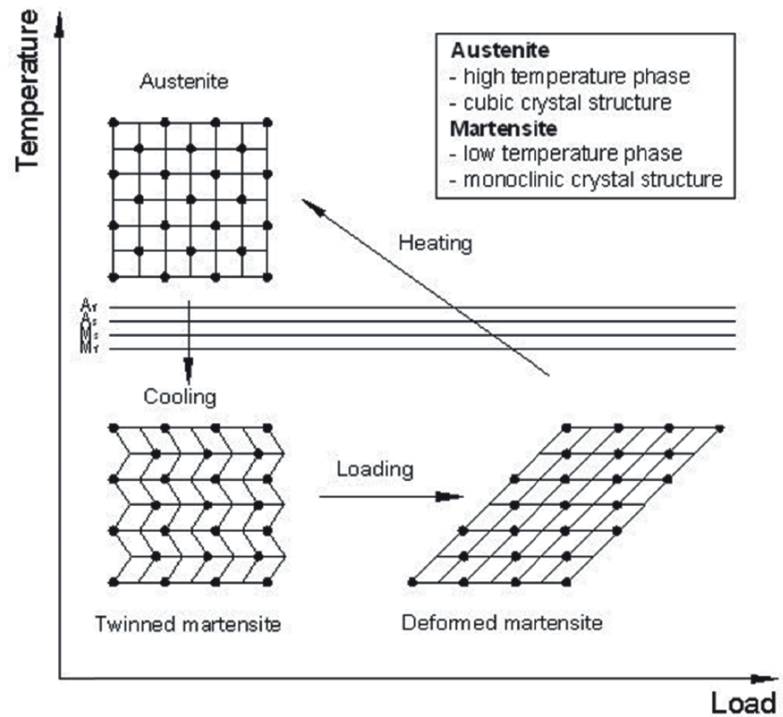


Fig. 2. Transformation from the austenite to martensite phase and shape memory effect [1]:  $A_f$  – austenite finish temperature;  $A_s$  – austenite start temperature;  $M_s$  – martensite start temperature;  $M_f$  – martensite finish temperature

8% strain recovery [1, 2].

The transformation temperature is a function of the alloy type and composition, as well as the thermomechanical treatments applied. The transformation from austenite to martensite (cooling) and the reverse cycle from martensite to austenite (heating) do not occur at the same temperature, due to a thermal hysteresis curve for every alloy that defines the complete transformation cycle (Fig. 3). The magnitude of the thermal hysteresis varies with the alloy type and is typically in the range of 10–50 °C.

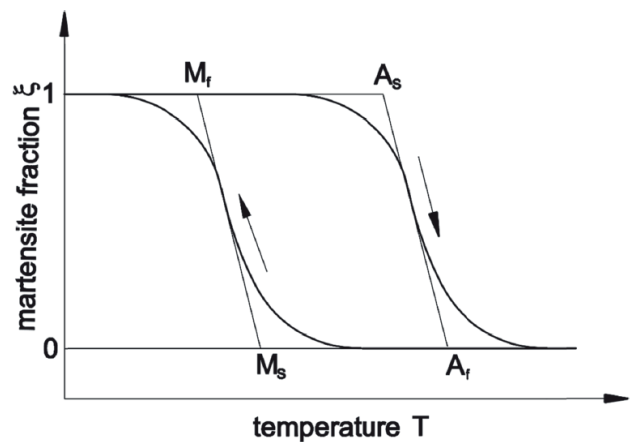


Fig. 3. Hysteresis curve for a thermoelastic martensitic transformation of a SMA, where  $\xi$  denotes the fraction of martensite in the material [1]

Despite a growing list of alloys with the shape memory effect, only two alloy systems have achieved some level of commercial exploitation. These are Ni-Ti (nitinol) and copper-based alloys (Cu-Zn-Al and Cu-Al-Ni). The properties of both systems are quite different. Ni-Ti alloys have greater shape memory strain (up to 7–8% versus 4–6% for copper-based alloys), tend to be much more thermally stable and have excellent corrosion resistance and much higher ductility. The composition of Ni-Ti alloys, which can change from 48% to 52% Ni, has a significant impact on the temperature of the high-temperature phase transformation into martensite (this temperature can vary from –40 to 100 °C). Ni-Ti alloys are frequently doped with other chemical elements to decrease or increase their transformation temperature. The main three-component alloys are Ni-Ti-Cu and Ni-Ti-Nb. Copper-based alloys are much lower in cost and exhibit higher actuation temperatures (approximately from –200 to 200 °C) than Ni-Ti alloys, and are sometimes the only choice for high-temperature applications above 100 °C. Unfortunately, these copper-based alloys tend to suffer from low mechanical strength and poor corrosion resistance.

## PIPE COUPLING DESIGNS BASED ON SMAs

Skilled pipe welders and brazers are in short supply. Expensive training efforts have failed to supply an adequate number of qualified personnel for shipbuilding programs. Field welded and/or brazed piping and tubing pose numerous installation problems. The recent introduction of heat recoverable pipe couplings into shipyard production methods provides a means to help alleviate some of these problems. Nitinol, a SMA, is usually selected for evaluation of its applicability to shipboard piping systems. Nitinol couplings are cryogenically cooled, expanded, installed on a pipe joint and allowed to warm, where they contract over the pipe to form a high-pressure sealed joint. The evaluation indicated potential labour savings warranting incorporation in ongoing contracts [6].

Figure 4 shows successive phases of making of a SMA-based high-pressure hydraulic tube coupling [7]. The coupling is machined at normal temperature to have an inner diameter

smaller by 4% than the outer diameter of the tubes to be joined (Fig. 4a). After cooling the coupling (in liquid nitrogen) at  $M_p$ , its inner diameter is expanded to become slightly greater than the outer tube diameter (Fig. 4b). Then, when the coupling is warmed to the austenite phase, it shrinks in diameter and strongly holds the tube ends together (Fig. 4c). The tubes prevent the coupling to recover its original shape. This generates stresses strong enough to create a more powerful joint than a weld.

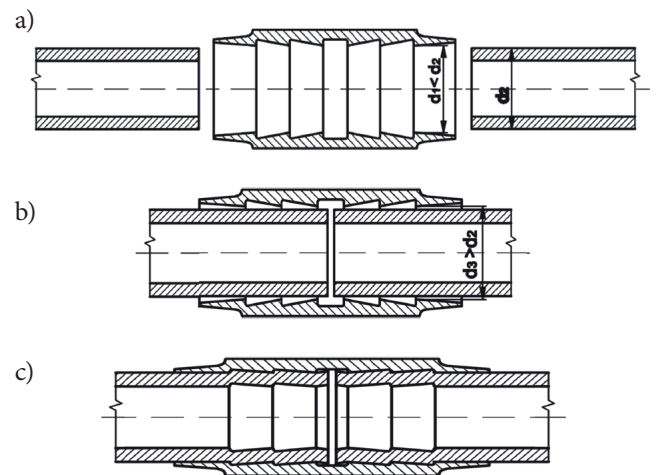


Fig. 4. Phases of joining for hydraulic SMA tube coupling: a) coupling is machined with an inside diameter slightly smaller than the tube outside diameter; b) expanded coupling have an inside diameter slightly larger than the tube outside diameter; c) tube is swaged by the warming coupling, but prevents complete recovery of the coupling

Figure 5 shows a high-pressure pipe coupling device comprising heat shrinkable sleeve 3 made from a memory shape metal and metallic insert 4 with a configuration that facilitates the formation of a secure coupling [8]. In the design shown in Fig. 5a, insert 4 is equipped with several rectangular teeth 4a placed on its interior surface, while in Fig. 5b, the rectangular teeth 4a are placed on the exterior surface of insert 4. Upon heat recovery of compression sleeve 3, insert 4 is compressed about the ends of pipes 1 and 2, as shown in Figs. 5a' and 5b', thus providing a tight pipe connection.

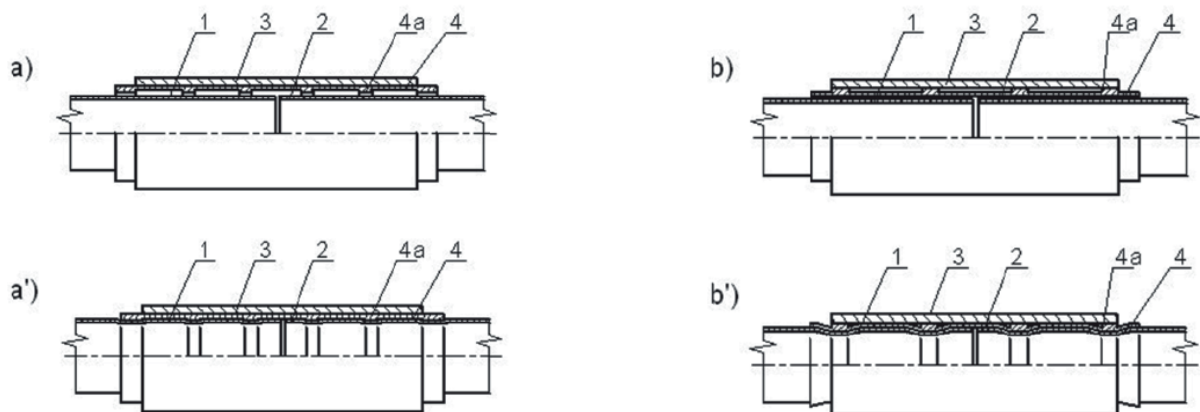


Fig. 5. High-pressure pipe coupling device: a), b) coupling before sleeve deformation; a'), b') coupling after sleeve deformation. 1 and 2 – ends of the pipes, 3 – heat recoverable sleeve made of SMA, 4 – metallic insert and 4a – circumferential tooth

Figure 6 shows a pipe coupling device with a flexible steel insert and clamping rings [9]. In this case, flexible insert 3 is mounted on the ends of pipes 1 and 2, and then the clamping rings 4, made from the SMA, are fixed around the insert. The inner cylindrical surface of insert 3 has projections 3a, with a triangular cross section, and longitudinal cuts 3b at both ends of the insert to facilitate its deformation.

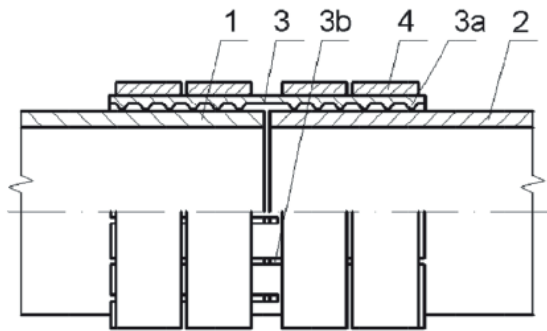


Fig. 6. Pipe coupling device with flexible steel insert and clamping rings made of SMA. 1 and 2 - ends of pipes, 3 - flexible steel insert, 3a - projection, 3b - longitudinal cut and 4 - clamping ring made of SMA

Figure 7 shows a tubular joint sealing system for use in high-temperature conditions, e.g., in equipment applied in the oil and gas industries [10]. The coupled connection consists of upper tubular member 1, lower tubular member 2, cylindrical sleeve 3, back-up ring 4 made from the SMA (e.g. nitinol) and elastomeric O-ring seals 5. Tubular members 1 and 2 are retained within sleeve 3 by threads formed on both the sleeve and tubular members. O-ring seals 5 are located in grooves formed at both end faces of the back-up ring 4 (Fig. 7a). After the connection has been mechanically completed, back-up ring 4 is heated, which makes it expand to its original axial dimensions (Fig. 7b) and fill the previously unoccupied spacing gaps between two tubular members 1 and 2. The back-up ring 5 prevents the compliant sealing rings 5 from extruding out of the grooves when subjected to high-temperature and pressure conditions.

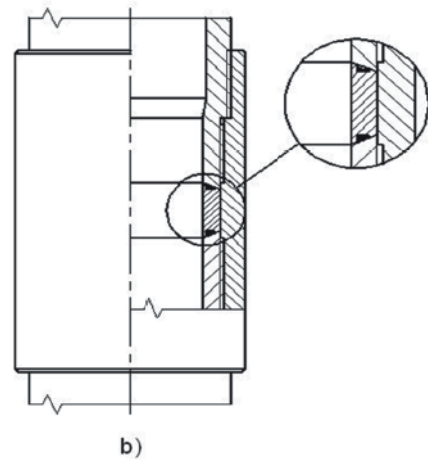
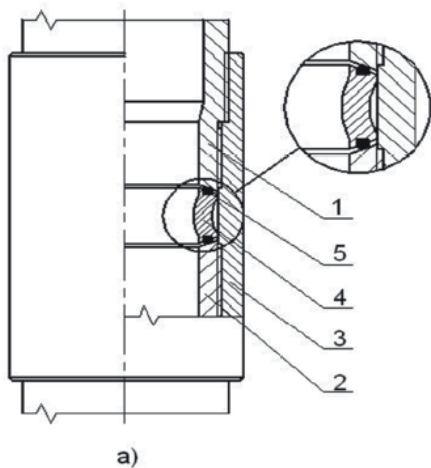


Fig. 7. Tubular joint sealing system with use of an element with shape memory effect: a) joint seal after assembly; b) joint seal in operating conditions after thermal deformation of SMA back up ring. 1 and 2 - tubular members to be joined, 3 - cylindrical sleeve, 4 - back up ring made from SMA and 5 - elastomeric O-ring seal

Figure 8 shows the sealing of a flange pipe joint by means of a SMA ring [5]. The SMA sealing ring 5 is fitted into grooves 4 of pipe flanges 1 and 2, and then fastening bolts 3 are preliminarily tightened to such an extent to bring flanges 1 and 2 into close contact with each other under no load. When the assembly is heated to or above the atmospheric temperature, sealing ring 5 resumes the originally memorised shape, and simultaneously, a reverse transformational stress works so that the faces of ring 5 are pressed, respectively, against face surfaces 4a and 4b of groove 4 in the flanges 1 and 2 to constitute sealing surfaces. Accordingly, it is unnecessary to provide any high fastening force by bolts 3, and it is sufficient to only preliminarily bring flanges 1 and 2 into contact with each other by bolts 3 under no load. In addition, the distribution of stresses in the circumferential direction is made to be relatively uniform. In the case shown in Fig. 8c, sealing ring 5 is made of a SMA and has a large diameter section of a cylindrical annular body, the diametral outer portion of which is opened. Sealing ring 6, also made of SMA and with a small diameter section of a similar cylindrical annular body, with the diametral inner portion opened, is fitted in the inner peripheral face of sealing ring 5. The sealing performance that is set can be achieved without causing abnormal deformation [11].



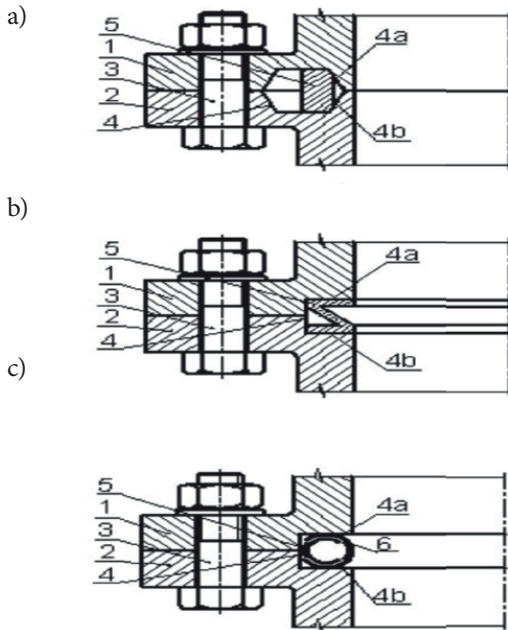


Fig. 8. Sealing of flange pipe joint by means of SMA rings with a-c) variants of design. 1 and 2 – flanges, 3 – bolt, 4 – groove, 4a and 4b – contact surfaces and 5 and 6 – sealing rings made of SMA

Figure 9 shows a method to seal a threaded pipe coupling with sealing rings made of the SMA [12]. These sealing rings are arranged between the butts of the interconnected tubing pipes. Earlier, the sealing rings are pre-cooled in a cryostat to low temperature, e.g., that of liquid nitrogen, to be stained therein, changing in shape and height. Thereafter, they are quickly fitted in place inside the coupling between the pipe butts. When the coupling is heated to or above the atmospheric temperature, the sealing rings resume the originally memorised shape, causing elastic and elasto-plastic deformation of the thread joint elements and thus providing a tight pipe connection.

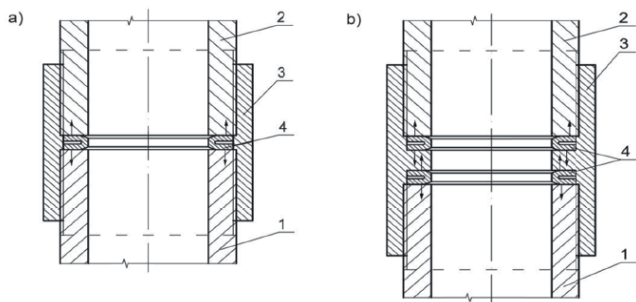


Fig. 9. Threaded pipe coupling with sealing rings made of SMA: a) coupling with one sealing ring; b) coupling with two sealing rings. 1 and 2 – ends of pipes, 3 – threaded coupler and 4 – sealing ring made of SMA

Figure 10 presents a device for detachably joining pipes [13]. The connection comprises sleeve 4 and split ring 3, which has a small axially extending gap formed on its interior surface with a shallow channel between two radially-inwardly extending

edge flanges 3a. The channel receives and locates two flanges 1a and 2a formed on pipes 1 and 2, respectively. Sleeve 4, positioned outwards of split ring 3, is made from the SMA, which can be used to compress the compressible split ring by closing the gap; hence, connecting pipes 1 and 2.

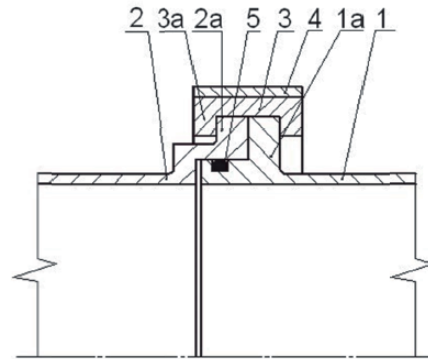


Fig. 10. Connecting device for detachable joining of pipes. 1 and 2 – ends of pipes, 1a and 2a – flanges of pipes, 3 – split ring, 3a – edge flange, 4 – sleeve made of SMA and 5 – elastomeric O-ring seal

Figure 11 shows a diameter-reducing member joint made of a heat-shrinkable type of the SMA [14]. The large diameter connection portion of diameter-reducing pipe joint 3 and large-diameter pipe end 1 are tightened to each other by the shape recovery force when heat-shrinkable sleeve 6 is thermally shrunk and the small-diameter connection portion at the other end of diameter-reducing pipe joint 3 is connected to the small-diameter pipe end 2 in a similar manner, thus providing simple and reliable pipe connection.

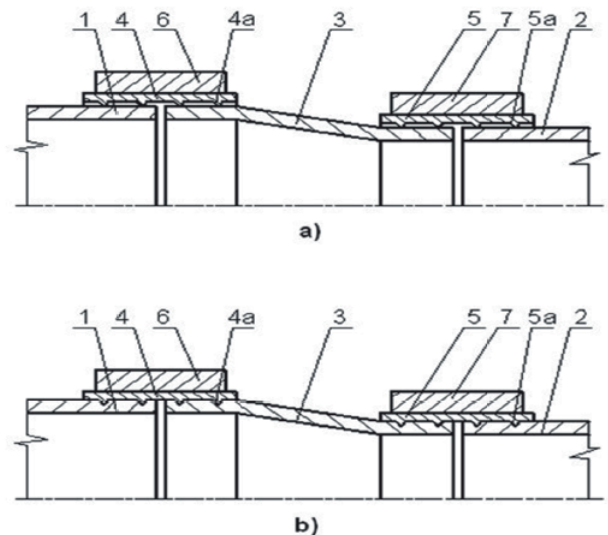


Fig. 11. Diameter-reducing member joint using heat-shrinkable sleeves made of the SMA: a) pipe joint before thermal deformation; b) pipe joint after thermal deformation. 1 and 2 – ends of pipes, 3 – diameter-reducing pipe joint, 4 – large-diameter liner, 5 – small-diameter liner, 4a and 5a – projections and 6 and 7 – heat-shrinkable sleeves made of SMA heating element

Figure 12 shows an SMA pipe coupling for underwater pipes [15]. The pipe coupling comprises tube 3 made of the



SMA and a cover, made of stainless steel 4 having high corrosion resistance, by which high-temperature water can be prevented from making the SMA brittle and from its corroding and damaging, particularly through galvanic corrosion, even in the case where such water exists inside or outside of the pipes.

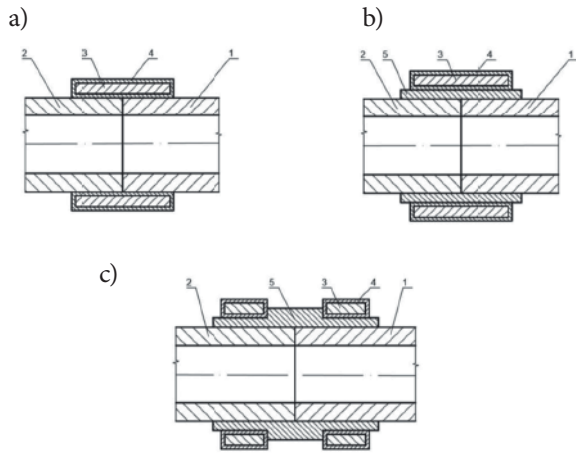


Fig. 12. SMA pipe coupling used for underwater pipe with a-c) variants of design. 1 and 2 - ends of pipes, 3 - tube of SMA, 4 - coating made of stainless steel and 5 - supporting tube

Figure 13 shows a high-pressure pipe coupling device, which is mainly applied in large-diameter undersea oil and gas transportation pipelines [16] or shafts [17]. In the design shown in Fig. 13a, the ends of coupled pipes 1 and 2 are placed inside a composite connector consisting of corrosion resistant liner 4, a number of clamping rings 5 made of SMA, two tensile rings 6, also made of SMA, a thin-walled metallic sleeve 3 and two external support rings 7. The liner 4, with projections on its inner cylindrical surface, is pulled over the ends of coupled pipes 1 and 2. Then, clamping rings 5 are mounted around liner 4. The entire assembly of liner 4 with clamping rings 5 and tensile rings 6 is placed inside the thin-walled metallic sleeve 3, closed with external support rings 7 at both ends. In the solution shown in Fig. 13b, a supplementary heating element 8 is arranged between clamping rings 5 and sleeve 3. The heat delivered by this element accelerates the transformation process and causes deformation of clamping rings 5.

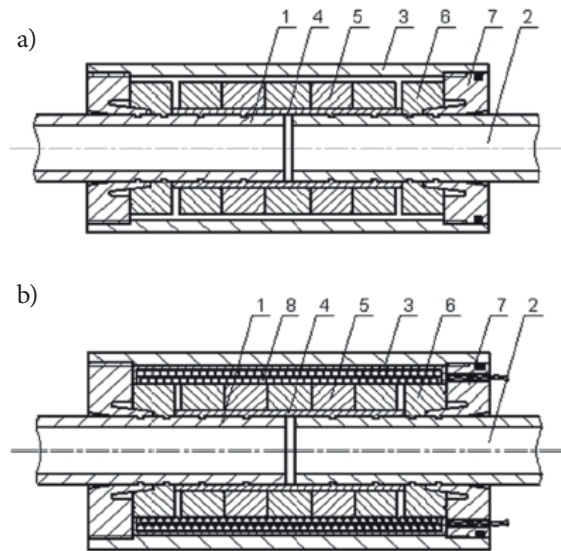


Fig. 13. High-pressure pipe coupling device, especially for large diameter pipe utilised in undersea gas and oil transport: a) design of coupling; b) design of coupling with supplemental heaters. 1 and 2 - ends of pipes, 3 - thin-walled metallic sleeve, 4 - corrosion resistant liner, 5 - clamping ring made of SMA, 6 - tensile ring made of SMA, 7 - external support ring and 8 - electric heating element

## CONCLUDING REMARKS

Metal alloys with shape memory (SMA) belong to a group of intelligent materials that have an ability to memorise the initial shape and, after permanent deformations, resume this shape in certain circumstances. The physical phenomenon which makes shape resuming possible is reversible martensitic transformation, which reveals large deformation and the shape memory effect when heated.

SMA fitting systems are an excellent example of a product that helps significantly reduce process costs in comparison with traditional assembly methods, such as welding, brazing or swaging, and offers as many advantages, such as:

- no expansive tooling;
- leak-proof and permanent connection;
- light-weight design;
- quick and easy installation;
- lower space required around the pipes or shafts.

The presented examples of constructional solutions of SMA-based pipe couplings provide opportunities for significant simplification of their structure, simultaneously ensuring extremely durable and leak proof coupling. They are used in hydraulic systems in aviation and shipbuilding, as well in oil and gas transportation pipelines, among other areas.

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