Study of the effects of cavitation and the development of mounting/dismounting principles for working elements of shut-off valves made of alloys that undergo thermoelastic phase transformations

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A notable issue with current ball valve designs pertains to the configuration of the split point within the body. This prefabricated body design facilitates the installation of operating elements within the body. The article presents a design for a ball valve that utilises a one-piece body, with the internal working parts of the valve being made from an alloy that undergoes thermoelastic martensitic transformations, which exhibits the shape memory effect during phase transition. The installation of the operational components within the ball valve body is enabled by the shape memory effect of the alloy from which they are fabricated. The present study investigates the cavitation resistance of an alloy that undergoes a thermoelastic martensitic transformation, using titanium nickelide (Ni55.9Ti44.1) as a model system. This investigation compares the alloy's behaviour with that of stainless steels of AISI304 and AISI430 grades. The proposed design solution, which involves the fabrication of a one-piece body for the ball valve and the utilisation of alloys with thermoelastic martensitic transformations for the manufacture of the ball valve's operating components, is expected to enhance reliability and performance characteristics, as well as the service life of the product in its entirety.

Key words: nitinol, shape memory effect, thermoelastic martensitic transformation, pseudoelasticity, ball valve, pipeline fittings.

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Introduction

Ball valves are a prevalent type of pipeline control valve in the oil and gas, and also the chemical industry, due to their capability of smooth closure (thus avoiding the occurrence of 'water hammer') and smooth regulation of the cross-sectional area [1]. Ball valve designs are subject to constant evolution in response to escalating performance and service life requirements. This evolution is characterised by an increase in design complexity, which, in turn, results in elevated production costs and more intricate regulatory procedures aimed at ensuring the reliability of the products that are manufactured [2].

The authors propose a series of enhancements to the ball valve design, including the incorporation of alloys exhibiting thermoelastic martensitic transformations (TMT). These alloys are characterised by their shape memory effect, which has the potential to streamline the design process by reducing the number of assembly units [3–5]. The utilisation of these classes of materials allows for a shift in the principles of assembly, thereby ensuring the execution of the body in one piece with manufacturing a locking element from an alloy with TMT (ball-shaped plugs), ensuring installation in the seat due to the manifestation of the shape memory effect, which makes it possible to predeform the product in the martensitic state. This makes it possible to easily perform assembly (disassembly) with subsequent restoration of geometric parameters of the product when heated to the temperature of the austenitic state.

Another interesting feature of these materials from an operational point of view is the phenomenon of pseudoelasticity/super-elasticity, which exhibits a strain-stress hysteresis loop when loaded or unloaded. This phenomenon is evident in the complete recovery of geometric characteristics (parameters) exhibited by products composed of alloys with TMT. This recovery is observed not only within the elastic deformation area (a characteristic of all metals and alloys), where Hooke's law and the 'strain-stress' diagram are applicable, but also within the domain specific to plastic deformation. This phenomenon has the capacity to augment the resistance of products to effects that exhibit a time-varying law of change in the applied load. This is a characteristic of both cavitation and abrasive (hydroabrasive) wear, as well as fatigue and contact loading, and in cases of sharp overload of shock dynamic load (hydro shock). The utilisation of these materials in the fabrication of functional components of shut-off and control valves, particularly ball valves employed in the oil, gas and chemical sectors, is a matter of significance.

Table 1
Chemical composition of $Ni_{55.9}Ti_{44.1}$ titanium nickelide alloy

Ti	Ni	Co	Cu	Cr	Fe	Nb	C	H	O	N
Rest	55.9	0.005	0.005	0.005	0.009	0.005	0.028	0.001	0.038	0.001

It is acknowledged that this class of materials exhibits corrosion resistance, a property that is characteristic of intermetallic compounds.

Materials and equipment

As demonstrated in **Table 1**, the titanium nickelide alloy ($Ni_{55.9}Ti_{44.1}$) is in the austenitic phase under standard conditions. The end of the austenitic phase transition (i.e. the reverse martensitic transition) is at A_f – 10 °C (i.e. the beginning of the martensitic transformation M_s – 37 °C). This alloy was used as a material for ball manufacturing.

Fig. 1 shows the diffractogram of the *X*-ray phase analysis obtained on an *X*-ray diffractometer instrument ‘Shimadzu XRD-7000 (Japan). The operational parameters of the instrument included Cu Kα –0.154 nm, 40 kV, 30 mA, an angle range of 20–90°, and an imaging speed of 1 deg/min. Reflexes have been observed in the region of angles 42.48° and 77.73°, with indices [110] and [211], respectively. These observations are indicative of the volume-centred cubic lattice, which corresponds to the B2-phase of titanium nickelide.

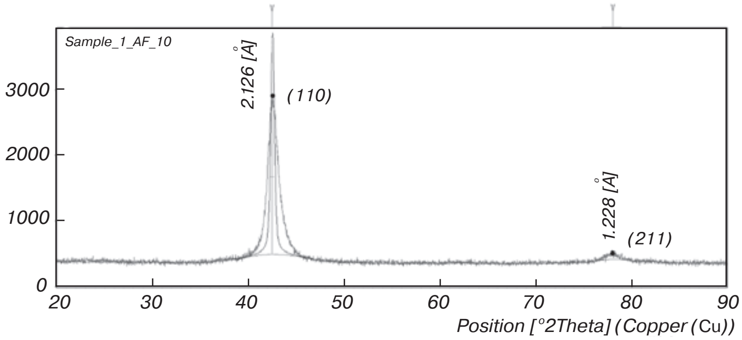


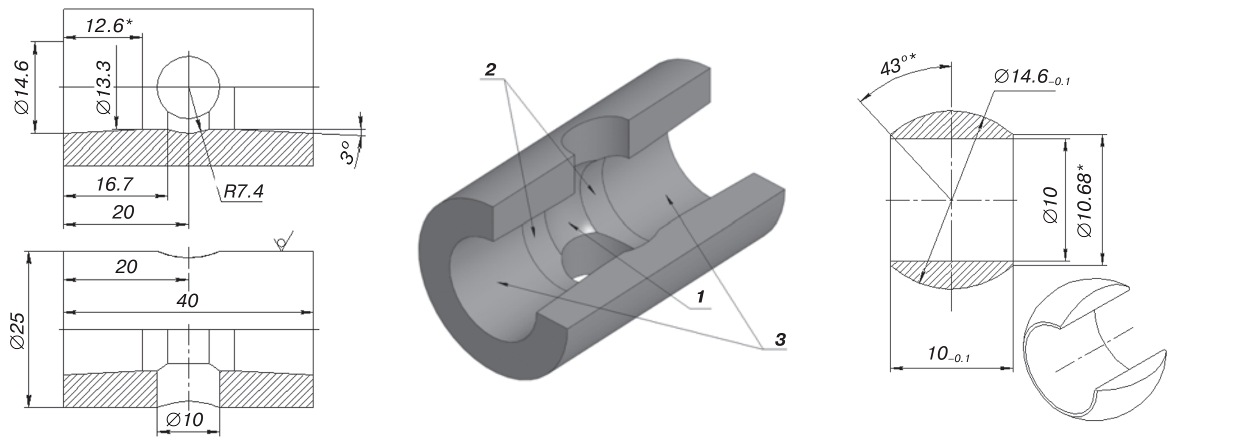
Fig. 1. Diffractogram of NiTi metal plate sample (cub.)

The selection of this material is predicated on its optimal demonstration of the installation process, aligning with the operational parameters of the ball valve at ambient temperatures of the transporting medium that exceed 10 °C. In the context of the prevailing operating conditions, this material is found to be in the austenitic phase. This phase is characterised by the material’s high physical and mechanical properties, in addition to the manifestation of pseudoelasticity and superelasticity.

In order to evaluate the technology and principles of installation, a demonstrative sample was fabricated. This sample comprised a model of the ball valve body, which was manufactured from 40X steel [6]. An exemplar possessing a specific spherical groove, which functions as the seating surface for the ball-shaped plug, and a plug fabricated from the above-mentioned $Ni_{55.9}Ti_{44.1}$ alloy (see **Fig. 2**) underwent a heat-treatment process known as quench hardening.

In order to deform the spherical plug by the outer diameter, a special tool was made, shown in **Fig. 3**, consisting of a sleeve with an inner conical hole and a stepped rod for drawing a ball through the inner conical hole of the sleeve.

The material selected for the tooling was steel grade 40X, which was subjected to a heat treatment process that involved a hardening process. The dimensions were manufactured to a tolerance of 7, with a roughness Ra1.25.



a *b* *c*

Fig. 2. Demonstration sample:
a – The body fragment of the drawing, executed with a tolerance of 10, with a roughness value of Ra2.0; *b* – 3D-model of the body, *1* – seating spherical groove with diameter ∅14.8 mm; *2* – cylindrical part with diameter ∅13.3 mm, *3* – conical entry part with conicity angle 6°; *c* – ball-shaped plug with a roughness value of Ra1.25

The extruding of the ball-shaped plug from the tooling was executed on a hand press NORDBERG. Subsequent to its installation in the demonstration case, the heating to the temperature of the end of the reverse phase transition (martensite – austenite) was conducted utilising a heat gun GHG 23-66 BOSCH with temperature control. The process of monitoring the heating temperature across the entire surface to the set temperature was conducted by means of a Guide T120 thermal imager.

An investigation was conducted into the primary cause of failure of the locking element of the ball valve (i.e. the ball plug) during operation. This investigation was carried out in accordance with the ASTM G32-16 (2021) e1 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus (see **Fig. 4**) [7]. The mechanical vibration was measured at a frequency of 20 ± 0.5 kHz. The power was set to 100%, the ambient temperature was recorded as 20 ±5 °C, and the medium was distilled water, which is in accordance with the aforementioned standard. Cavitation erosion marks are the result of a process of deterioration, caused by the action of cavitation [8–10]. It is well known that TMT alloys have the ability to enhance the cavitation resistance of products due to pseudoelasticity/superelasticity. As illustrated in Figure 4 below, the test's configuration and setup are designed to assess the cavitation effects of materials through the utilisation of ultrasonic vibrations.

Development of assembly and disassembly principles

There are two primary methods of mounting and dismounting in the body of the ball valve with a special spherical groove, which functions as a seating surface and provides fixation of the ball plug from movement in the direction along the axes *X*, *Y*, *Z* with the possibility of rotational movement around these axes. The ***first method*** involves the direct pressing of a ball-shaped plug in the martensitic state (having previously been cooled to the temperature of the end of the martensitic transformation, Mf) into the tube up to the seating place. Subsequently, the product is heated to the temperature of the end of the austenitic transformation, Af. At this temperature, the restoration of the shape corresponding to the austenitic phase (operational geometry) will occur. In the process of restoring the shape

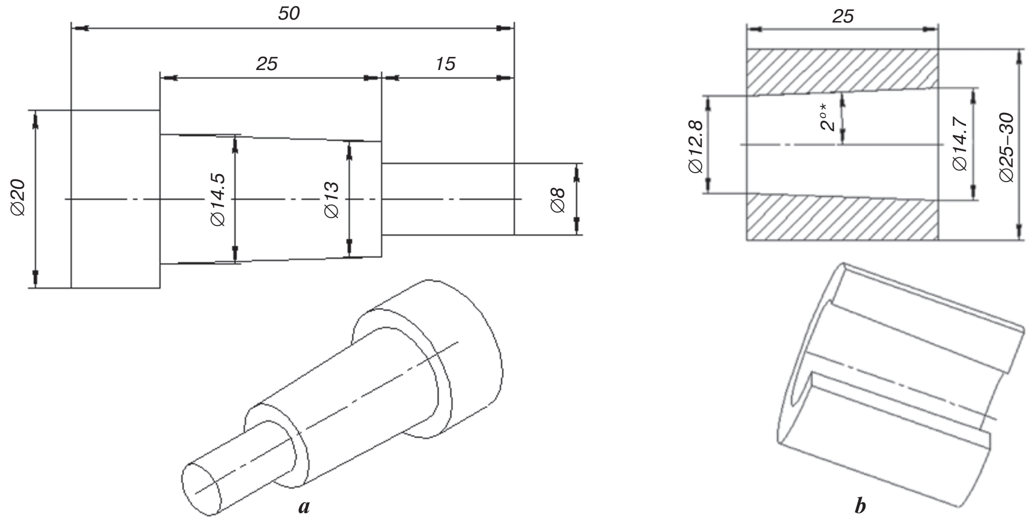


Fig. 3. Special tooling for adjusting the deformation of a spherical plug: *a* – stepped rod; *b* – sleeve with an inner conical hole

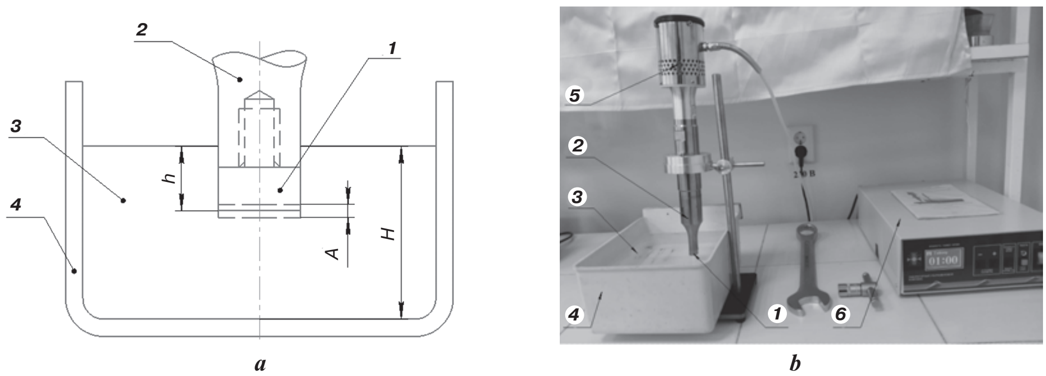


Fig. 4. *a* – schematic diagram of ASTM G32-10 'Standard Test Method for Cavitation Erosion' test procedure; *b* – installation for the study of cavitation resistance of materials (*1* – tip; *2* – waveguide; *3* – liquid; *4* – container; *5* – cooling system; *6* – control unit; *A* – amplitude 50 μm ±5%; *H* – height of liquid column in the container 100 ± 10 mm; *h* – tip immersion height in liquid 12 ± 4 mm) (*photo by authors*)

of the plug, it is possible to observe the phenomenon of self-positioning and self-fixation in the seating place. This is due to the arising forces from return stresses, which are sufficient for displacement and reorientation of the plug. The subsequent occupation of the required position relative to the body is then facilitated by these forces, as is the plug's fixation due to the features of its shape, the dimensions of the seating surface of the spherical groove in the body bore, and the spherical shape of the plug itself.

It is important to acknowledge that this method is more appropriate in cases where the material used to manufacture the body possesses a significantly higher degree of hardness compared to the material exhibiting shape memory effect in the martensitic state. This is attributable to the fact that during the process of pressing

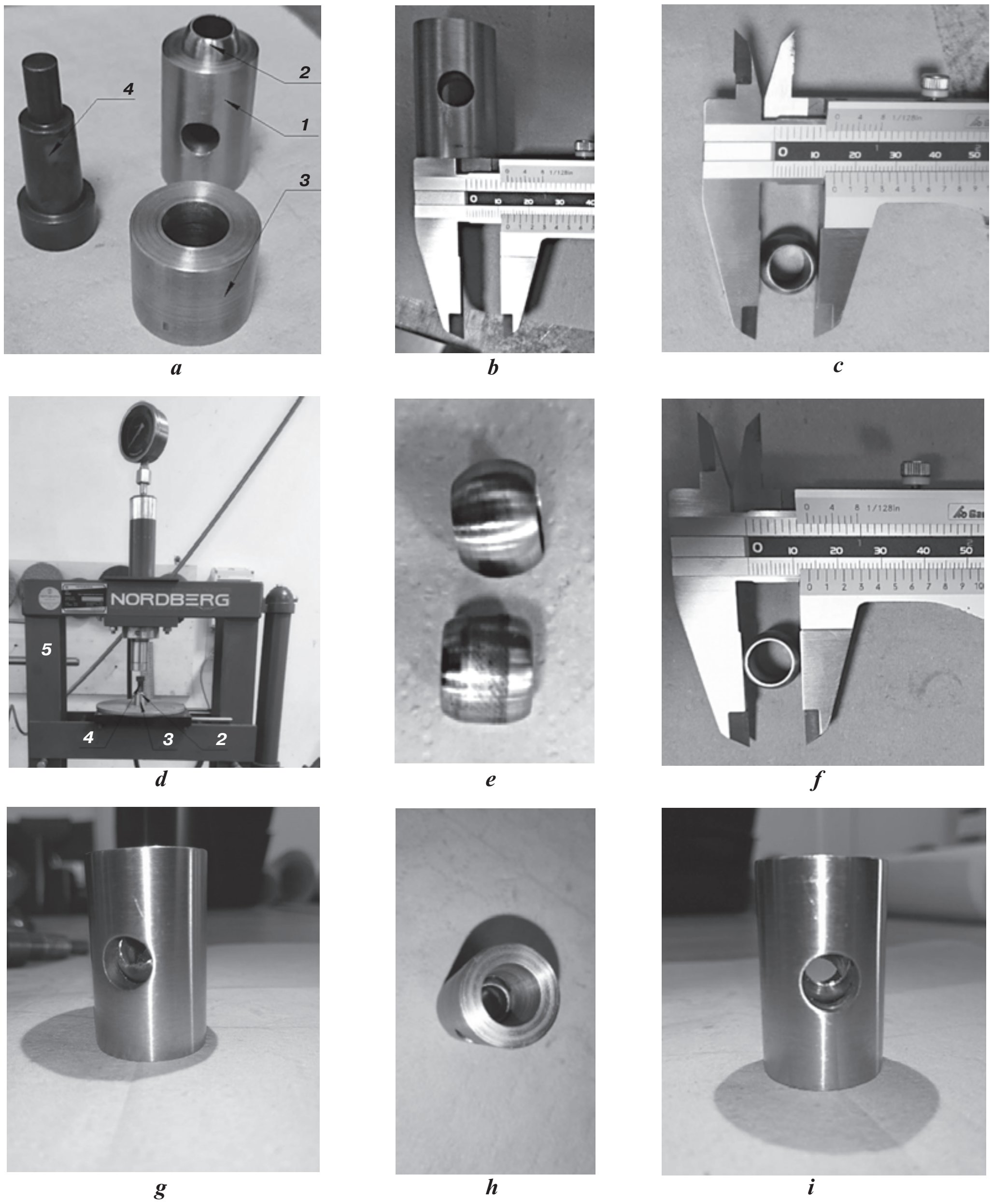


Fig. 5. Installation of a spherical-shaped plug in a body, with the preliminary setting of the ball shape by special tooling:
1 – body; *2* – ball; *3* – bushing with a conical hole; *4* – rod; *5* – press; *a* – ratio of the ball to the body hole and special tooling bushing-rod; *b* – smaller diameter of the spherical groove ∅13,3 mm; *c* – ball-shaped plug before deformation in austenitic phase state of $Ni_{55,9}Ti_{44,1}$ alloy with shape memory effect with diameter ∅14.7 mm; *d* – the process of pulling a ball-shaped plug after cooling in liquid nitrogen to the temperature corresponding to the martensitic phase state of $Ni_{55.9}Ti_{44.1}$ alloy with thermoelastic phase transformations through the conical bore of the bushing on a hand press; *e* – comparison of shape features of a ball-shaped plug before and after broaching; *f* – ball-shaped plug that has been deformed in the martensitic phase of the $Ni_{55.9}Ti_{44.1}$ alloy, which exhibits shape memory effect with diameter ∅13.35 mm; *g*, *h*, *i* – the ball-shaped plug is installed in the designated seating area of the body, followed by heating to the temperature at which the $Ni_{55.9}Ti_{44.1}$ alloy undergoes an austenitic phase transformation. This process incorporates shape memory effects, resulting in the restoration of the original shape and dimensions, corresponding to the austenitic phase state (operational characteristics) prior to deformation (*photo by authors*)

the ball-shaped plug into the housing until it reaches the seating place, deformation of the internal surfaces of the housing becomes possible.

In the course of composing the article and conducting a search for technological features of installation, the second method of installation was proposed and considered. **Fig. 5** below illustrates the process of installing the ball-shaped plug into the seating place (groove of spherical shape) of the housing.

The ***second method*** of mounting involves preliminary deformation of a ball-shaped plug made of an alloy with shape memory effect in the martensitic state (pre-cooled to the temperature of the end of martensitic transformation, Mf). The plug is pulled through a conical sleeve with the help of special tooling, which facilitates the setting of the mounting shape of the ball and its straightforward installation in the seating place of the body. This is followed by heating to the temperature of the end of austenitic transformation Af, at which point the shape corresponding to the austenitic transformation is restored. In this process, it is possible to observe the self-positioning and self-fixing mechanisms as the shape of the ball plug is restored. This method is suitable for any combination of body material, hardness and shape memory alloy in the martensitic state.

Investigations of cavitation resistance of the alloy with TMT

The operating conditions of ball valves in the oil and gas industry demonstrate that the working elements are vulnerable to the destructive effects of cavitation. This complex phenomenon involves a simultaneous mechanical, thermal and corrosive effect on the working elements of shut-off and control valves. Furthermore, ball valve components are also subjected to water hammer when the flow is abruptly shut off.

The resistance of shape memory alloys to corrosive effects is well known, as is their resistance to various kinds of shock and alternating loads. There are numerous publications that address the resistance of such alloys to the cavitation effect, as well as comparisons with materials used for the manufacture of pipeline valves that operate in aggressive environments. The enhanced resistance of alloys with TMT to cavitation-type fracture is attributable to the pseudoelasticity/superelasticity effect exhibited by the alloys. This phenomenon can be attributed to the deceleration of the accumulation of residual deformation and stresses following the impact at bubble collapse. This is due to the restoration of the original surface shape post-impact, which serves to mitigate the likelihood of contact pitting and the initiation of contact cracks, consequently preventing the subsequent ejection of material particles from the surface of the components (samples).

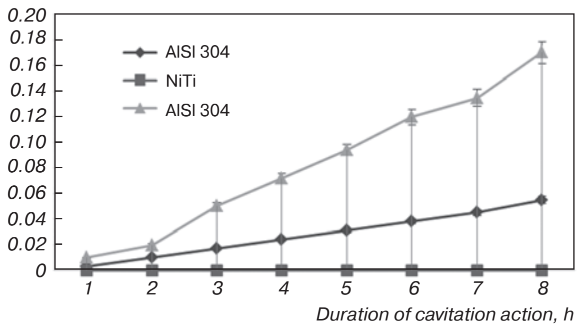


Fig. 6. Diagram of mass wear versus time under cavitation action

It is important to note that the study by Richman, Rao and Hodgson [11] on the behaviour of alloys with TMT, using titanium nickelide as a case study, is the primary source for a comprehensive investigation of the cavitation resistance of alloys with TMTs. Nevertheless, the research was not conducted in accordance with the ASTM Designation: G32-09 and G32-10 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus, and this has resulted in a number of drawbacks. The study was conducted on plates, between which and the tip of the oscillating element with ultrasonic frequency, the conditions for cavitation were created. Concomitantly, this study imposes a mandatory prerequisite: the perpetual observation and preservation of a distance of 0.5 mm between the waveguide ultrasound apparatus's tip and the plate. This prerequisite is rendered unfeasible during operation due to the occurrence of wear, which results in an augmentation of the distance. This, in turn, engenders a modification in the intensity of the impact of cavitation. It is important to note that different materials exhibit varying degrees of wear. As a consequence, the obtained result does not provide a comprehensive and reliable depiction of the correlation between the resistance of materials and their fracture (mass wear) during cavitation. This phenomenon is illustrated in Figure 6 for AISI 304 steel [12], as well as in the works of Brennen [11] and Zhen and Jiesheng [13]. These experiments were conducted in accordance with the ASTM Designation: G32-09 and G32-10 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus, resulting in a smoother wear curve. Concurrently, the work [11] provides a depiction of the cavitation fracture process of alloys with TMT and the nature of resistance associated with pseudoelasticity/superelasticity.

The present study has investigated the resistance of $Ni_{55.9}Ti_{44.1}$ alloy (with Af 10 °C) to cavitation at room temperature when the alloy is in the austenite phase, as well as that of the stainless steels AISI304 and AISI430 grades. **Fig. 6** below shows the diagram of mass wear versus time for cavitation.

As illustrated in the diagram, the $Ni_{55.9}Ti_{44.1}$ alloy sample (with a temperature of Af 10 °C) exhibits a high degree of cavitation resistance while in the austenite phase. This observation is further corroborated by the image of the surface, as depicted in **Fig. 7**, it is evident that the surface cleanliness has undergone a transformation (becoming matt), while the mass remains constant and there is no discernible progression in the change of surface relief. This stands in contrast to the samples fabricated from stainless steel grades AISI304 and AISI430, which exhibit different behaviour.

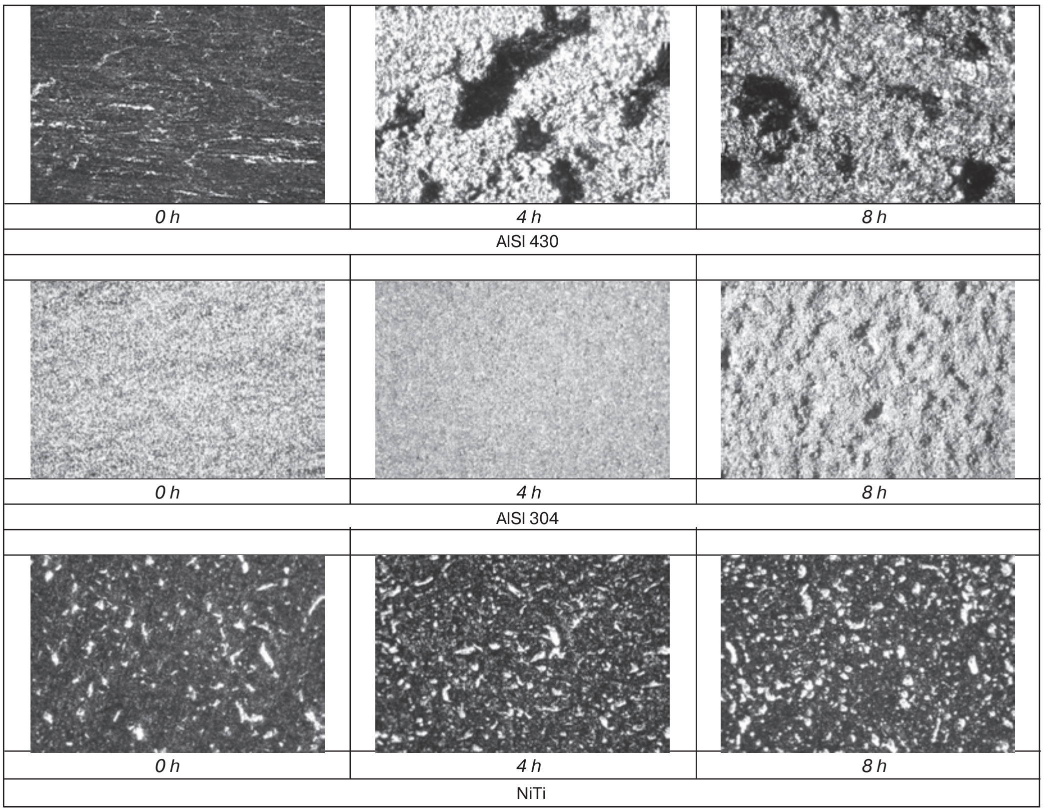


Fig. 7. Cavitation wear (×225 magnification) of the surface of samples made of AISI430, AISI304 and NiTi alloys as a function of cavitation exposure time

Conclusion

In summary, it can be concluded that the proposed design of the ball valve, in which the body is manufactured as a single piece and the ball plug is made of an alloy with shape memory effect, exhibits greater strength than existing analogues. The conducted experiments demonstrated not only the feasibility of the proposed installation method, but also the presence of advantages that enhance the accuracy of installation. In view of the proven resilience of alloys with thermoelastic martensitic transformations to cavitation, owing to the phenomenon of pseudoelasticity, the proposed technical solution holds great promise for implementation in pipeline systems of industries working with aggressive media.

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