Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2022 vol. 24 no. 1 pp. 61–72
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2022-24.1-61-72

NSTU NETI
Obrabotka metallov -
Metal Working and Material Science
Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Comparative study of cavitation erosion resistance of austenitic steels with different levels of metastability

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ARTICLE INFO

Article history:
Received: 17 December 2021
Revised: 17 January 2022
Accepted: 28 January 2022
Available online: 15 March 2022

Keywords:
Cavitation erosion resistance
Metastable austenite
Martensitic phase transformation
Microstructure
Deposited coatings

Funding
The work was carried out within the framework of the state assignment of the IMF UB RAS on topics No. AAAA-A18-118020190116-6, No. AAAA-A19-119070490049-8. This study was supported by project No. IRA-SME-66316 "cladHEA +" under the M-ERA.NET program, Call 2019-II.

Acknowledgements
Research were partially conducted at core facility "Structure, mechanical and physical properties of materials"

ABSTRACT

Introduction. Reliability-critical components of equipment working in contact with high-speed liquid media (for example, turbine blades of hydroelectric power stations, pump impellers, ship propellers) are subjected to one of the types of wear – cavitation erosion. **The current study aims** to select and scientifically substantiate the type of coating and its structural-phase state for the effective protection of parts from cavitation erosion. **Research methods.** The study carries out a comparative analysis of differences in the cavitation erosion resistance of characteristic austenitic steels, in the form of bulk material (*316L*) and coatings (*E308L*, *60Cr8TiAl*), used for protection against cavitation Arc surfacing, i.e. *MMA* and *MIG*, is used for depositing the coatings. The tests are carried out on an original installation for evaluating the cavitation resistance of materials with applying ultrasound and the electrical potential difference. **Results and Discussion**. The results show that the *60Cr8TiAl* has a higher resistance to cavitation erosion than that of *E308L* and *316L* by 4 and 10 times, respectively. The structural factors that determine the resistance to cavitation erosion damage are identified to analyze the reasons for the differences in material resistance. Firstly, a strong dependence of the cavitation erosion resistance of austenitic steels on the intensity of the deformation martensitic transformation, developing under the influence of cavitation, is confirmed. This structural transformation contributes to an increase in cavitation resistance of the surface layer. In metastable austenitic steel, a deformation martensite (α') is formed in the surface layer during the initial test period. This causes an increase in hardness, dissipation of the energy of external action, and the appearance of compressive stresses that prevent the occurrence of microcracks. Subsequently, additional hardening of the previously formed dispersed crystals of α'-martensite occurs. In *60Cr8TiAl*, these effects are significantly stronger than that of *E308L* and *316L* due to the higher level of metastability of austenite and formation of carbon deformation martensite.

For citation: Korobov Yu.S., Alwan H.L., Makarov A.V., Kukareko V.A., Sirosh V.A., Filippov M.A., Estemirova S.Kh. Comparative study of cavitation erosion resistance of austenitic steels with different levels of metastability. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2022, vol. 24, no. 1, pp. 61–72. DOI: 10.17212/1994-6309-2022-24.1-61-72. (In Russian).

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Introduction

The high-effective machinery parts operating in contact with high-speed liquid media (for example, turbine blades of hydroelectric power plants, pump impellers, ship propellers) are subjected to cavitation erosion [1–5]. During the cavitation process high-pressure shock waves (1,500 MPa [6, 7]) are initiated, and the velocity of emerging liquid microjets can exceed 120 m/s [8–10]. On the surface subjected to cavitation, local plastic deformation occurs, followed by the destruction starting from the surface layers [11, 12].

As a result, defects that appear in this case (micro pits or cavities) lead to reduction of the equipment efficiency and increasing repair costs [13]. Fig. 1 represents a typical example of cavitation erosion damage occurring in pump impeller blade made of *AISI 316L* austenitic stainless steel used in power plant-cooling systems. As reported, steel *AISI 316* cavitation erosion resistance is not high enough [14].

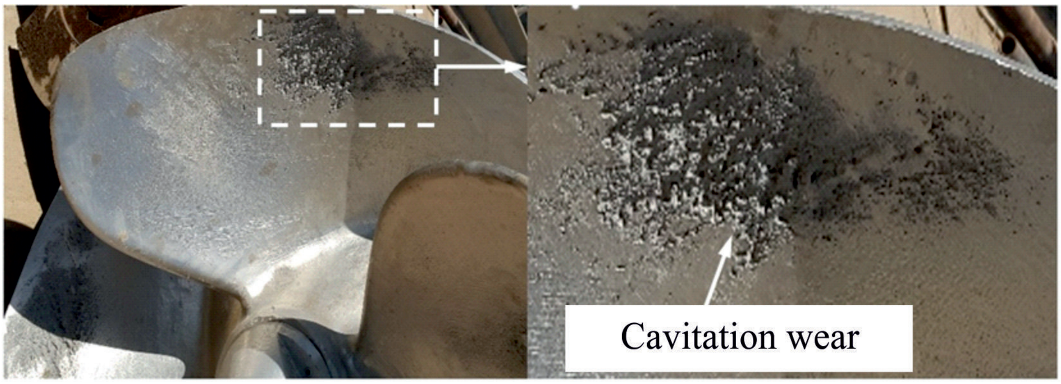


Fig. 1. Cavitation wear of water pump impeller

Surface treatment is promising way for reducing the cavitation damage [15, 16]. Another way to increase the resistance of parts against cavitation erosion is the deposition of coatings by arc surfacing [17–19] and thermal spraying [5, 20, 21]. Arc surfacing is widely used due to low cost and the possibility of formation dense coatings [22]. Particularly, austenitic electrodes/wire of the *E308L-17* type (Russian analogue *03Cr19Ni10*) has become widespread due to good weldability and adequate cavitation resistance [23, 24]. Metastable austenitic steels (*MAS*) are potentially promising alternatives to more expensive alloys based on *Co* and *Ni*. When the external load is applied to *MAS*, a phase transformation from austenite to martensite ($\gamma \rightarrow \alpha'$) takes place accompanied by synergistic effects. First, an increase in the proportion of the martensite phase leads to an increase in hardness. Second, the energy of the external load, applied to the surface, is dissipated due to the strain induced nucleation of martensite. Also, due to the phase transformation ($\gamma \rightarrow \alpha'$), compressive stresses arise in the surface layer of the part, preventing the occurrence of microcracks [25]. As a result, wear resistance is improved under various conditions (for example, abrasive, hydro- and gas-abrasive, erosive, cavitation, adhesive, and fatigue loads) [26, 27]. For *50Ni9Cr5 MAS*, it is shown that the phase transformation ($\gamma \rightarrow \alpha'$) occurs at a threshold level of external load from 1,000 to 2,500 MPa with an increase in the initial amount of martensite from 15 to 75 %. At strains exceeding the threshold value, the amount of deformation martensite increases linearly with increasing strains [28]. The authors obtained similar results for *50Cr18 MAS* deposited coatings under the action of highly dynamic impact loads [29] and for *60Cr8TiAl MAS* coatings under abrasive action [30]. The presented external loads correspond to cavitation loads, which exceed 1,500 MPa, as shown above [6-10]. This suggests the possibility of ($\gamma \rightarrow \alpha'$) phase transformation in *60Cr8TiAl MAS* coating during the cavitation.

The purpose of this study is to evaluate the cavitation erosion resistance and analyze structural changes in the deposited coating of steel *60Cr8TiAl* in comparison with austenitic steels *316L* (bulk workpiece) and *E308L-17* (deposited layer).

Methodology

In this work, *AISI 316L* stainless steel (bulk workpiece) and two coatings (*60Cr8TiAl* formed by deposition of ∅1.6 mm flux-cored wire and *E308L-17* formed by deposition of ∅2.5 mm electrode) have been studied. The coatings were deposited using *Shtorm-LORCH S-series* welding machine, (Shtorm, Ekaterinburg, Russia). The chemical compositions of materials, Wt%, according to manufacturers, is shown in Table 1The chemical compositions of materials, Wt%, according to manufacturers, were the following

AISI 316L:

C ≤ 0.03, *Cr* 16.5-18.0, *Ni* 10.0-13.0, *Mo* 2.0-2.5, *Mn* ≤ 0.03, *P* ≤ 0.045, *S* ≤ 0.03, *N* ≤ 0.1, *Fe* balance;

60Cr8TiAl:

0.6 *C*, 8.0 *Cr*, 1.5 *Al*, 1.0 *Ti*, Fe balance;

E308L-17 electrode:

0.04, *Cr* 17.50, *Ni* 7.92, *Si* 0.86, *Mn* 0.51, *Nb* 0.30, *P* 0.03, *S* 0.01, *Fe* balance.

The *60Cr8TiAl* coating was deposited by tungsten inert gas welding (*TIG*) in the following modes: current 90-110 A, voltage 12 V, argon feed rate 12-15 l/min. The *E308L-17* coating was deposited by manual metal arc welding (*MMA*) in the following modes: current 70-75 A, voltage 25 V. The test specimens were prepared in accordance with the requirements of the *ASTM G32–10* cavitation erosion test [31], Fig. 2. Surfacing was carried out on specimens of ∅16 mm and 16 mm high. After that, the specimens were cut out and ground according to Fig. 2. The end part of the specimen ∅16 mm was subjected to cavitation.

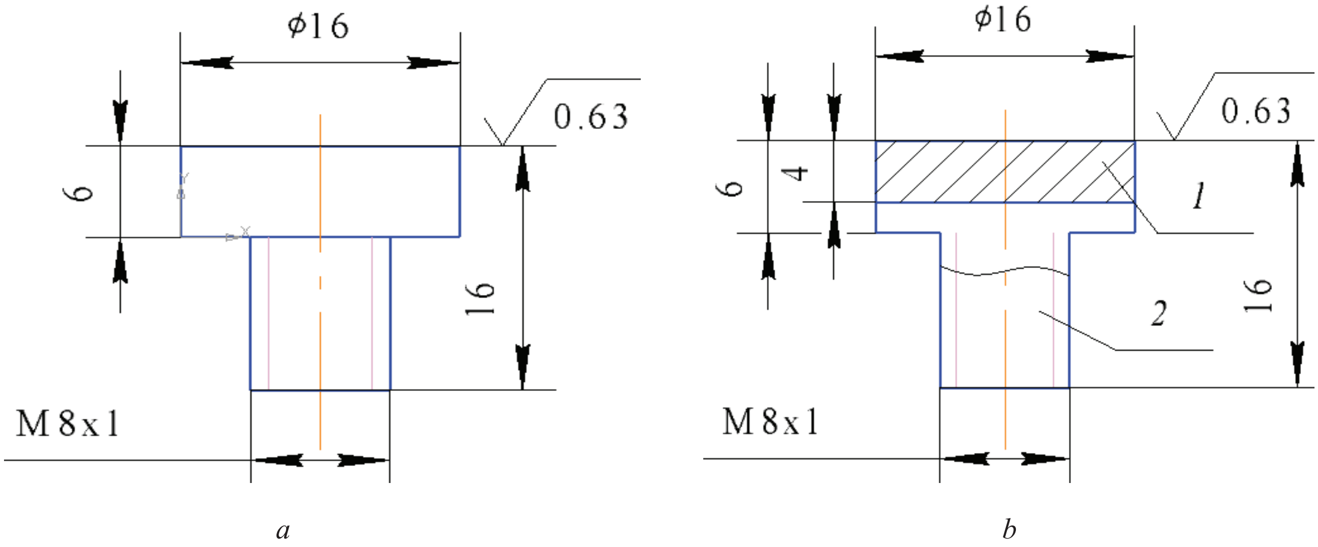


Fig. 2. Samples for the cavitation tests:

a – *AISI 316L* steel sample, *b* – the sample with a deposited coating, *1* – deposited layer, *2* – substrate

Cavitation erosion was evaluated using an original installation [32], in which the cavitation occurs under the effect of ultrasound on a liquid jet contacting the sample surface, Fig. 3. The constancy of the composition, flow pressure and temperature of the liquid is controlled by the feedback algorithm that maintains recycling the liquid. Applying a voltage between the nozzle and the sample contributes to adding an electrochemical effect due to anodic polarization, which increases erosive wear. The voltage value is chosen to be the minimum, at which the effect of erosion acceleration appears.

The proposed scheme for cavitation test differs from the standardized one [31] in terms of the location of the sample relative to the water jet as well as the design features mentioned above. This allows speeding up testing, increase the reliability and stability of the results in comparison with analogues [33, 34].

The conditions of carrying out cavitation tests are given in Table 1.

The cavitation erosion resistance was evaluated depending on a weight loss criterion. The tests were interrupted at irregular intervals to weigh the test sample. Before and after each interval, the sample was

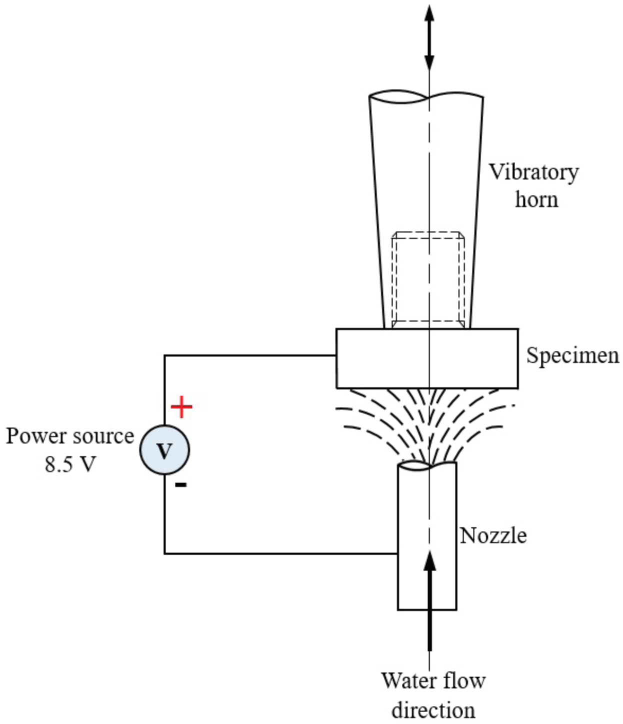


Fig. 3. Scheme of the installation for cavitation erosion testing

Table 1

Cavitation test modes

Parameter	Value
Vibration frequency, kHz	20 ± 0.1
Peak-to-peak displacement amplitude, µm	53 ± 3.0
Test environment	Tap water, pH 7.5 ± 0.20
Applied voltage, V	8.5
Testing time, min	300
Temperature	Room

cleaned with acetone, dried with warm air for 30-40 seconds, and weighed on a balance with an accuracy of 0.5 mg. The difference between the initial mass of the sample and the measured mass after cavitation represents the mass loss at each test interval.

To study phase transformations occurring during cavitation, X-ray diffraction analysis (*XRD*) was performed on a Shimadzu XRD-7000 diffractometer (Shimadzu, Japan) in a *Cu* K_α radiation, graphite monochromator (angular range 2θ from 30° to 115° with 0.04° scanning step for 3 s exposure). The analysis was performed for samples after tests, the duration of which corresponded to the time of measurements of weight loss.

Results and discussion

The results of cavitation tests are given in Table 2. As seen, the cavitation erosion resistance of 60Cr8TiAl is about 10 and 4 times higher comparing to AISI 316L and E308L-17, respectively.

Table 2

Cavitation test results

Testing time, min	Weight loss, mg		
	AISI 316L	E308L-17	60Cr8TiAl
0	0.00	0.00	0.00
5	0.67	0.47	0.10
10	1.10	0.75	0.31
20	1.65	0.90	0.66
40	2.02	1.03	0.87
60	2.90	1.13	0.99
90	5.04	1.57	1.24
120	7.74	2.43	1.48
180	15.44	4.72	1.76
240	22.13	8.07	2.06
300	28.65	12.13	2.49

A noticeable increase in the wear rate for *AISI 316L* and *E308L-17* in comparison with *60Cr8TiAl* is observed after 40 and 90 minutes, respectively.

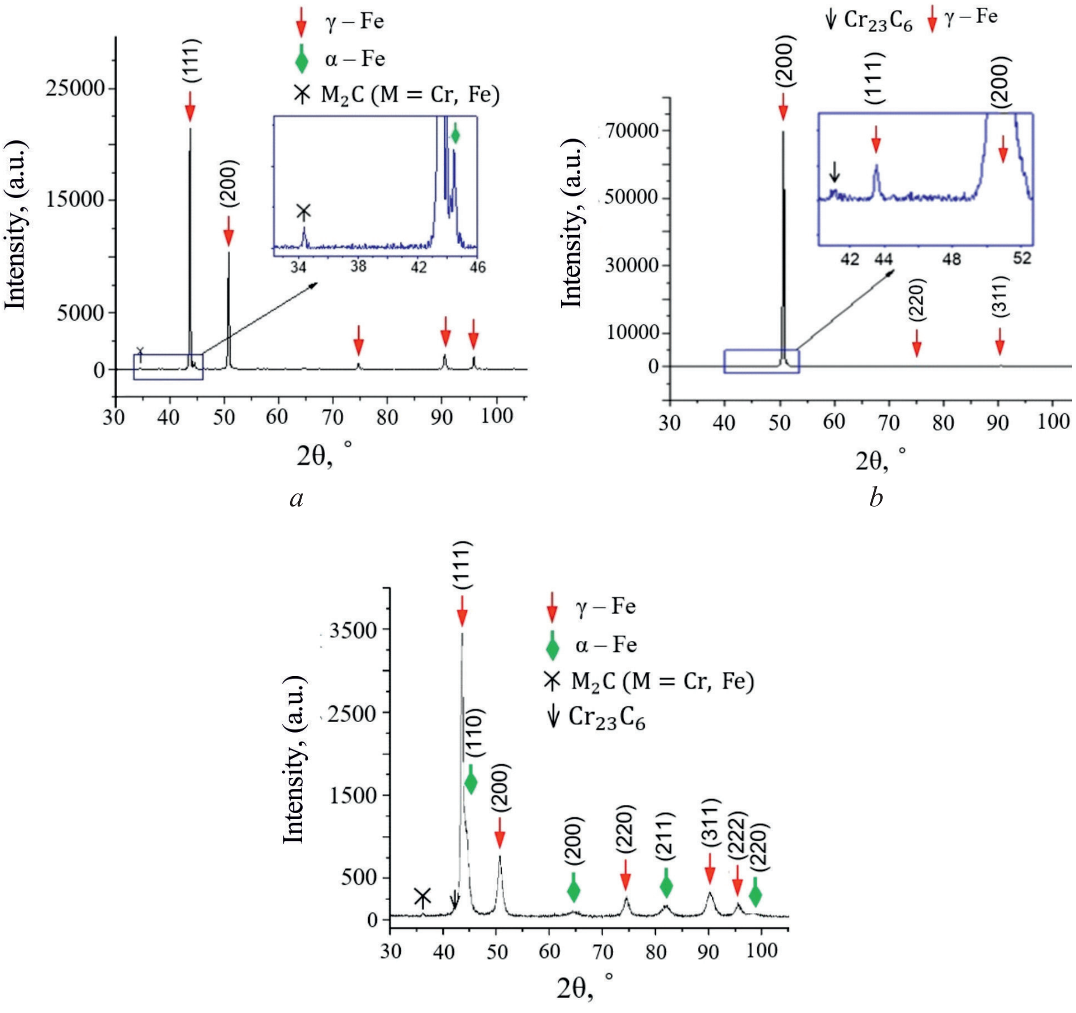
According to *XRD*, Fig. 4, it is noticed that, before cavitation tests, the share of the α-phase in the surface layer was 29.5 % in *60Cr8TiAl*, 2 % in *AISI 316L*, and was not found in *E308L-17*.

The presented combination of austenite and martensite in *60Cr8TiAl* is due to the influence of alloying elements. Carbon is a strong austenitizer, and at a given *C/Cr* ratio, the initial martensitic transformation temperature (*Ms*) decreases. Calculations using predictive equations for the main chemical composition of 0.6 % *C* and 8 % *Cr* [35] showed that *Ms* is in the range of 170–220°C. Aluminum and titanium within the indicated limits induce $\gamma \rightarrow \alpha'$ transformation, contributing to increasing the number of crystallization centers and obtaining a fine-grained structure [36]. As indicated by *XRD* analysis an increase in the amount of deformation martensite was observed in the surface layer of all samples during the cavitation tests, Fig. 5.

In *60Cr8TiAl*, the quantity of martensite increased to 73 %, which is much higher than that of *E308L-17* and *AISI 316L*. This indicates a significantly lower austenite stability in *60Cr8TiAl*.

The deformation martensite causes an increase in hardness, dissipation of the energy of external loading, and development of compressive stresses preventing the formation of microcracks. For *60Cr8TiAl* and *E308L-17*, the slope of the curves for the dependence of the proportion of martensite on the duration of testing changes, which indicates the stabilization of austenite. Therefore, at latest test stage with a slight increase in the quantity of martensite, there is an additional strain hardening of the previously formed dispersed crystals of α'-martensite. For *AISI 316L* steel, during the first 60 min of cavitation, no noticeable formation of α'-martensite was observed. This indicates a high stability of austenite, which is also confirmed by other studies [26]. Only prolonged for 300 min cavitation exposure led to the formation of 25 % martensite on the metal surface. This means that the formation of α'-martensite occurs in the already hardened austenite of this steel.

Comparing the results of cavitation tests and *XRD* data, it can be concluded that there is a correlation between the erosion resistance of austenitic steels and the intensity of the martensitic transformation. The latter one develops under the influence of cavitation, contributing to erosion resistance increase, Fig. 6.



a

b

c

Fig. 4. XRD patterns of the samples before cavitation tests:
a – AISI 316L, b – E308L-17, c – 60Cr8TiAl

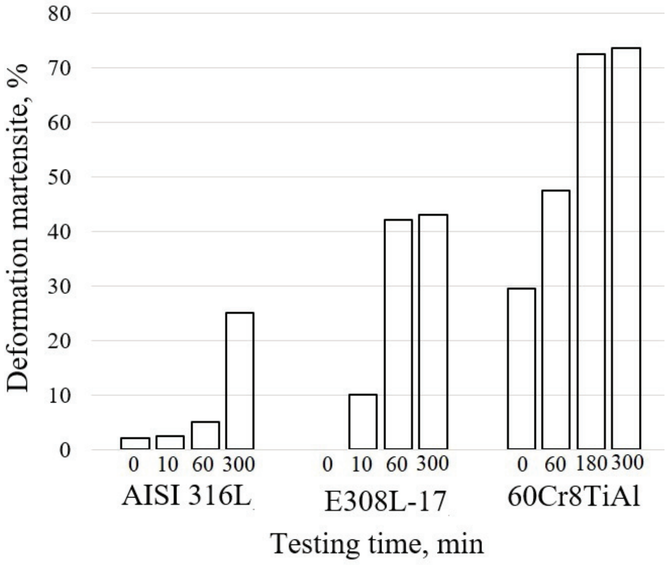


Fig. 5. Change in the proportion
of martensite during cavitation tests

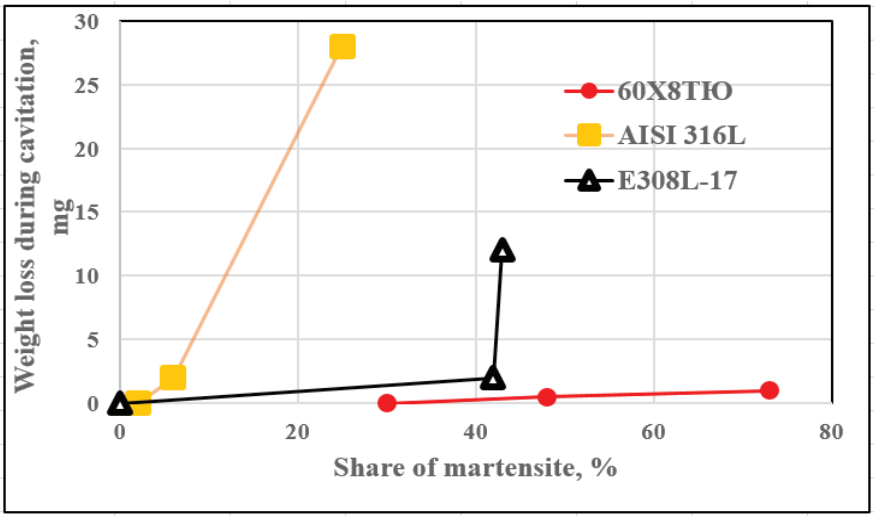


Fig. 6. Correlation between erosive wear and the intensity of martensitic transformation during cavitation

A strong effect of martensitic transformation on cavitation erosion resistance was also shown for austenitic steel 304 [37, 38], which is similar in alloying system to the considered *AISI 316* steel and *E308L-17* coating.

Thus, it can be concluded that cavitation loading of the *60Cr8TiAl* coating leads to a phase transformation ($\gamma \rightarrow \alpha'$), similar to abrasive action. This causes synergistic effects inherent in metastable austenitic steels, such as increased hardness, energy dissipation, and increased stresses in the surface layer. The result of these effects is increasing the cavitation resistance of *60Cr8TiAl* coating in comparison with widespread materials used for parts operating in applications requiring cavitation resistance.

Conclusions

1. The mechanism of surface hardening in metastable austenitic steel during cavitation is shown and confirmed. In the initial period of testing, deformation martensite (α') is formed in the surface layer. Subsequently, additional strain hardening of previously formed dispersed α'-martensite crystals occurs.
2. Cavitation effect on the surface of metastable austenitic steel leads to the deformation transformation of martensite, as in the cases of previously considered effects on similar steels at highly dynamic impact loads and abrasive wear. This indicates the same level of external specific loads for all these types of loading.
3. There is a correlation between the erosion resistance of austenitic steels and the intensity of the martensitic transformation developing under the action of cavitation. The resistance to cavitation of the *60Cr8TiAl* coating, having the highest intensity of martensitic transformation, is higher than that of *AISI 316L* steel and *E308L-17* coating by 4 and 10 times, respectively.

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Conflicts of Interest

The authors declare no conflict of interest.