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Test Procedure of Cladded Alloys for Resistance against High Temperature Abrasive Wear

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Abstract—This article discusses the development of procedure and assembly for testing metals and alloys for abrasive wear at ambient and higher temperatures of up to 600°C. The procedure can be applied both to evaluate the operating properties of alloys used to clad of machine parts and tools of metallurgical and refractory purposes, and to test various metal and composite materials. The wear of alloys as a function of temperature, the pressure on specimen, and its shape, as well as of the composition and dispersity of abrasive mass have been determined. Hardness and wear resistance of some experimental and commercial alloys have been presented, and the influence of alloy doping and modifying on their wear resistance at higher temperatures has been established.

Keywords: testing procedures, wear resistance, hardness, abrasive, temperature, cladded alloy

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INTRODUCTION

The tools and parts of metallurgical equipment (pipe rolling mills, rollers of rolling tables and continuous casting machines, charging troughs); refractory and cement processes (scrappers and blades of mixers, parts of rotary kilns); facilities of mining, drilling, and other machinery operate in complicated environment of abrasive, fatigue, oxidizing abrasion at high (up to 600°C) temperature in contact with processed materials. This stipulates their low operation lifetime, and its increase is related to the cladding of operating surfaces with wear-resistant alloys. Commercial types of wear-resistant cladding alloys are not always characterized by sufficient wear resistance at higher temperatures, which can be attributed to their impractical structure and phase composition, as well as the low thermal stability of their structure, which leads to the weakening of the alloy matrix and the coagulation of particles of the strengthening phase [1]. In this regard, the development of innovative alloys that are highly resistant to wear in abrasive medium upon thermal impact, as well as an efficient procedure for their laboratory test at high temperature, which provides reliable results, is a challenging scientific and engineering problem.

The existing test procedures [2, 3] are based mainly on the adhesion mechanism of high-temperature wear on metal-to-metal abrasion. The results of high-temperature testing of alloy hardness [4] makes it possible to evaluate their resistance against plastic deformation without destruction, but they poorly reflect the actual resistance against impact of abrasive particles and are applied mainly to evaluate the wear resistance of alloys intended for the hot deformation of steels. The results obtained in abrasive hardness tests are more reliable [5]. However, this procedure prevents the sufficient evaluation of the impact of strengthening on the wear resistance of the alloy, as well as of the destruction of its plastically deformed bulks upon multiple impacts of abrasive particles. In addition, the influence of composition, shape, dispersity, and hardness of abrasive particles on kinetics and the wear rate of the metal is not considered.

Test procedures [6, 7] that take into account mechanisms of metal abrasion against continuously refreshing abrasive surface are the most preferable. However, they either have significant constraints with regard to test temperature and pressure on the specimen, or do not make it possible to perform tests upon interactions between the tested specimen and counterbody via the abrasive interlayer, or do not allow for the heating of the abrasive material in contact with the heated specimen. These drawbacks prevent reliable results from being obtained, since test conditions often do not correspond to the actual wear conditions of machine parts and tools.

The aim of the work is to develop rapid test procedures of metals and alloys for wear resistance upon metal to metal abrasion via the abrasive interlayer at ambient and higher temperatures of up to 600°C.

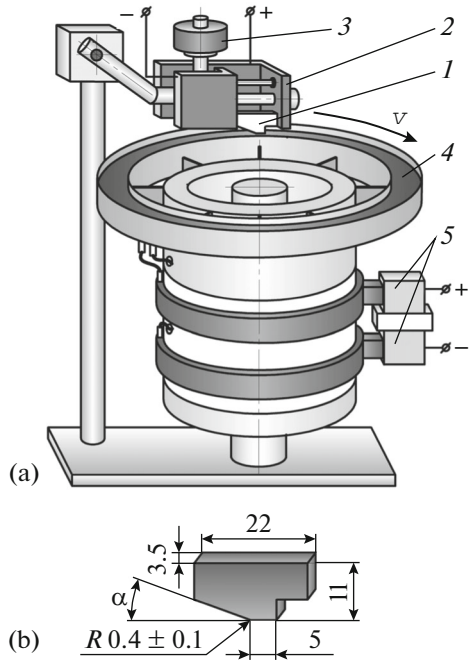

Fig. 1. Schematic diagram of assembly (a) and specimen (b) for wear test: (*1*) test specimen; (*2*) conducting holder; (*3*) weight; (*4*) counterbody with heater; (*5*) sliding conductors; v is direction of counterbody rotation; α is the skew angle of the operation area of the specimen.

EXPERIMENTAL

The development of rapid test procedure was caused by the need to test materials using the laboratory assembly (Russian patent no. 2564827), as illustrated in Fig. 1. The assembly is comprised of the rotating counterbody, the surface of which is coated by abrasive bulk, and pressed stationary metal specimen fixed in the conducting holder (Fig. 1a). The counterbody is a ring made of grade-12Cr18Ni9Ti steel; it is heated from above by electric resistance and powered via direct current sliding conductors. A specimen fixed in a copper conducting holder is heated by passing current from the welding supply. The specimen edges are equipped with pads for fixation and the current supply from the holder, and the operation area is skewed, thus enabling the free penetration of abrasive particles below the specimen and the creation of an abrasive interlayer between the specimen and counterbody surface (Fig. 1b). Upon testing alloys with high current conductivity, e.g., copper, specimens are made in bimetallic form; the main portion is of low carbon steel and the operation portion is of the tested alloy.

Abrasive mass is comprised of the following powders: iron scale of grade-08kp steel (Russian GOST State Standard 503–81); a mix of iron scale and white electrocorundum, grade 25A (Russian GOST State Standard 28818–90) in a 1 : 1 volumetric ratio; and quartz sand. Three types of abrasive powders were applied: with particle size in the range of 250–500 μm, 100–250 μm, and less than 100 μm. Abrasive masses of various dispersities were prepared by grinding coarse raw material with subsequent sieving. Prior to use, the powders were dried in an oven in order to remove moisture. The repeated use of the abrasive was not allowed.

The assembly design enables heating and stable temperature maintenance of specimen and counterbody during the entire test period in the range of ambient temperature to 600°C. The temperature of specimen operation area was continuously monitored according to readings from an LA-20USB analog digital converter connected to chromel–copel thermocouple. The temperature of counterbody prior to tests was monitored by a similar thermocouple and during tests by an C-20.4 infrared pyrometer. The topology of the thermal field across the surface of the specimen and counterbody was analyzed using a HotFind-L infrared camera.

The volume loss of tested specimens after their abrasion was used as the criterion of wear resistance as follows:

$$\Delta V = \frac{\Delta m}{\rho}. \quad (1)$$

Upon minor differences in the density of materials, it is possible to apply the absolute values of weight loss after tests. The density of the considered alloys calculated by hydrostatic method was in the range of 7.5–8.1 g/cm^3. Specimens were weighted using a VIBRA HT-124RCE analytical balance with an accuracy of up to 0.1 mg.

The tests were performed under the following conditions: a temperature of 20–600°C, pressure on the specimen of 1.0–2.5 MPa, a traveling speed of the specimen of 0.12 m/s, and a test time of 417 s. The abrasion length of specimens equaled 50 m and was selected in accordance with the requirements of Russian GOST State Standard 17367–71 and Russian GOST State Standard 23.208–79 concerning the minimum allowed values of their wear (5 mg). The hardness was measured by the Rockwell method using a TH-500 hardness meter.

The tests were performed with specimens of wear resistant alloys cladded by electric arc in protective argon carbon dioxide gaseous mix using flux cord wires. The following specimens were tested: 25Cr5VMoSi and 150Cr15B3Ti2 (PP-Np-25Cr5VMoSi and PP-Np-150Cr15B3Ti2 according to Russian GOST State Standard 26101–84) and 350Cr22Mo3V (OK Tubrodur 55 OA, ESAB) commercial alloys, as well as 300Cr13Mo2TiNiB experimental alloy and 400Cr13Mo2Ti2NiB experimental alloy modified with ultrafine particles of titanium nitride TiN in the amount of 0.8 wt % and heat-resistant (up to 800°C) Cr3Ni50MoW5Al9Ta4 nickel alloy (where the remainder is iron).

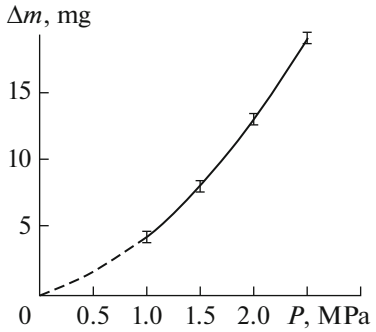

Fig. 2. Weight loss Δm of 25Cr5VMoSi alloy as a function of pressure P on specimen after testing (friction path = 50 m, angle $\alpha = 90°$, temperature = 20°C).

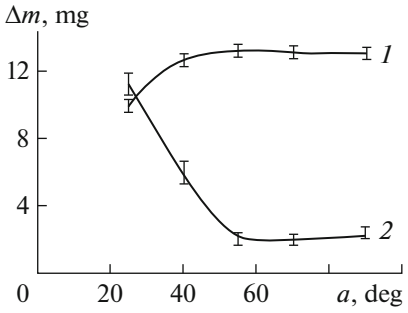

Fig. 3. Weight loss Δm of 25Cr5VMoSi alloy as a function of angle α at various abrasive dispersity (friction path = 50 m, angle $\alpha = 90°$, temperature = 20°C, $P = 2$ MPa): (*1*) 100–250 μm; (*2*) 250–500 μm.

RESULTS AND DISCUSSION

The main variables of the rapid test mode are as follows: test temperature, pressure onto the specimen, the speed of its motion with regard to the counterbody, the length of the abrasion, the test time, the composition of the component and particle size distribution of the abrasive mass, dimension, and the shape of the specimen. The optimum parameters were determined in a series of tests with a specimen made of 25Cr5VMoSi heat and wear-resistant alloy widely applied in metallurgy for the manufacturing and cladding of tools for processing of hot metal (up to 600°C). The tests were aimed at achievement of maximum wear rate and its steady level upon tests, as well as provision of high reproducibility of test results.

It is known [8, 9] that the ratio of harness of applied abrasive to that of the alloy H_{abb}/H_{all} influences significantly on its wear intensity. It is established that upon testing of highly hard alloys in combination with iron scale (microhardness $H = 4–8$ GPa) and quartz sand ($H = 10–12$ GPa) the ratio $H_{abb}/H_{all} < 1$, which stipulates very low wear rate and requires for significant increase in test time. Possibility of increasing wear rate by means of increase in slip speed of specimen over abrasive interlayer is restricted by heating plastically deformed surface layers of alloy [10], it can hardly be controlled by experimental and computing methods. Thus, subsequently in rapid tests that simulate the operating conditions of metallurgical tools the maximum slip velocity was restricted by 0.12 m/s, the test time was set to 417 s, which corresponds to an abrasion length of 50 m, and while the abrasion mass was prepared on the iron scale and corundum ($H =$ 20–21 GPa) was prepared in a bulk ratio of 1 : 1.

The influence of pressure on the wear resistance of the cladded alloy was studied. It is illustrated (Fig. 2) that the pressure increase in the range of 1–2.5 MPa results in an increase in wear, which is attributed to deeper penetration of abrasive into specimen surface, as well as by an increase in the fixation rate of abrasive particles in the interlayer between specimen and counterbody. This promotes a decrease in the fraction of particles, which plastically deform the specimen as a consequence of rolling over its surface and intensification of cutting and spalling of alloy structural components by means of semi-fixed particles. The pattern of the presented dependence is also probably stipulated by the destruction of abrasive wear under the impact of an increased load with the generation of new sharp edges, which accelerates the wear of the specimen [11].

The influence of the angle of skew α of the operating area (Fig. 1a) on the wear intensity and stability of the obtained results was studied. It is obvious that the skew on the specimen results in the instability of the wear rate, which is related to the decrease in pressure on the specimen during testing upon a gradual increase in the surface area of its operating area S. This leads to a slight overestimation of the wear resistance of the considered alloy. The error can be decreased by increasing in angle α; hence, in subsequent experiments, its maximum value was determined, which would provide a uniform supply of the abrasive mass under the specimen.

The specimens with angles α of 25°, 40°, 55°, 70°, and 90° were tested with an abrasive mass of various dispersities. It is established that the use of abrasion with a particle size of less than 100 μm is unreasonable, since it leads to extremely low weight loss in the tested specimens. With the use of abrasive mass with particle sizes in the range of 100–250 μm, the wear of the considered alloy increases; here, with an increase in the angle α of up to 40°, the weight loss in the specimen increases, then remains steady (Fig. 3). This is related probably to the fact that, at low angles α, finer abrasive particles are compacted in the vicinity of the front edge of the operating area, which acquires some load on the specimen, which in combination with the relatively high increase in the area of the contact surface during tests leads to underestimated values of its weight loss.

When the abrasive with particle sizes in the range of 250–500 μm is used, the reverse dependence is observed, i.e., an increase in the angle α from 25° to

60° leads to a sharp decrease in the wear intensity and, when α is more than 60°, the specimen wear becomes steady. Here, the weight losses of specimens are highly scattered in the series of tests, which decreases the reliability of the experimental results. This can be attributed to the fact that, at relatively high values of the angle α abrasive mass, which consists of coarse particles, it is accumulated in front of the moving specimen and does not actually penetrate it. The wear mechanism is transformed into adhesion and abrasion with a significant decrease in the wear rate.

Therefore, in the considered pressure range on the specimen, it is possible to recommend the following optimum angles α of skew of operation area: sizes of abrasive particles should be 100–250 μm for angles of 90°, and 250–500 μm for angles of 30°.

Using calculations and an experimental approach, the measurement error of the wear resistance of 25Cr5VMoSi alloy was approximately determined while testing the specimen with an angle $\alpha = 30°$. Weight loss Δm of specimen as a function of pressure P, using the data in Fig. 2 can be presented as follows:

$$\Delta m = 2.39\times10^{-16}P^2 + 1.41\times10^{-11}P. \quad (3)$$

Then, rewriting P as the ratio of the load F onto specimen to the surface area S of its operation area, the error Δm_{err} of measurement of weight loss stipulated by the instability of wear rate can be determined as follows:

$$\Delta m_{\text{err}} = \Delta m - \int_0^{t_{\text{test}}} \frac{2.39\times10^{-16}\left(\frac{F}{S_i}\right)^2 + 1.41\times10^{-11}\left(\frac{F}{S_i}\right)}{t_{\text{test}}}dt, \quad (4)$$

where Δm is the weight loss of specimen after testing, kg; S_i is the surface area at time t, m^2; and t_{test} is the testing time, s.

Assuming that the surface area S_i of operation area during testing varies linearly, we obtain the following:

$$S_i = S_n + t\frac{(S_k - S_n)}{t_{\text{test}}}, \quad (5)$$

where S_n is the surface area prior to testing, m^2, and S_k is the surface area after testing with duration of t_{test}, m^2, determined by the equation

$$S_k = \sqrt{S_n^2 + \frac{2\Delta m b}{\rho\tan(\alpha)}}, \quad (6)$$

where b is the width of specimen operation area, m; ρ is the density of specimen material, kg/m^3; and α is the angle of skew of specimen operation area, rad.

The value of Δm_{err} calculated by Eq. (4) at F = 3.57 kg, S_n = 17.5 mm^2, b = 3.5 mm, ρ = 7.8 g/cm^3, t_{test} = 417 s, Δm = 12.9 mg, $\alpha = 30°$ does not exceed 3% of the measured weight loss. Therefore, the rapid test procedure at low angles α and coarse abrasive particles provides high confidence of the obtained results.

The shape of tested specimen with lengthwise variable cross section provides the generation of a fairly homogeneous thermal field and the achievement of minimum temperature gradient in the operating area. Specimen heating by the passing current makes it possible to vary the heating rate in a wide range (2–30 deg/s). The rapid heating in combination with low testing time makes it possible to analyze the contribution of abrasive constituent of wear to total wear of specimen without taking into account the weight loss of the specimen or increment due to oxidation of its surface. An important feature of the developed procedure is provision of heating of counterbody and abrasive mass, which makes it possible to maintain the preset temperature conditions of specimen wear without overcooling its operating area, as well as to improve the confidence of the experimental results by accounting for variations in the mechanical properties of abrasive at increase in temperature (for instance, the hardness of Al_2O_3 at heating to 500°C decreases by 1.8 times [12]).

Figure 4 illustrates the experimental results of various alloys regarding hardness and the wear resistance using the proposed procedure, as well as the standardized (according to Russian GOST State Standard 17367–71) procedure upon abrasion against fixed abrasive particles. An analysis of the obtained results demonstrated that the hardness and wear resistance measured by the standardized procedure of variously doped alloys do not correlate with their high temperature wear resistance. A close correlation (Pearson correlation coefficient k = 0.784 at confidential probability p = 0.9) is observed between weight losses of alloys worn at 20°C using the proposed and standardized procedures, which indicates similar wear mechanisms due to the microcutting by abrasive particles, which under pressure on the specimen equal to 2 MPa, are significantly fixed between the specimen and counterbody. This is confirmed by an analysis of the abrasion surfaces, which in both cases have peculiar tracks that result from the impact of fixed abrasive particles (Fig. 5).

It has been demonstrated that the wear resistance of alloys at higher temperatures is determined by their structural and phase composition, which is influenced by the content of carbon, dopants, and modifiers. For instance, for experimental alloys of the Fe–C–Cr–Mo–Ni–Ti–B dopant family (Fig. 4, specimens 4 and 6), increased resistance is achieved under conditions of high temperature wear at decreased carbon content, which is stipulated by its reasonable ratio with the amount of carbide generating elements. Thus, upon a decrease in carbon content from 4 to 3 wt %, the increase in wear resistance at 20°C is 29% and at 500°C already to 85%.

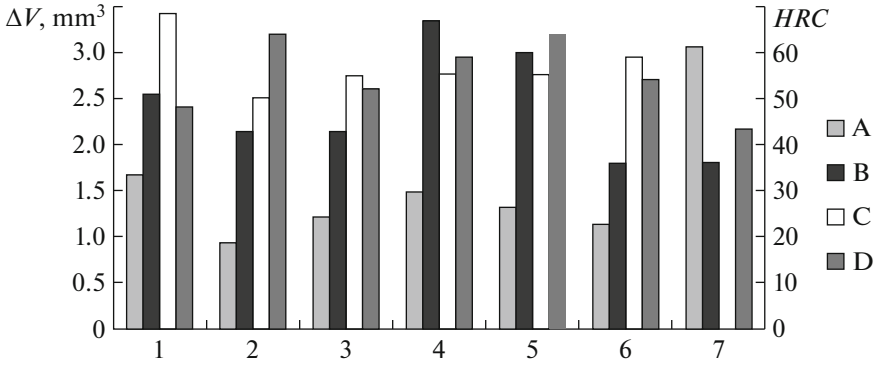

Fig. 4. Volume loss ΔV of welded alloys measured according to the developed procedure at (A) 20°C and (B) 500°C according to (C) Russian GOST State Standard 17367–71, as well as (D) hardness HRC of alloys: (1) 25Cr5VMoSi; (2) 150Cr15B3Ti2; (3) 350Cr22Mo3V; (4) 400Cr13Mo2Ti2NiB; (5) 400Cr13Mo2Ti2NiB + 0.8 wt % TiN; (6) 300Cr13Mo2TiNiB; (7) Cr3Ni50MoW5Al9Ta4.

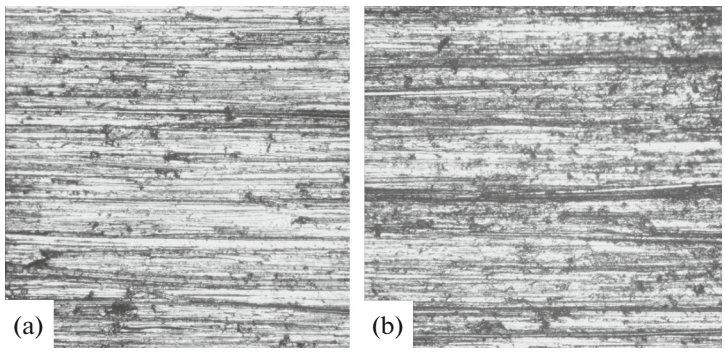

Fig. 5. Surface of 350Cr22Mo3V alloy after wear determined according to (a) Russian GOST State Standard 17367–71 and according to (b) developed procedure at 20°C (×100).

The increase in degree of doping for alloys with carbide and boride generating elements such as chrome, molybdenum, vanadium, titanium, accompanied by an increase in fraction of strengthening solid phase, does not lead to a proportional increase in their wear resistance. For instance, the 2.5–3 fold cumulative content of dopants in 150Cr15B3Ti2 and 350Cr22Mo3V commercial alloys compared with sparingly doped 25Cr5VMoSi alloy increases their wear resistance by no more than by 20% at 500°C. Here, the reasonable doping of 300Cr13Mo2Ti2NiB experimental alloy stipulates its resistance against high-temperature abrasive wear, which exceeds that of 25Cr5VMoSi alloy by 43%. Here, the intensity of the drop of its wear resistance with an increase in temperature is 10–50% lower than that of its analogs (Figs. 5, 6). This is stipulated by the sufficiently high thermal stability of the metal structure with the high bulk fraction of the fine strengthening phase, which is mainly presented by the frame of eutectic carboborides $(Fe,Cr)_7(C,B)_3$.

The loss of the wear resistance of the alloy upon short-term heating to 600°C, when the rate of development of diffusion (which leads to its weakening) is restricted, is related mainly to the decrease in hardness of its matrix and, to a lesser degree, of the hardening phase (for instance, the microhardness of carbides Cr_7C_3 only decreases by 20%). On the other hand, the solid solution and intermetallic hardening mechanisms of nickel-based alloys, in particular Cr3Ni50MoW5Al9Ta4, stipulate the extremely low impairment of their mechanical properties compared with iron-based alloys. The hardness of these alloys in the temperature range of 20–500°C decreases by no

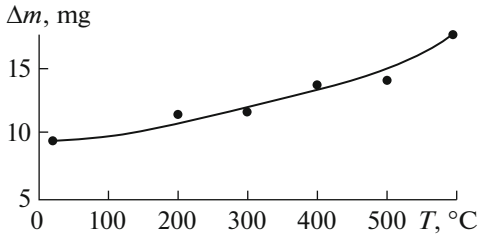

Fig. 6. Weight loss Δm of 300Cr13Mo2Ti2NiB alloy as a function of test temperature T.

more than 10%, which significantly decreases their wear in combination with the significant loss of microhardness of the abrasive.

The modification of 400Cr13Mo2Ti2NiB alloy by ultrafine TiN particles promotes an increase in the wear resistance of the alloy by 12% at both normal and higher temperatures (Fig. 5). This can be attributed to the dispersion of carbon boride eutectic in the alloy structure, as well as by the deposition of carbides $(Ti,Mo)C_{1-x}$ generated on TiN particles.

CONCLUSIONS

(1) The developed procedure of rapid testing of material for resistance against abrasive wear at higher temperatures of up to 600°C makes it possible to improve the reliability of evaluating the operating properties of alloys for the cladding of tools and machine parts for metallurgy and other industries.

(2) The recommended variables in the process of testing the mode and specimen shape provide high stability and reproducibility of results under the short-term impact of abrasive material of various dispersities.

(3) High properties of hardness ad the bulk fraction of the strengthening phase and doping rate of alloys do not serve as criteria that guarantee a high level of wear resistance at higher temperatures. The wear resistance of alloys determined by structure and phase composition, as well as by the thermal stability of the mechanical properties of the matrix and strengthening phase.

NOTATION

F	load on specimen
P	pressure on specimen
v	direction of counterbody rotation
α	skew angle of specimen operation area
b	width of specimen operation area
S	surface area of specimen operation area
ΔV	volume loss of specimens after tests
Δm	weight loss of specimens after tests
ρ	alloy density
H	microhardness
t	time
k	Pearson correlation coefficient
p	confidence probability

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