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ON CAPABILITIES OF THERMOMECHANICAL TREATMENT IN INCREASING DURABILITY OF SHORT SERVICE LIFE ELEMENTS OF MINING AND PROCESSING EQUIPMENT

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Hadfield steel (110G13L) is the basic material for fast wornout items of mining equipment: beaters, hammers, liners, refractory plates of crushers and mills. By way of example, the effect of cold hardening was specifically analyzed on the rate of wear of mining equipment parts for various types of wear by hard (more than 1100 HV) and soft rock. A unique ability of that steel to resist shock wear is noted. It is shown that this steel exhibits low resistance to abrasive rock wear. Meanwhile wear by rock of hardness lower than steel (less than 1100 HV), may be substantially increased by pre-hardening of samples (up to 10-fold).

In case of wear by high hardness rocks, shock impact that should contribute to hardening of the material, fails to increase abrasive wear resistance of Hadfield steel, and in that parameter it does not differ from the conventional medium carbon steel 45. Also, the authors of this article describe a technique they developed of high-temperature thermomechanical treatment of specimen of Hadfield steel (free forging at 1150-950ºC and subsequent quenching in water) and experiments in their abrasion. The results of tests show that hardness and wear resistance of Hadfield steel to hard abrasive (corundum 25A with aggregate hardness of ~2500 HV) increases with plastic deformation at HTMT. For maximum plastic deformation intensity (deformation magnitude of $\alpha = 2.25$), reached in the experiments by the authors, wear resistance grew by 70% as compared to undeformed steel. The dependence is presented of wear resistance of steel on hardness, HV, achieved in the result of plastic deformation. Since a similar positive effect was obtained earlier by the authors for 35HGSA steel, also used in mining machinery, they conclude that the HTMT technique may be recommended for treating short lived parts of the mining and mineral processing equipment to increase their service life.

***Key words*:** Hadfield steel, cold hardening, thermomechanical processing, abrasive wear resistance.

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Currently a substantial part of operational expenses in mining and processing of mineral resources at mining enterprises are expenses on changing and repairing short-lived parts of the equipment and machinery used. Therefore the task of extending their wear resistance is quite topical.

During mining and processing of rock minerals, parts of the equipment and machinery suffering the heaviest wear are those coming in direct contact with rock mass: excavator bucket teeth, caterpillar tracks of road machinery, beaters, hammers, refractory and reflection plates of crushers and rock mills. The material most often used to produce such elements is the austenite high Manganese steel 110G13L (0.9-1.4 C, 11.5-15.0 Mn, 0.5-1.0 Si, % wt), known as Hadfield steel by the name of its inventor. It is unique in its shock wear durability; it has been in use for many decades (actually, for more than 100 years) and so far o equal substitutes have been found for it. Such a behavior of Hadfield steel is explained by high self-hardening (cold hardening) capability of manganese austenite under shock impact, so that it increases its hardness from 200 to 700 HV. During the first years of studying the nature of hardening of that steel it was related to transformation of austenite into martensite along the slipping lines (the martensite theory of Hadfield steel hardening [1]). According to more recent ideas [1, 12] the high durability and hardening of that steel during cold hardening is explained by three main reasons:

- formation of secondary phases (ε-martensite with face-centered close-packed lattice) in austenite displacement planes, which are effective barriers hampering plastic flow;
- kern fragmentation, change of the block structure and emergence of micro-tensions;
- intense formation of packing defects in austenite under foreign impact.

It is assumed [6, 12], that when affected by purely abrasive forcing or abrasive wear with slight shock impacts steel 110G13L manifests low wear resistance, while high specific loads and shock impacts when the metal of surface layer is subjected to intense cold hardening result in exceptionally high abrasive wear resistance of that steel. While that statement (see studies [2, 9],]) is only true for steel worn out by relatively soft rocks (below 1100 HV), e.g. by marble, its hardness remaining lower than

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the hardness of cold hardened steel, such preliminary cold hardening may significantly increase wear resistance of steel material (up to 10-fold). In case rocks of higher hardness are working that steel out, considerable specific loads and shock impacts that promote cold hardening fail to increase abrasive resistance of Hadfield steel, so in that parameter it does not differ from the common medium carbon steel 45 [2, 3, 9, 13, 15, 16].

Lack of effect of cold hardening on abrasive resistance of steel agrees with the general dependence confirmed by many experiments involving different metals and alloys [16] wear resistance of materials that have gained different levels of cold hardening remains practically unchanged during plastic deformation, despite increase in hardness. Such a dependence is explained the following way: in the process of abrasive wear when abrasive particles scratch on the worn metal more cold hardening happens at their interaction points, that hardening being higher than preliminary cold hardening, and, most probably, being the topmost possible for the given material [16]. When Hadfield steel pieces come into friction with rocks of hardness lower than that of steel, metal disintegrates not because of scratching by rock kerns, but because of metal fatigue due to repeated elastic deformation of its surface layer. Since disintegration process during fatigue wear starts with the emergence of fatigue fracture at the surface, cold hardening of that surface makes it possible to slow down the emergence of that fracture, hence increasing the fatigue resistance of the metal, as observed in experiment [2, 9].

Meanwhile it is known [4, 5, 8, 10, 11, 14, 17-20], that one of the most efficient ways of increasing the whole complex of mechanical properties, wear resistance of a wide range of steels being among them expectedly, is their hot plastic deformation with subsequent quenching, i. e. high temperature thermomechanical treatment (HTMT). Data are available in references on applying that treatment technique to steel 110G13L, too.

E.g., study [14] reported on improving physico-mechanical properties and wear resistance of high manganese steel in the result of it hot plastic deformation by forrging and subsequent quenching. It is suggested to do deforming at 950-1200 °C, when steel 110G13L is most malleable, and specimen of that steel produced from such forgings, quenched in water at the temperature of forging end displayed the highest mechanical properties. Such HTMT results in improving both hardness and plasticity of steel. To define wear resistance of that steel, its specimen treated the described way were placed in a rattle drum loaded with steel balls of 40 mm diameter. After continuous operation of such a drum for 100 h specimen were weighted to define their mass wear. Such an experiment demonstrated that as the degree of forging of such specimen increased to reach 3, steel wear resistance increased by 40 % after which it changed only insignificantly.

To see how much the effect achieved in the experiment [4] would hold as resistance to wear typical for operation of the mining processing machinery, we studied the effect of HTMT on the rate of wear of steel 110G13L specimen when they are in friction with abrasive material.

Tests were run following the updated technique [2, 3, 9] at the facility laid out in Fig.1, at spindle RPM of 11,4 s^{-1}. For the abrasive medium 1 (Fig.1) electric corundum 25A was used as a material of aggregate hardness (~2500 HV) well exceeding the hardness of Hadfield steel in its cold hardened state. The butt surface of specimen 2 was subjected to cyclic wear each 3.5 min (7 cycles of 30 s each) at a constant static load, its mass controlled after each cycle. Prior to each new cycle the abrasive disk was shifted against the specimen so that metal came in contact with fresh abrasive surface each time. The loss of mass Δm was determined for each cycle, referenced then to contact area ($S \sim 50$ mm^2) with the abrasive. Prior to the test, specimen hardness, HRC was measured at the butt then reduced to the HV value.

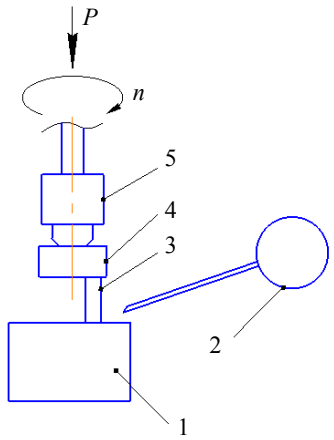


Fig.1. Specimen abrasive wear test facility layout:
1 – abrasive medium disk; 2 – tested specimen; 3 – holder; 4 – spindle, vertical drill; 5 – water feeding device

Test specimen were manufactured as cylinders ($D \sim 8$ mm) freely forged at 1150-950ºC from larger size forgings (12 and 10 mm), which gave the forging factor α for the metal of 2.25 and 1.56, respectively. One part of the specimen was quenched in water at forging temperature, in other words they were sub-

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jected to HTMT. The other part, to relieve the effect of plastic deforming was subjected to ~15 minutes in the kiln at 1150 °C, which was the temperature of quenching in water thus imitating the regime of thermal treatment(RTT) usual for manufacturing elements of steel 110G13L [7].

The dependence of specific mass deterioration in specimen subjected to different treatment modes on the duration of abrasive effect is illustrated by Table 1.

Table 1

Abrasive wear resistance by Hadfield steel specimen, test results

Specimen	Treatment mode	Forging factor α	$\sum\Delta m/S$, mg/mm^2 over time t, min.						
			0.5	1	1.5	2	2.5	3	3.5
1	Quenching at forging temperature	2.25	2.20	3.86	5.62	6.97	8.32	9.60	10.74
2	Quenching at forging temperature	2.25	2.12	3.74	5.08	6.09	7.13	8.12	8.88
3	Quenching at forging temperature	1.56	2.18	3.80	5.36	6.72	8.65	9.97	11.23
4	Quenching at forging temperature	1.56	2.01	3.37	5.05	6.68	7.96	9.12	10.34
5	Heating and exposition at 1150 °C with subsequent quenching	–	2.17	4.06	5.91	7.87	9.66	10.99	12.77
6	Heating and exposition at 1150 °C with subsequent quenching	–	2.09	3.84	5.73	7.28	8.94	10.62	12.10

As indicated by processing of experiment results (Table 1) all the experimental points of the dependences $\sum\Delta m/S = f(t)$ extrapolate satisfactorily as direct lines, their tangents yielding the rates of abrasive wear, K_i of the specimen. Values inverse to K_i were adopted as wear resistance of steel, R_i, deformed in the course of HTMT at a given intensity.

Fig.2 presents graphic dependences of $\sum\Delta m/S = f(t)$ образцов for specimen demonstrating the highest (specimen No. 2 α = 2.25, quenching at forging temperature) and the lowest (specimen No.5, heating and exposition at 1150 °C with subsequent quenching) wear resistance.

Experimentally retrieved wear rates, K_i, their corresponding wear resistance values, R_i and the results of specimen hardness measurements, following the order of growing HV are presented in Table 2. Fig.3 illustrates the dependence of steel wear resistance on hardness achieved in the result of high temperature treatment.

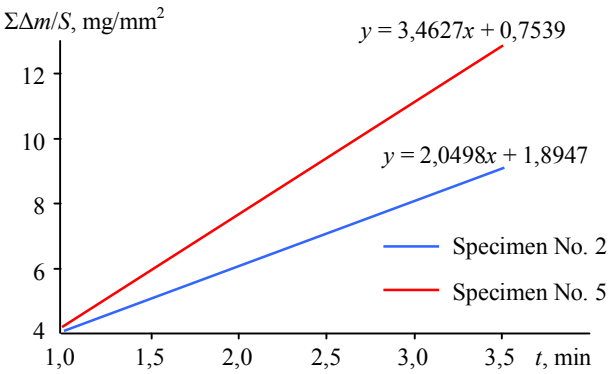


Fig.2. Relative specimen mass loss vs. test duration

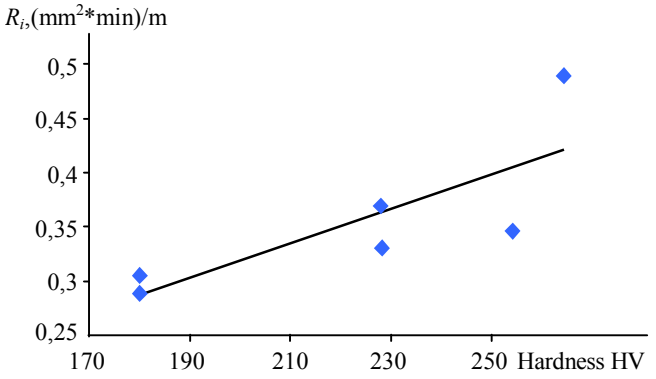


Fig.3. The dependence of wear resistance of steel specimen on their hardness achieved in the course of treatment

Table 2

Wearing characteristics and hardness of Hadfield steel specimen for different treatment modes

Specimen	Specimen treatment mode	α	Hardness, HV	K_i, mg/(mm^2·min)	R_i, (mm^2·min)/mg
5	RTT	–	180	3.46	0.29
6	RTT	–	180	3.29	0.30
3	HTMT	1.56	228	3.02	0.33
1	HTMT	2.25	228	2.72	0.37
4	HTMT	1.56	254	2.88	0.35
2	HTMT	2.25	264	2.05	0.49

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Comparing test results (Table 2, Fig.2) one may see that high temperature deformation of material prior to quenching, same as in friction and shock treatment experiments [16] when specimen were hit by steel balls works to increase hardness and wear resistance of high manganese steel under the conditions of abrasive wear; these increase for higher intensity deformations (forging factors): the specimen deformed with the strongest intensity (specimen No.2 vs. No.5) had these parameters increased by 47 and 70 %, respectively.

The results obtained testify that high temperature thermomechanical treatment is capable to increase significantly abrasive wear resistance of steel 110G13L. Since such a positive effect was obtained for steel 35HGSA [2], as a material also used to manufacture parts of mining machinery too, the very technique of HTMT may be recommended for implementation as part of manufacturing technology for short service life parts of mining and mineral processing equipment to extend their service life.

REFERENCES

1. *Bogachev I.N.*, *Egolaev V.F.* Structure and properties of ferromanganese alloys. Moscow: Metallurgija, 1973, p.296 [in Russian].

2. *Bolobov V.I.*, *Chupin S.A.* The effect of type of strengthening treatment on wear resistance of material for mining machinery. Zapiski Gornogo instituta. 2015. Vol.216, p.44-49 [in Russian].

3. *Bolobov V.I.* Hadfield steel wear resistance at high specific loads. Gornoe oborudovanie i jelektromehanika. 2012. N 10, p.12-14 [in Russian].

4. *Blyukher V.V.*, *Parfenov L.I.*, *Volchok I.P.* Properties of plastically deformed high manganese steel. Metallovedenie i termicheskaya obrabotka metallov. 1970. N 12, p.32-33 [in Russian].

5. *Smirnov M.A.*, *Pyshmintsev I.Yu.*, *Laev K.A.*, *Akhmed'yanov A.M.* Effevt of high temperature thermomechanical treatment on the properties of high chromium steel. Vestnik Yuzhno-Ural'skogo gosudarstvennogo universiteta. Seriya: Metallurgiya. 2012. N 39 (298), p.85-88 [in Russian].

6. *Gulyaev A.P.* Metal Science. Moscow: Metallurgija, 1986, p.544 [in Russian].

7. *Davydov N.G.* High manganese steel. Moscow: Metallurgiya, 1979, p.176 [in Russian].

8. *Zasypkin A.D.*, *Dement'ev V.B.* Hardening of caterpillar machinery track fingers by HTMT screw compression. Traktory i sel'khozmashiny. 2012. N 4, p.37-39 [in Russian].

9. *Bolobov V.I.*, *Batalov A.P.*, *Bochkov V.S.*, *Chupin S.A.* Wear resistance of steel 110G13L in different abrasive media. Zapiski Gornogo instituta. 2014. Vol.209, p.17-22 [in Russian].

10. *Gur'yanov D.A.*, *Tesker E.I.*, *Zamotaev B.N.*, *Rubezhanskaya I.V.* Studying the effects of deformation parameters of meral rolling during repeated HTMT on the mechanical properties of steel. Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta. 2009. Vol.3. N 11, p.134-137 [in Russian].

11. *Zamotaev B.N.*, *Eremin M.P.*, *Chechin S.V.*, *Kandaurov A.S.* Studying the effects of thermal and deformation rolling parameters during repeated HTMT with interim tempering on the mechanical properties of steel. Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta. 2013. Vol.8. N 15, p.96-99 [in Russian].

12. *Lahtin Ju.M.*, *Leont'eva V.P.* Material Science. Moscow: Mashinostroenie, 1990, p.528 [in Russian].

13. *Parfenov P.I.*, *Sorokin G.A.* Structure and wear resistance of steel G13L. Metallovedenie i termicheskaya obrabotka metallov. 1969. N 1, p.67-68 [in Russian].

14. *Smirnov M.A.*, *Pyshmintsev I.Yu.*, *Laev K.A.*, *Khramkov E.V.*, *Alyutin D.M.* Effevt of high temperature thermomechanical treatment on the properties of high chromium steel. Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G.I.Nosova. 2015. N 3 (51), p.78-82 [in Russian].

15. *Tenenbaum M.M.* Wear resistance of parts and longevity of mining machinery. Moscow: Gosgortekhizdat, 1960, p.238 [in Russian].

16. *Khrushchov M.M.*, *Babichev M.A.* Studies of metal wear. Moscow: Izd-vo AN SSSR, 1960, p.351 [in Russian].

17. *Shavrin O.I.*, *Dement'ev V.B.* Experience in applying the HTMT process of screw compression to manufacture axially symmetric parts. Metallovedenie i termicheskaya obrabotka metallov. 2002. N 8, p.27-29 [in Russian].

18. *Barroqueiro B.*, *Dias-De-Oliveira J.*, *Pinho-Da-Cruz J.*, *Andrade-Campos A.* Multiscale analysis of heat treatments in steels: Theory and practice. Finite Elements in Analysis and Design. 2016. Vol.114, p.39-56. DOI: 10.1016/j.finel.2016.02.004

19. *Dobrzański L.A.*, *Czaja M.*, *Borek W.*, *Labisz K. & Tański T.* Influence of hot-working conditions on a structure of X11MnSiAl17-1-3 steel for automotive industry. International Journal of Materials and Product Technology, 2015, N 51(3), p.264-280. DOI:10.1504/IJMPT.2015.072246

20. *Krishna S.C.*, *Tharian K.T.*, *Chakravarthi K.V.A.*, *Jha A.K. & Pant B.* Heat treatment and thermo-mechanical treatment to modify carbide banding in AISI 440C steel: A case study. Metallography, Microstructure, and Analysis, 2016, N 5(2), p.108-115. DOI:10.1007/s13632-016-0266-0

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