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Tribological Properties of High Manganese Austenit Strengthened by Explosion

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Abstract: The plastic explosive Hardex-70, employed during the research work, has caused serious changes in microstructural and functional properties of Hadfield cast steel. A complex investigation has been carried out on this material concerning the mechanism of its strengthening by explosion energy. It has been found that the strengthening of Hadfield cast steel caused by a detonation wave of great energy and velocity is a result of multiple defects of various kinds introduced to the austenitic matrix. Quantitative measurements concerning the occurrence of main types of defects have enabled giving the hierarchical order to their contribution to the strengthening effect. The significant increase, of one or two orders, in density of uniformly distributed dislocations secures about 600-2700% increase in abrasive wear resistance.

Keywords: Hadfield cast steel, strengthening by explosion, tribology

Introduction

The Hadfield cast steel of the traditional composition as developed by the inventor, as well as its numerous subsequent modifications, still find broad applications as materials resistant to wear, corrosion and oxidation; steels for cryogenics and railway engineering; and in nuclear reactors, submarines and railway transport systems using superconductive magnets for generating a "magnetic cushion", where their paramagnetic properties are utilized [1-3]. Nevertheless, the ability of strengthening under natural service conditions still remains the most important feature of this material. The tribological properties of the top layer are determined, by the dynamics and level of working stresses – too low stresses do not guarantee the sufficient strengthening and shorten the service lifetime. An alternative in that case is prestrengthening by means of ageing heat treatment, burnishing mechanical treatment or, less conventionally, by explosive treatment.

According to the literature data and the authors, own research results, pre-strengthening done using explosion energy increases the lifetime of railway turnouts by 30 to 300% [4, 5]. Unfortunately, such effects are not always achieved, what is most likely attributable to the discrepancy between the operational activities (associated with carrying out the explosion) and the required profound knowledge of the microstructural aspects of strengthening. It should also be emphasized that there is none universal model for a structure assuring high wear resistance. However, a definite opinion prevails in the relevant literature that in order to obtain high wear resistance and a long lifetime of elements, a combination of two parameters, often difficult or even impossible to agree, *i.e.* hardness and ductility, is required. Research results show that the pre-hardened Hadfield cast steel exemplarily meets these conditions.

Materials and Methods

The Hadfield cast steel pre-hardened with explosion energy was used in the study. It had the following chemical composition [in wt. %]: 1.31 C, 0.76 Si, 13.6 Mn, 0.07 P, 0.003 S, 0.55 Cr, 0.76 Ni, and 0.036 Al. The test material, were: ~30-mm-thick cast steel plates which, after austenitizing at 1323 K and solutioning in water, hardened with a skew wave created by the single, double or triple detonation, directly on the plate surfaces, of the 2-, 3- or 4- mm-thick Hardex-70 plastic explosive of a detonation velocity of approx. 7200 m s^{-1}, that generated a detonation pressure of approx. 18 GPa during explosion. The adopted designations „1x3 mm", *etc.*, define the number of detonations done on the surface (the first digit) and the thickness of the explosive charge used (the second digit). The lower limit of thickness of the explosive used was determined by the critical diameter of the explosive, whereas the upper limit – by the possibility of occurring too strong thermal effects, damage to the surface, or complete destruction of the element. The thermal conductivity of Hadfield cast steel (12.98 W/mK), being four times lower than that of carbon steels, slows down the processes of equalization of temperature resulting from the dissipation of mechanical energy in the shock wave, which may lead to partial or complete destruction of the strengthening effects.

To minimize the microstructural changes occurring in a mechanical treatment process, all specimens used in the tests were cut out using an electric-spark technique. The thin foils were obtained by way of mechanical pre-thinning followed by electrolytic jet polishing and ion thinning. The microstructural analysis was performed with a Philips EM-301 (100 kV) and a CM20 TWIN (200 kV) transmission electron microscopes. In the X-ray analysis, an XRD 3003TT diffractometer by Seifert was employed, with a Cu lamp of a power of 2000 W, an accelerating voltage of 40 kV, step angle variation by 0.01°, and a counting time of 15 sec. In the nuclear resonance method (using the Mössbauer spectrometer) the emitter of radiation with an energy of 14.4 keV was Co^{57}. With the source velocity $v = \pm 6$ mm s^{-1} and the specimen thickness ~20 μm, the exposure time was 24 hours. For tribological tests, a „roller-block" type tester was used, whose construction allows the measurement of wear and friction according to the ASTM: D 2981 and D 3704-78 standards. The tests were conducted at dry sliding contact, in metal-metal contact conditions, with a constant contact load of 50 N, a rotational speed of 3 rpm, and a roller diameter of 35 mm (roller hardness of ~62 HRC). A measure of wear rate were: losses of the mass of specimens weighted to an accuracy of 0.0001 g after a specified friction time (or path).

Results and Discussion

A feature that distinguishes the strengthening of Hadfield cast steel under explosive treatment conditions is the absence of texture – a structure typical of strongly hardened polycrystalline materials. Deformations, expressed by changes in the thickness of specimens, followed by an almost two-times increase in the hardness of the surface layer (2 to 6 mm deep) were 4 to 9%, depending on the strengthening variant [6]. Thus, the passage of a dynamic detonation wave with as short duration as fractions of a millisecond was accompanied by a very strong disturbance in the grain internal structure.

Substructure components that have undergone the strongest changes in relation to the initial supersaturated state are: dislocation density and distribution, deformation twins, and the disturbance in the sequence of atomic planes arrangement manifesting itself in the presence of numerous stacking faults (Figures 1-4). In cast steel subjected to the action of detonation, two forms of occurring dislocations may be distinguished. The first form are areas of a uniform distribution of dislocations whose density has increased from a level reaching $1x10^9$ disl cm^2 for the supersaturated state by about one to two orders of magnitudes, depending on the explosion variant. The second form is caused by the accumulation of dislocations on active slip planes and results in the occurrence of structure inhomogeneity in the form of dislocation bands with a much greater dislocation density. The determination of dislocation density was carried out by the random secant method on several tens microphotographs with magnifications of 25000X and 5000X, respectively.

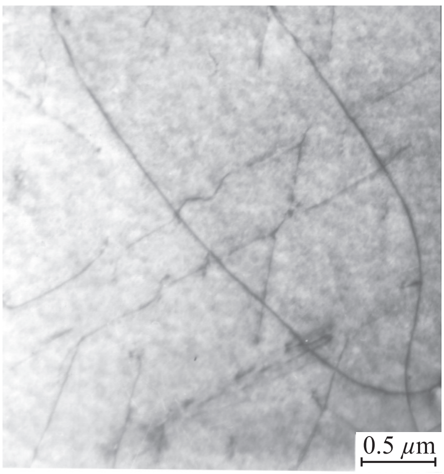

Figure 1. Single dislocations in the structure of a supersaturated state; thin foil.

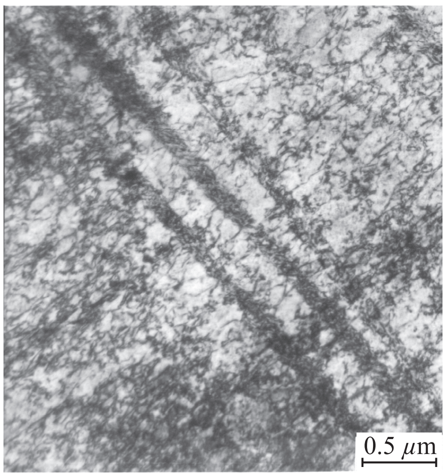

Figure 2. Numerous dislocations and dislocation bands for the "1x3 mm" variant at a distance of 2 mm from the surface; thin foil.

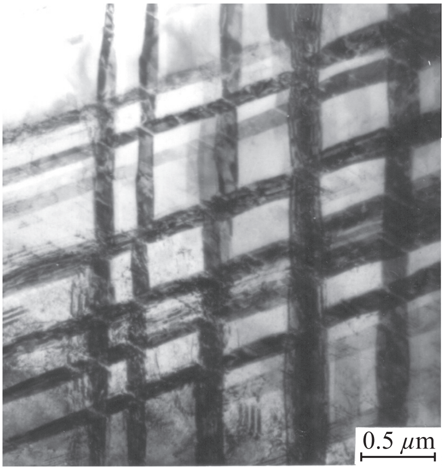

Figure 3. Numerous stacking faults for the "1x3 mm" variant at a distance of 2 mm from the surface; thin foil.

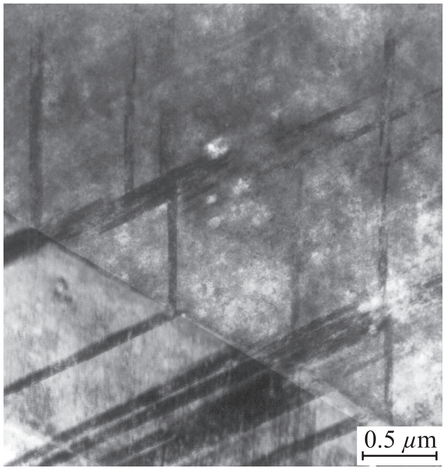

Figure 4. Dislocation structure and twins in the subsurface layer for "2x4 mm" variant; thin foil.

The quantitative SF (Stacking Faults) analysis was carried out based on the assumptions worked out by K. Paterson, B. I. Warren, B. L. Averbach, C. N. Wagner *et al.* [7-9], who have calculated theoretically the effect of SF on X-ray interference in metals with the A1 lattice. The presence of SF in metals with this lattice causes characteristic changes in the angular positions of diffraction reflections, and the magnitude of those displacements is dependent on the SF density and the type of deflecting planes. The X-ray analysis method allows the determination of the SF probability, α, and the twin fault probability, β. The presence of twins (β) generates a symmetry of diffraction peaks, whereas the both faults (α and β) have additionally their contribution to broadening the peaks. Using the peak asymmetry effect resulting from the presence of twins, J. B. Cohen and C. N. Wagner [8] have proposed a method allowing for the effect of shifting the centers of gravity of peaks in relation to diffraction peak maxima. This method does not require a reference specimen, *i.e.* the one that does not contain twin faults, and in addition, as the authors have shown, it minimizes several instrumental errors and the occurrence of doublets or directional deformations. The final relation enabling the determination of the probability β using pairs of the peaks (111) and (200) is described by the following formula:

Table 1. Stacking fault of probability, α, and the twin probability fault, β, in Hadfield cast steel after strengthening treatment operations

Variant	Distance from surface [mm]	2 Q (111)		2 Q (200)		Probability	
		Maximum	Centreof gravity	Maximum	Centreof gravity	b [%]	a [%]
Supersaturated state		43.2082	43.2252	50.2924	50.2822		
"1x2 mm"	Surface	43.2023	43.2120	50.1593	50.1129	-	2.9700
	2	43.1926	43.2043	50.1663	50.1176	-	2.7340
	7	43.2127	43.2263	50.2413	50.1902	-	1.7690
	12	43.2202	43.2289	50.2419	50.2031	-	1.5730
	20	43.2257	43.2293	50.2401	50.2035	-	1.5730
"2x2 mm"	Surface	43.2089	43.2059	50.1756	50.1733	-	1.7030
	2	43.1398	43.1670	50.0997	50.0996	-	2.3680
	7	43.1540	43.1574	50.0492	50.1041	0.4910	2.0998
	12	43.1359	43.1411	50.1115	50.0837	-	2.1790
	20	43.1000	43.1090	50.1605	50.0684	-	1.8590
"1x3 mm"	Surface	43.2243	43.2288	50.1512	50.1003	-	3.5290
	2	43.2467	43.2547	50.1586	50.1098	-	3.8410
	7	43.2339	43.2353	50.1307	50.1068	-	3.5290
	12	43.2315	43.2491	50.1696	50.2089	0.1937	1.8496
	20	43.2176	43.2242	50.1438	50.1637	0.1190	2.2340
"3x3 mm"	Surface	43.2137	43.2204	50.1400	50.1093	-	3.1980
	2	43.2012	43.2117	50.1728	50.1355	-	2.5370
	7	43.2080	43.2248	50.1645	50.1423	-	2.6530
	12	43.2298	43.2312	50.1945	50.1313	-	2.9840
	20	43.2289	43.2355	50.1200	50.1253	-	3.1800
"1x4 mm"	Surface	43.2602	43.2321	50.2322	50.1311	-	3.0050
	2	43.2809	43.2946	50.2543	50.1551	-	3.7340
	7	43.2235	43.2268	50.0933	50.0577	-	4.3050
	12	43.2455	43.2372	50.0940	50.1118	0.2330	3.4690
	20	43.2341	43.2274	50.1083	50.1250	0.2090	3.0320
"2x4 mm"	Surface	43.4722	43.4848	50.4200	50.3784	-	3.0760
	2	43.4140	43.4297	50.3368	50.3154	-	3.2430
	7	43.2340	43.2435	50.2095	50.1734	-	2.4150
	12	43.2187	43.2268	50.1196	50.1409	0.1180	2.7170
	20	43.2017	43.2080	50.2344	50.1970	-	1.2920
"3x4 mm"	Surface	43.2104	43.2238	50.1994	50.1834	-	1.8511
	2	43.2165	43.2163	50.1636	50.1202	-	2.9130
	7	43.2284	43.2473	50.1775	50.0951	-	3.9810
	12	43.2401	43.2382	49.9806	50.0505	0.6430	4.6590
	20	43.2393	43.2333	50.1323	50.0877	-	3.8560

$$\Delta C.G.\left(^\circ 2\Theta\right)_{(111)} - \Delta C.G.\left(^\circ 2\Theta\right)_{(200)} = \left(11tg\Theta_{(111)} + 14.6tg\Theta_{(200)}\right)\beta_3$$

where: ΔC.G.(° 2Θ) – difference between the angular positions of the centres of gravity and the maximum of selected diffraction peaks.

The values of the SF probability α, and of the twin fault probability β, are shown in Table 1.

The percentage share of SF in 7 examined variants of explosive strengthening is in the range from 1.7% to 3.5% in the surface layer and from approx. 2.4% to 3.8% at a depth of 2 mm. In deeper layers, a decrease in SF density occurs for most variants. A different variation of SF concentration occurred in variants hardened using the thickest, 4-millimeter explosive charge. In the „3x4 mm" variant, as compared with the very low SF concentration at the surface, a high increase at SF concentration, *i.e.* by a factor of nearly 3, occurred at a depth of approx. 12 mm. Thus, it can be assumed according to H. Schumann's suggestions [10] that there is a possibility of rebuilding the stacking fault structure to reduce the elastic stresses caused by the presence of stacking faults. The obtained values indicate that in a material that is characterized by the greatest stacking fault density after strengthening every 25-30 (111) plane contains SFs. Although the direct energy action of stacking, faults is small, they make the cross slip difficult and cause the annihilation of dislocation, resulting in an increase in the stored energy. In plastically deformed fcc-lattice metals, the dislocation distribution depends on the intensification of cross slip from the main slip plane (111), onto the coupled plane $(1\bar{1}1)$. The condition for occurring cross slip is, however, a prior recombination of the dissociated partial dislocations $\frac{a}{6} < 112 >$ into complete dislocations. Numerous electron diffraction patterns and X-ray examination results that do not confirm the presence of the hexagonal phase allow one to presume that the size of SFs occurring after explosion does not provide grounds for them to be recognized as the phase ε, therefore they should be regarded as typical stacking faults in the mechanism of explosive strengthening of Hadfield cast steel.

The concentration of twins revealed during thin foil observation, to which a significant contribution to the strengthening of Hadfield cast steel is ascribed in a considerable part of studies [11-13] shows that the contribution of twins to strengthening in explosive strengthening conditions is only complementary, and the determined values did not exceed 0.6%. In spite of the generally small twin concentration in the cast steel being hardened, they are elements stabilizing the formed substructure due to the high coherence of twin boundaries. The twin shear of the structure containing dislocations leads also to a change in the length, orientation and mobility of dislocations – which has been demonstrated by some authors, including M. Szczerba [14], using the correspondence matrix method – causing their conversion into settled dislocations.

The evaluation of the structural changes occurring during explosion was carried out by the nuclear resonance method – the Mössbauer spectroscopy. The character of the spectra – the absence of the traces of the sextet typical of the ferrite α - indicates that the explosive treatment does not lead to phase transformations, and the only phase occurring in the structure is the paramagnetic phase. Employing the least squares method, the curves were subjected to mathematical analysis, and the best fit of experimental spectra was obtained after decomposing the spectra into one Lorentz singlet and two quadruple doublets. The parameters of those fits are summarized in Table 2.

Table 2. Parameters of the fits of Mössbauer spectra

Parameters		State of material		
		Supersaturated	"1x3 mm"	"3x3 mm"
Isomeric ShiftIS [mm s^{-1}]	L_1	-0.0549	-0.0536	-0.0539
	Q_1	-0.0181	-0.0119	-0.0103
	Q_2	-0.0141	-0.0063	-0.0065
IntensityI	L_1	0.2078	0.1926	0.1796
	Q_1	0.0954	0.0795	0.0659
	Q_2	0.0542	0.0423	0.0509
Quadruple SplitEQ	L_1	-	-	-
	Q_1	0.7019	0.7104	0.7181
	Q_2	0.4227	0.4592	0.4714
Relative AreaA	L_1	0.5814	0.6126	0.6061
	Q_1	0.2669	0.2528	0.2223
	Q_2	0.1517	0.1346	0.1716
Line Width W [mm s^{-1}]	L_1	0.4550	0.4397	0.4139
	Q_1	0.2670	0.2542	0.2428
	Q_2	0.3021	0.2664	0.2812

Despite the apparent absence of differences in the shape of the spectra shown, the analysis of the mathematical fits yields some interesting information. The singlet L corresponds to those Fe atoms that do not have a carbon atom in the first coordination zone. The 13% increase in the corresponding value of the quadrupole Q_2 observed for the „3x3 mm" variant indicates an increase of the number of iron atoms with one C atom in the first coordination zone, which causes a broadening of the range of action of C atoms in the austenite. The strengthening action of carbon atoms has been shown analytically by W. S. Owen and M. Gujicic in their work published in 1998 [15]. Employing a quasi-chemical model for the calculation of the Helmholtz energy in the conditions of changing number and distribution of the atomic pairs of the closest neighbours in the Fe-Mn-C solution, they have found an increase in the exchange energy of the Fe-Mn-C system in relation to the Fe-Mn system. Also, the change in the internal energy of the Fe-C pair is much greater than that of the Mn-C pair. Thus, assuming the Shockley model of dislocation movement, the internal energy increase caused by the presence of C atoms hampers the displacement of the vector b_1 of the dissociated dislocation b, whereas the vector b_2, when reestablishing the position consistent with the direction [110], does not restore the previous position of metal-carbon atoms. In the Hadfield cast steel subjected to triple explosion, besides the dynamic aid of carbon diffusion by the detonation wave, the intensification of carbon atom displacements may suggest a thermal action of the explosive strengthening treatment. The value of thermal conductivity, being almost four times lower than that of carbon steel, may lead to a local temperature increase which, by activating carbon diffusion, will promote the formation of „Cottrell atmospheres" around dislocations. Decreasing width of the „W" line of the Mössbauer spectrum suggests an increase in atom ordering in relation to the supersaturated state, and a decrease in deviations from the ideal lattice.

The tribological test results shown in Figure 6 indicate a significant, relative to the supersaturated state, increase in the wear resistance of the cast steel subjected to explosive treatment. For seven variants examined, wear resistance has increased by 6 to 27 times. The respective 7- and 27-times increases of wear resistance for the „1x3 mm" and „3x3 mm" variants cannot be, however, explained by approx. 15% increases in hardness that are reported in work [6]. This indicates that the tribological properties of alloys are often governed by factors difficult to determine quantitatively. A relationship of the wear resistance increment versus the dislocation density, interesting from both cognitive and utilitarian point of view, is shown in Figure 7.

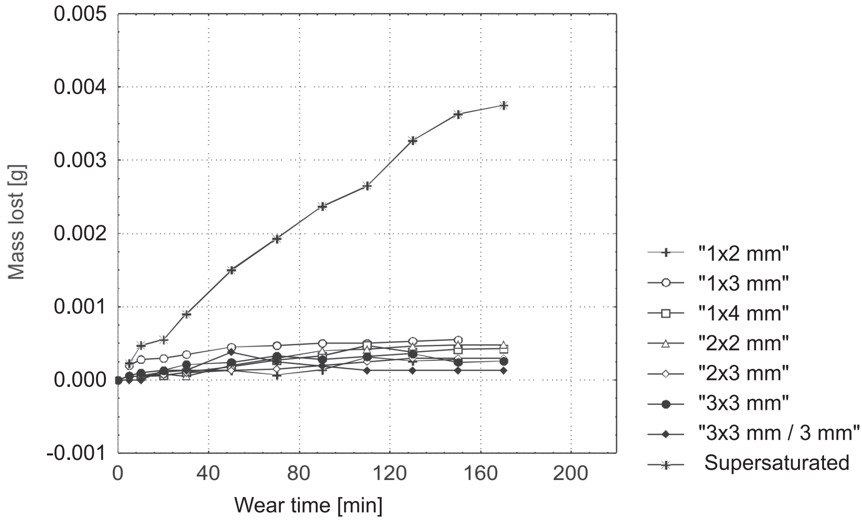

Figure 6. Results of the wear test performed after different strengthening treatment operations.

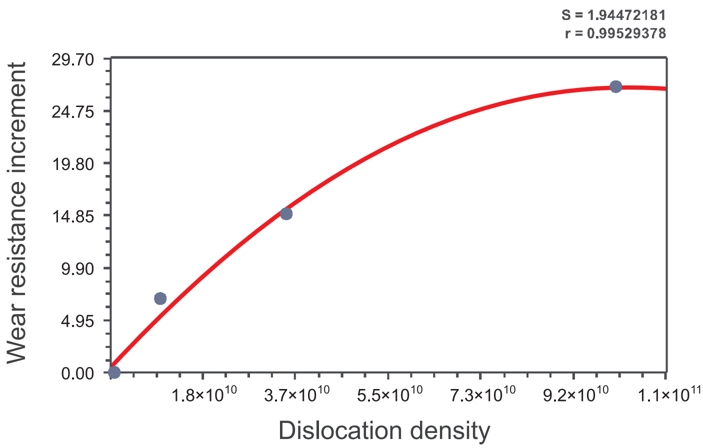

Figure 7. Wear resistance increment as a function of the dislocation density.

Summary

The results of thin foil microstructural examination and electron and X-ray diffraction definitely indicate that the strengthening of Hadfield cast steel subjected to explosive treatment is the result of a strong defecting of the austenitic matrix rather than phase transformations leading to the formation of the martensite α or the hexagonal phase ε. Rising state develops about 6-27 time growth of wear resistance in comparison to the supersaturated beginning state.

The characteristic dislocation structure occurring in the explosive-hardened cast steel results, to a considerable extent, from the low level of the stacking fault energy, whose value is reported in the literature to be in the range 10-50 mJ m^{-2}. So small SFE is chiefly associated with the Mn content, and determines a specific behavior of the material during plastic deformation, leading to the formation of a uniform dislocation structure with the absence of a cellular structure and easy formation of micro-twins. In contrast to fcc structures with their typical dislocation-free areas between dislocation bands, the dislocation density in those areas is very large in Hadfield cast steel. The strongly extended reciprocal lattice nodes suggest a considerable deformation of the matrix; however, it should be noted based on the theory of dislocation, that the occurred defected structure with a dislocation density reaching to $1x10^{11}$ disl. cm^{-2} is lower by two orders of magnitudes than the critical values at which cracking of the material results. The formed state assures obtaining excellent tribological properties, while guaranteeing good plasticity at the same time, which is proved by the absence of cracks during detonation strengthening.

The low SFE promotes also the dissociation of dislocations and the formation of numerous stacking faults, whose strong dissipation caused by the millisecond detonation duration warrants regarding them by the author as typical SFs, and not the ε phase. For the assumption has been made that occurred SFs, in the light of the theory of dislocation, play the role of strengthening elements, rather than a second phase typical of, for example, the „double-phase" mechanism. However, in other strengthening variants, such as service strengthening, the phenomena of SF ordering leading to the formation of measurable quantities of the ε phase should be excluded.

The use of thin-layered explosives of a very high detonation velocity protects the strengthening treatment against the occurrence of adverse phenomena, such as temperature increase, causing relaxation phenomena and reducing strengthening effectiveness.

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