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INCREASING THE EROSIVE WEAR RESISTANCE OF SELECTED IRON ALLOYS BY MECHANICAL STRAIN HARDENING OF STRUCTURE

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Summary. The article presented here describes the initial stage of studies on the hardening potential of some selected iron alloys under the effect of internal stresses. Tests were conducted on these alloys when subjected to compressive and tensile stresses. It has been proved that tensile stresses do not cause hardening of alloy; this effect is due to the presence of compressive stresses, though their effect on the degree of work hardening may differ considerably. Investigations were also made on the erosive wear rate, regarded as a factor inducing very complex surface phenomena in castings on performance.

Keywords: iron alloys, strain hardening, wear, erosion

INTRODUCTION

Strain hardening is a phenomenon which occurs during cold plastic deformation of the processed material. It involves the continuous increase of deformation resistance. Therefore, to obtain higher deformation, the value of the deformation forces must be raised accordingly. Then the processed material undergoes hardening and decrease of its plastic properties. Many materials that are plastic by nature, under the influence of strain hardening may completely lose this property. The effect of strain hardening increases with the deformation rate. Increasing the temperature reduces the effect of strain hardening, because higher mobility of atoms facilitates "slides" and "jumps" in the atomic structure and thus reduces the possibility of the formation of dislocations. An important role in the strain hardening of materials is played by, along with dislocations, other lattice faults. Their mutual relations consist in an interaction of the stress fields. For example, the interstitial dopant atoms are attracted to the edge dislocations, and as a result of this effect the so called Cottrell atmosphere, i.e. clusters of atoms of the impurities inhibiting the movement of dislocations, is formed. Dislocations are also blocked by grain boundaries, particles of foreign phases, or other dislocations.

RESEARCH MATERIAL

As mentioned above, strain hardening is the phenomenon that occurs during cold plastic deformation of the processed material. Among the cast iron alloys, this phenomenon is mainly observed in materials with the austenitic structure. In these alloys, the strain hardening mechanism may consist, on the one hand, in blocking the movement of dislocations, especially in the presence of micro-and nanoprecipitates (e.g. nitrogen compounds) and, on the other - in initiating, under the effect of external stress, the transformation of austenite into martensite. Such alloys are, for example, cast high-manganese steels, cast chromium-nickel steels, and austempered ductile iron.

The following alloys were selected for the studies: cast Cr-Ni-Mo steel with low nitrogen content (less than 0.2%) and with high nitrogen content (about 0.4%), cast high-manganese steel and austempered ductile iron, for which a reference material was the same cast iron but without heat treatment. The chemical composition and designations of the cast alloys are compared in Table 1.

Table 1. The results of melt chemical analysis

Alloy	Chemical composition; %											
	C	Si	Mn	P	S	Cr	Ni	Mo	V	N	Mg	Cu
A	1,20	0,30	13,0	0,040	0,005	0,75	0,20		3,2	0,04		
B	0,19	0,68	5,0	0,025	0,015	24,3	5,40	3,35	1,10	0,39		
C	0,16	0,87	5,0	0,025	0,015	24,9	4,80	3,35	0,95	0,19		
D and E	3,40	2,10	0,34	0,03	0,01		1,80			0,04	0,07	1,00

MECHANICAL TESTS

Typical tensile test was performed for alloys designated with symbols A, B, C, D and E. The test was conducted on specimens pre-stressed with a force equal to 0.8 $\mathbf{F}_m$ for individual non-pre-stressed alloys.

Hardness was measured by Rockwell technique on heads of the specimens designed for mechanical tests: directly and in indentations formed by prior measurements of Brinell hardness.

Measurements were also made by Rockwell method on cross-sections of the working parts of the mechanical specimens: not subjected to external stress, and subjected to compressive stress with a force of $-\mathbf{F}_m$ value and to tensile stress with a force of $+\mathbf{F}_m$ value.

STRUCTURE EXAMINATIONS

Using a FERRIKOMP device and a magnetic technique, the content of ferromagnetic phases was measured in the specimens. The measurements were taken in the material non-pre-stressed, and then on specimens subjected to cold work with a breaking force $\mathbf{F}_m$ applied in static tensile test and with a force $\mathbf{F}$ equal to 0.8 value of the force $\mathbf{F}_m$. Tests were also carried out on specimens fractured after the preliminary application of force $\mathbf{F} = 0.8\ \mathbf{F}_m$, withdrawn after 1 minute.

Microstructure was examined under a Neophot 32 optical microscope. Colour etching technique and differential contrast were applied.

Metallographic examinations were carried out on alloys not loaded with external stress and on alloys subjected to tensile stress until specimen failure.

EROSION TESTS

Erosion tests were performed using a device of the authors' own design, which enables simultaneous testing of 27 specimens.

The erosive media successively used included water-based silica sand slurry, copper slag grit, and coal dust. Erosive wear tests were carried out each time for 40 hours (total of 120 hours). Specimens of all alloys were tested simultaneously, due to which the same experimental conditions were created and the possibility of a comparative assessment of different alloy types. As a measure of erosion resistance of various alloys, the wear rate Z/h [mg/h] was adopted, specifying the weight loss per unit time.

Tests were carried out on specimens not pre-stressed and pre-stressed with a force equal to 0.8 $\mathbf{F}_{\mathbf{m}}$. The technique of pre-stressing and the magnitude of the applied stress were discussed earlier.

Summing up the results of erosive wear in three types of abrasive media, the wear rate of the specimens of the examined alloys was determined in different and changing abrasive environments.

ANALYSIS OF RESULTS

Static tensile test at room temperature, carried out on specimens not subjected to external stress and on specimens pre-stressed with a tensile force equal to 0.8 $\mathbf{F}_{\mathbf{m}}$ gave no evidence in any of the investigated alloys of the visible effect of hardening.

On the other hand, the effect of hardening was observed in the examined alloys after the application of initial compressive stress due to a pressure exerted by a 10 mm dia. ball acting with a force of about 30 kN.

For the examined alloys, this effect is graphically shown in Figure 1.

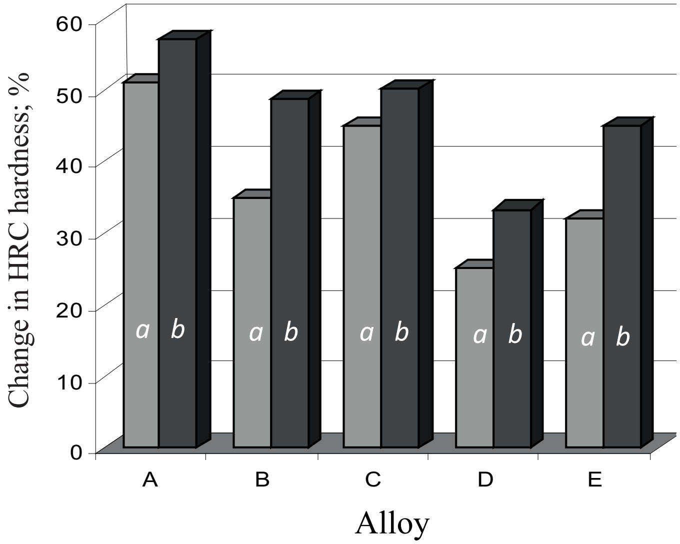

Fig. 1. Effect of compressive stress on the strain hardening of the tested alloys
a - without pre-stressing
b - in HB indentations

Rockwell hardness measurements were also used as another method for the evaluation of hardening effect in the investigated alloys. The effect of hardening was evaluated in the 8 mm dia. specimens subjected to both tensile stress acting with a force equal to + $\mathbf{F_m}$, and compressive stress acting with a force equal to -$\mathbf{F_m}$. The results of this hardening were quantified and shown graphically in Figure 2.

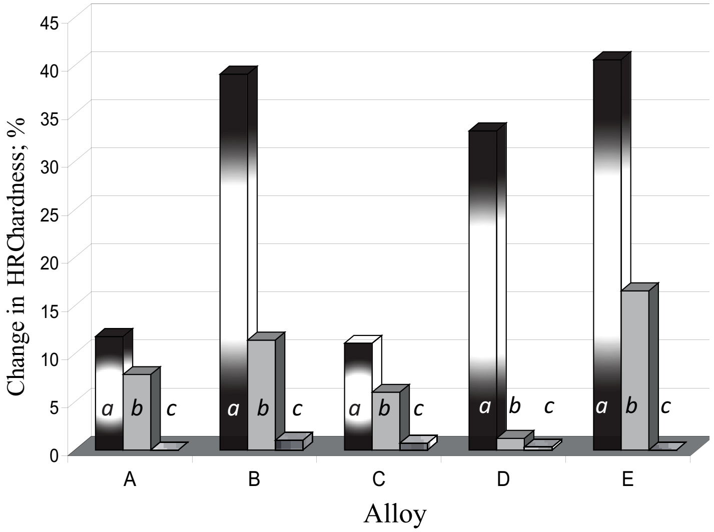

Fig. 2. Relative increase in HRC hardness in the tested alloys
a - in HB indentations
b - after application of **-Fm** compressive force
c - after application of **+Fm** tensile force

One of the hardening mechanisms can be the γ → α transformation under the influence of external stress. Paramagnetic austenite is then transformed into ferromagnetic martensite.

In the examined alloys, the main ferromagnetic phases are ferrite, martensite, and cementite (both free and combined in pearlite). The paramagnetic phases mainly include austenite and graphite (in cast iron), occupying a small volume, especially when in the form of spheroids.

The measurements of the volume content of ferromagnetic phases showed that under the influence of external tensile stress in cast high-manganese steels and ductile iron (without austenite), the γ → α transformation did not occur. To some extent it did occur in the cast Cr-Ni-Mo steel with high nitrogen content (0.4%) and in austempered ductile iron (ADI). This effect occurred but only under loading with a force equal to 0.8 F_m; at higher loads it occurred no longer.

A pronounced effect of γ → α transformation under the influence of external stress was observed in cast Cr-Ni-Mo steel with low nitrogen content (0.2%). This effect, depending on the magnitude and method of application of tensile stress, caused an increase in the amount of ferromagnetic phases in this alloy from 24% to 30% or 36%, sometimes even up to 43%, i.e. by nearly 20%. This fact has been confirmed by metallographic observations.

7. CONCLUSIONS

The lack of the hardening effect observed in specimens subjected to pre-stressing with the external tensile stress acting with a force equal to **0.8** $\mathbf{F_m}$ may result from the fact that the load relief for a short period of time does not lead to the aging process after cold work. This phenomenon is of a diffusive nature. To disperse Cottrell atmosphere grouped around the dislocations it is necessary to relieve the load for a period of a few months at ambient temperature or preheat the specimens to temperatures above 400°C.

The hardening effect observed with the application of compressive stress can be caused by a number of factors, including:

- a much higher deformation rate in the case of compression (up to 3 kN/s) compared with tension (0.5 kN/s) strongly favours hardening,
- specimen fracture along the grain boundaries during the tensile test releases the accumulated dislocations, resulting in relaxation of material,
- due to significant compressive stress, the intermolecular distances are reduced, which increases the cohesive forces resulting in alloy hardening.

Measurements of the amount of ferromagnetic phases in alloys before and after cold work and metallographic examinations of these alloys have shown that the $\gamma \rightarrow \alpha$ transformation occurring under the influence of external tensile stress was distinctly observed to take place only in the cast Cr-Ni-Mo steel with the addition of about 0.2% nitrogen. In other alloys (cast high-manganese steel, cast Cr-Ni-Mo steel with about 0.4% nitrogen, ADI) austenite was stable enough to practically prevent the occurrence of the transformation. In all these cases, the austenite stabilising factor was the high content of either carbon or nitrogen; in the case of ductile iron without heat treatment, austenite did not occur in the as-cast state, thus preventing the occurrence of the $\gamma \rightarrow \alpha$ transformation under these conditions (cold work at room temperature).

Comparing these results with the hardness measurements leads to a conclusion that hardening of the examined alloys under the effect of pressure did not result from the transformation of austenite into martensite, but rather generally from transformation into the α phase. The hardening was definitely stronger in a Cr-Ni-Mo steel with 0.4% nitrogen and ADI than it was in the, undergoing this transformation, cast Cr-Ni-Mo steel with 0.2% nitrogen. The reason for the observed hardening effect may therefore be the formation and concentration of dislocations at grain boundaries and on micro-and nanoparticle precipitates. The mechanism of such hardening was proposed by Orowan.

During erosive wear, the material is exposed to continuous pressure exerted by small particles of abrasive media. This pressure causes the formation of local internal stress in the examined material. In the crumple zone, cyclically variable stresses of different nature are operating. The surface microareas of the substrate are exposed to compression, stretching, bending, shear, etc. This, practically impossible to grasp, variability of stresses makes outer layers of the substrate, attacked by the particles of abrasive medium, undergo fatigue wear and tear off from the surface uncovering the successive layers.

Thus, the alloy tendency to hardening under the effect of external stress should be characteristic of its increasing resistance to erosive wear. Studies of the wear rate may, therefore, serve as a tool for validation of the results obtained by other laboratory tests.

A comparison of the erosion wear rate in corresponding specimens (prestressed with tensile stress or not) showed that pre-stressing of specimens with a force of 0.8 $\mathbf{F_m}$ increased in a significant way the resistance to erosive wear only in alloy B (cast Cr-Ni-Mo steel with an addition of 0, 4% nitrogen). In the case of other examined alloys, the application of this cold work did not give positive results.

The results obtained show high complexity of the hardening phenomena. The, occurring as a result of external stress, transformation of γFe into α Fe, as well as the increase in alloy hardness due to the formation of dense dislocations during cold work need not be the factors leading to an increased resistance to erosive wear. Equally important factors are: the quantitative content of different phases in the matrix (resistant austenite, non-resistant ferrite), their morphology, or the presence of possible precipitates (graphite, carbides, nitrides, intermetallic phases, etc.). These factors change the run of the process of the loss of coherence in material subjected to the effect of destructive loads.

Higher resistance to erosive wear observed in cast Cr-Ni-Mo steel with 0.4% nitrogen (35HRC) subjected to preliminary cold work, compared with the same cast steel but with a nitrogen content of about 0.2% (45 HRC), can prove that it is nitrogen that plays here the decisive role. On the one hand, nitride precipitates are formed inhibiting the dislocation movement and acting as a source of dislocation loops (Orowan mechanism), while - on the other - the presence of nitrogen as such increases the impact of Cottrell atmosphere on the movement of dislocations.

The, observed in the case of cast Cr-Ni-Mo steel with 0.2% nitrogen (alloy C), increased erosion wear rate in some abrasive media of the specimens after prestressing indicates that the γ → α transformation occurring under the effect of pressure (the content of paramagnetic phases reduced from 76% to even 57%) need not be the transformation of austenite into martensite, as confirmed by metallographic observations.

The results of the executed studies, although marking only a preliminary step in the research, have already undergone the first practical trials. A series of the pilot castings operating as parts of agricultural machines working in soil have been produced. They successfully passed the stage of performance tests and, at present, their production is being launched in cooperation with PIMR Poznan within the framework of a Structural Project (SPO_WKP; Action 1.4.1).

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ZWIĘKSZENIE ODPORNOŚCI WYBRANYCH STOPÓW ŻELAZA NA ZUŻYCIE EROZYJNE POPRZEZ MECHANICZNE ODKSZTAŁCENIA STRUKTURY

Streszczenie. Artykuł opisuje początkowy etap badań na temat możliwości hartowania wybranych stopów żelaza pod wpływem naprężeń wewnętrznych. Przeprowadzono badania tych stopów w warunkach ściskania i rozciągania i udowodniono, że naprężenia rozciągające nie powodują stwardnienia stopu; na efekt ten wpływa obecność naprężeń, choć ich wpływ na stopień umocnienia może się znacznie różnić. Zbadano również tempo zużycia erozyjnego, traktowane jako czynnik indukujący bardzo złożone zjawiska powierzchniowe w powstających odlewach.

Słowa kluczowe: stopy żelaza, odkształcenia, ścieranie, erozja