

Investigating the Effect of Carbide Disperse Particles on Hardness and Wear Resistance of Experimental Materials in Cast and Deformed Conditions

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Abstract

Over the last decades the investigations have been actively under way to develop the methods, aimed at increasing the strength characteristics of metals. To increase the strength indicators it is most practicable to apply the metal processing technologies, focused on refining the grain structure. However, now the industry employs the processes, by applying which metals form clearly expressed coarse-grain structure, for example, casting. The fact that the casting manufacturing technologies are widely spread is related to their low cost of production. The cast items, in most cases possess coarse-crystalline structure, which affects negatively the chemical and the physical/mechanical characteristics of materials. Refining the coarse-grain structure represents a difficult (from the view point of technology and economic effectiveness) technical task. One of the most prospective approaches to refining the material grain structure is the way of grinding it at the stage of solidification upon melting. This can be achieved by introducing the additional particles in the molten pool, which perform the function of "micro-coolers" (crystallizing centers); they, merely by their presence, make obstacles for the movement of grain boundaries during crystallization. One more prospective method for structure refining is that of hot plastic deformation, when the structure is refined mechanically.

The article gives an account of the process and of the results of the experiments to obtain castings with refined structure due to introducing the disperse particles in the melt at the casting stage. Part of the obtained castings underwent hot plastic deformation. While investigating the obtained materials the alteration of the microstructure in the castings has been estimated depending on the amount of introduced particles, and also the investigations on hardness and wear resistance alteration were undertaken both in cast and in deformed conditions.

Keywords: Disperse and Dispersive Hardening, Grain Refinement, Metal Hardness, Microstructure, Molded Pieces, Plastic Deformation by Forging, Strength, Wear-Resistance

1. Introduction

At this stage of technical and technological development the technical progress cannot be realized without creating new materials and technological processes. These materials should possess the chemical, physical, mechanical and operational characteristics to such high a degree which would enable withstanding the extreme loads in, for example, mining operations in the Arctic region or, under the conditions of the open space. The methods of improving the operational characteristics are

quite numerous: thermal and thermal and mechanical surface processing, chemical and thermal metal processing, ultrasonic and electrochemical metal hardening, methods of laser, electron-beam, plasma and detonation hardening of machinery details. 1-6 All those methods and their modifications have their advantages and disadvantages. However, when the disadvantages, intrinsic for those methods are analyzed, the only two common ones will be as follows: 1) to implement them quite complex and expensive equipment is required; 2) extra processing increases the cost of the produced item.

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Thus, the most preferable ways to improve the operational characteristics of the materials are those enabling achieving high mechanical characteristics at the stage of melting and casting. Traditionally, improving the mechanical characteristics at melting is achieved by introducing the alloying elements (chromium, nickel, molybdenum etc.); however, one of the main drawbacks to those elements is their high cost, moreover their deposits are limited and are of irreplaceable nature. Therefore, one of the most practicable methods to improve operational characteristics is the method of refining the metal structure at the stage of casting and solidifying or as a result of the ensuing plastic transformations.

For measuring the structure dimensions a term “grain size” is applied all over the world. This parameter depends on the amount of crystallization centers (“micro-coolers”) and on such parameter as the velocity of crystallites growth. Increasing the number of crystallization centers will inevitably result in grain refining. The size of crystallites, formed under crystallization, depends on the amount of arbitrarily generated crystallization centers and on the concentration of hardly soluble and insoluble admixtures (compounds) present in the melt. Those compounds represent the already generated crystallization centers. They could be oxides, carbides, nitrides, sulfides, complex compounds. To ensure that the particle could become a crystallization center, its size should be comparable with the atomic structure of the basic melt. In the crystal grid structure and parameters the particle should be similar to the structure and the parameters of the grid of the metal which is being crystallized. The amount of crystallization centers affects directly the grain size of the crystallized metal: the more accomplished centers are there, the finer is the grain grade of the crystallized metal.

One more factor effecting the crystallization centers formation is the velocity of cooling. The dependence of grain grade on the velocity of cooling is the same as grain grade dependence on the number of crystallization centers: the faster the cooling, the finer the grain of metal.

To obtain the fine grain the artificial crystallization centers (called modifiers) are introduced in the melt. These modifiers, when interacting with the melt, generate the high-melting compounds (carbides, oxides, nitrides).⁷ The major advantage of the introduced modifiers is their large amount per volume unit, which predetermines the degree of the materials crystal structure refinement. The production cost of disperse particles within the industry is becoming lower from year to year in direct proportion

to the industrial demand. This circumstance is bases for improving the economic efficiency of material hardening process, applying the fine disperse particles. For the tasks related to ensuring the high constructive strength characteristics of the high-duty units, the discussed technology of introducing the particles is economically viable even under conditions of today. Thus, the problem of material hardening in casting processes is urgent and possesses both scientific and application-oriented significance.

Two methods of obtaining the disperse particles within the material structure could be identified: dispersive and disperse hardening.

Dispersive hardening is hardening the metal or the alloy, by means of separating the non-metal micron size phases, which impede the dislocation movements under high temperature⁸. According to Mott and Nabarro⁹, such mechanism of hardening could be explained by the effect of internal stresses, occurring as a result of introducing into the crystal grid either solved atoms or the particles of another phase. This mechanism is most effective, when the hardening particles are capable of solving in the hard crystal grid, or of being separated and preserved in dispersed condition under heating and cooling modes. As an example, cementite may be considered, which is solved in the hard solution easily, however, it is impossible to preserve the isolated cementite in fine dispersed form, because it coagulates actively under annealing temperatures. According to this mechanism, such phases in steel as Fe₃C, ZrN, TiN and some others, do not produce effective disperse hardening. Effective disperse hardening can only be caused by the phases, which solve in austenite relatively easily and are isolated at ageing as particles (VN; WC; V(C, N) etc.).

This type of hardening results in considerable improvement of steels and alloys characteristics: their strength characteristics become much better. Disperse hardening affords regulating a sufficiently large range of hardness, plasticity and viscosity of steel, creating the required combinations of these characteristics. For instance, if the contents of vanadium and carbon in steel are increased, then, upon some thermal processing, it becomes possible to increase the yield point from 200-300 MPa to 1200-1500 MPa (that is 5-6 times), at this preserving the plasticity of austenite steel at a high level (for example, the value of relative elongation could be preserved at the level of below 10-20%)^{10,11}.

Notwithstanding all the advantages of this method it has some disadvantages as well:

Thermodynamic instability of the isolated disperse particles, as a result of their being cut many times by dislocations, as a consequence of which the particles solve in the matrix at temperature increase; and generation of zones with lesser mechanical characteristics, which deteriorates the overall hardness of an alloy;

Isolated particles, large in size, are predominantly located at the borders of the grains; they depreciate the hardness of metal, because they facilitate cracks propagation in between the grains, the interaction of which is made weaker by these particles;

Quick softening under temperatures of (0.6-0.7) of the melting temperature due to the fact that coagulation of the phases starts and their solving takes place either in full or partially, depending on time;

Quick softening under temperatures of 0.4 of the melting temperature due to re-crystallization processes, setback and polygonization processes (for the material which is hardened by deformation);

No possibility to forecast and control the distribution of the generated disperse phases, no guaranty that they will be evenly distributed over the volume of the obtained material.

Thus, the most rational approach seems to be the one of creating the materials possessing stable disperse phases which do not interact or hardly interact with the matrix.

Disperse-hardened materials are the metals or alloys, in the structure of which the disperse particles of high-melting compounds were introduced, the later being insoluble (or partially soluble) and non-coagulating in the material under high operational temperatures. The finer the particles of the filling compounds and the less the distance between them, the harder the composite material is. These disperse particles build resistance to the dislocations movement under load, which makes their plastic deformation difficult, but makes the material harder at the same time. Achieving the high degree of hardness is possible when the disperse particles are distributed evenly in the matrix, or, when the distribution of particles can be forecast for the areas, where they are required^{7,12}.

Disperse-hardened materials are considerably different from the age-hardening alloys used in mechanical engineering, both regarding the structure and the methods of manufacturing. The most important difference is that the dispersive hardening is achieved due to isolating the particles from supersaturated solution, but the disperse hardening is achieved by means of introducing the particles in the material at the stage of melting,

processing or casting. The investigations show that introducing different disperse particles (oxides with high energy value of their formation BeO, CaO, TiO, Al₂O₃, ZrB₂, etc.; insoluble high-melting metals W, Mo, Nb, Ti; high-melting carbides WC, TiC, VC, NbC etc.) and their dispersed phases has a considerable effect on decreasing the heterogeneity of macro- and microstructure, on decreasing chemical and physical heterogeneity, as well as on the physical and mechanical characteristics of steel and alloys^{13,14}.

In principle, three methods of introducing the disperse particles in solidifying melt could be identified:

Introducing the disperse phases in the stream of metal while casting steel top-down into the mold¹⁵; Introducing palletized disperse phases into the melting unit in centrifugal electric slag casting¹⁶; Introducing disperse phases in the tundish or in the solidifying mold of the continuously casting machine¹⁷.

All these methods have one peculiar feature: it is impossible to control the process of distributing the introduced particles throughout the volume of the manufactured units, and this means, that it is impossible to forecast the mechanical characteristics of the obtained material.

2. Concept Headings

In this study for obtaining the hardened material with refined structure the authors apply the method of introducing the disperse particles at centrifugal casting machine. With this method of introduction there appears a possibility to control the distribution of the introduced particles across the section, using the difference of densities of the introduced particles and of the material that is being hardened, as well as the centrifugal forces, affecting the introduced particles¹⁸⁻²⁰. Upon obtaining the experimental samples, a part of them underwent hot plastic deformation by forging.

The purpose of this study is to investigate the alteration of the grain grade of the microstructure of the experimental materials and to estimate the alteration of mechanical characteristics (wear-resistance and hardness) in both cast and deformed state.

As the charging materials for the experiments the soft iron of steel grade 10880 was used. The chemical analysis is shown in Table 1.

Melting of the charge materials was implemented in the melting furnace SELT-001-40/12-T, at the generator

maximum capacity operation. As the charged materials melted, the remaining charge materials were added.

Upon melting, before casting the metal was deoxidized with Al, and then it was charged into the centrifugal casting machine. While casting to obtain experimental samples No. 2 and 3 of samples 2, 3, 4 in the stream of the molten metal the dispersed particles were fed (Table 2). When obtaining the samples, before casting C and FeTi were fed on the surface of metal to ensure wettability of the introduced particles and to secure their interaction with metal.

The obtained samples underwent cutting to perform the investigation on the microstructure grain grade alteration, as well as on hardness and wear-resistance. For cutting the samples from the experimental material according to the developed schemes, the Ergonomic 320.250 DGH contour band saw and the Delta Abrasimet abrasive cutoff machine tools were used, those capable of cutting the metal under the cooling suspension stream, thus preventing overheating and securing good quality and precision of cutting.

For investigating the microstructures the cut samples of the obtained material were prepared according to the following procedure: inserting the samples in the tar with the help of Simplimet 1000 automated fitting press manufactured by BUEHLER, grinding and polishing were implemented at the EcoMet 250 / 300 grinding machine tool, equipped with the AutoMet 250 / 300 semi-automated head.

The investigation of the grain grade alteration was done by the method of measuring the circumference

Table 1. Chemical analysis of steel grade 10880 acc. to GOST 3836-83 in percentage

C	Si	Mn	S	P	Cu
not more than 0.035	not more than 0.3	not more than 0.3	not more than 0.03	not more than 0.02	not more than 0.3

Table 2. Contents of the introduced particles in the samples

No. of sample	Mass of the introduced carbides, % of the billet weight	
	WC (density 15.6 (g/cm ³))	TiC (density 4.93 (g/cm ³))
1	0	0
2	0.5	0.5
3	1	0

chords (GOST 5639). The investigation of the grain grade alteration was performed at the outer radius and at the inner radius of each cylinder-shaped billet, as well as at 1/2 of the radius (the middle of the billet). The microstructure was studied with C.Zeizz Observer.D1m inverted microscope, equipped with the Thixsomet.PRO image analysis complex.

The hardness of the obtained samples was determined using the TR-5014 and TB-5004 hardness gages. These gages are intended for measuring hardness by methods of Rockwell and Brinell in conformity with the standards ISO 6508-86, DIN 50 103 and ASTM E 18-74.

Plastic deformation by forging was done at the pneumatic hammer; the thickness of the sample was reduced from 5 cm to 1 cm.

The test for wear-resistance was done at a specifically developed machine. The wear-resistance of the obtained material was investigated by means of calculating the mass loss of the sample resulting from passing a specified distance along the abrasive paper under specified load. This task is solved by way of protracting the abrasive ribbon under the sample on which the load rests. During all the period of the test the sample is constantly in contact with the continuously renewed section of the abrasive ribbon. The friction process is practically isothermal. The length of the abrasive ribbon is chosen according to the tested material: the wear, which is measured by the sample weight alteration before and after the test, is quite noticeable and is determined quite precisely by means of weighing on analytical balance.

The deformation of samples was done by forging at the pneumatic hammer according to the attached schematics (Figure 1).

3. Discussion

As a result of performing the experiment, three cylinder-shaped samples were obtained with different contents of the introduced disperse particles. Those samples were cut for testing.

Investigation of the cast metal microstructure showed that in sample No.1 (with no introduced carbides), at the outer edge the grain grade is considerably lower, than that at the inner edge and varies within the range of values: 5-6 at the outer radius, 5 in the middle, 2 at the inner radius (Figure 2). Those data are well in conformity with the available literary sources: such noticeable difference in grain grade at the outer and at the inner radius is

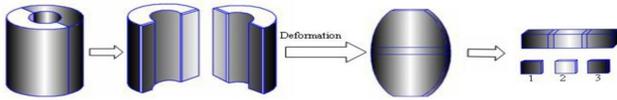


Figure 1. Schematic of cutting the samples out of the deformed billets: 1 – for microstructure study; 2 – for chemical analysis study; 3 – sample for hardness measuring.

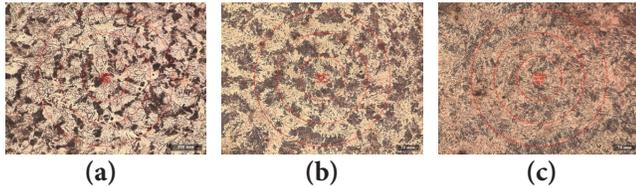


Figure 2. Investigation of billet No. 1 microstructure: a) outer radius; b) the middle of the billet; c) inner radius.

explained by different velocity of solidification²¹. At the outer radius the metal, coming into contact with cold mold, solidifies very fast, as the result of which the grain is very small in size. Then the conditions of solidifying change, the process becomes slower, and the size of the grain starts getting bigger.

While investigating the microstructure of sample No. 2 (with titanium carbide and wolfram carbide), at the outer radius the grain size proved to be much smaller than that at the inner radius and varied within the range of values: 8 at the outer radius, 6 in the middle, 7 at the inner radius (Figure 3). As compared to sample No. 1, there is a slight reduction in grain size at the outer radius and very considerable reduction of the grain size at the inner radius and in the middle of the billet. This is explained by increase in velocity of solidification, which took place because of the introduced disperse particles. The peculiar feature of the structure is that the size of the grain in the middle of the sample is bigger than that at the inner radius. This fact confirms the distribution of the introduced particles depending on density: smaller grain at the inner radius is explained by presence of titanium carbide in this area.

Investigating the microstructure of sample No. 3 (with the introduced wolfram carbides) showed that the structure of the sample is quite homogeneous: grain grade 8 at the outer radius, 7 in the middle, 7 at the inner radius (Figure 4). That is the introduced wolfram carbides were distributed across the section of the sample more or less evenly, from the outer radius to the inner one. As compared to samples No.1 and No.2 the grain became even finer, due to introducing wolfram carbide in larger amount.

Investigation of sample No.1 upon deformation showed that the structure at the edges of the sample is finer; in the middle it is coarser and has clearly expressed striation. The structure of the material remained ferrite-perlite. The grains of ferrite are more plastic and, as the metal was processed by pressure, they became somewhat longer, generating fibrous structure. The deformation affected the grain size very much: the structure all over the area of the sample became even with grain grade of 9.15 (Figure 5a).

Investigation of sample No 2 upon deformation showed that the structure, as compared to that of the cast metal, became even finer and achieved the value of 11.2 points. The structure represents very fine ferrite-perlite mixture, probably, a sorbitol structure (Figure 5b).

Microstructure of sample No.3 upon deformation also became homogeneous and fine, reaching the value of 11.9 points: ultra-fine structure (Figure 5c).

The hardness of each of the obtained samples was measured in three places of each sample: 1 – at the outer radius; 2 – at 1/2 of the sample radius; 3 – at the inner

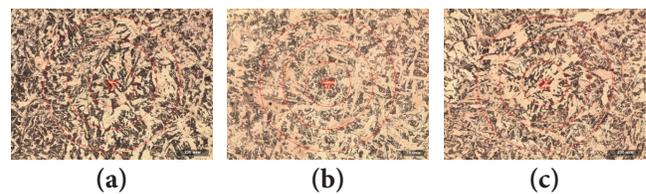


Figure 3. Investigation of billet No. 2 microstructure: a) outer radius; b) the middle of the billet; c) inner radius.

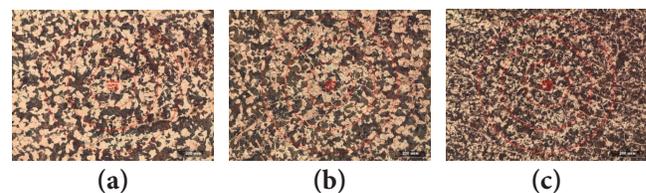


Figure 4. Investigation of billet No. 3 microstructure: a) outer radius; b) the middle of the billet; c) inner radius.

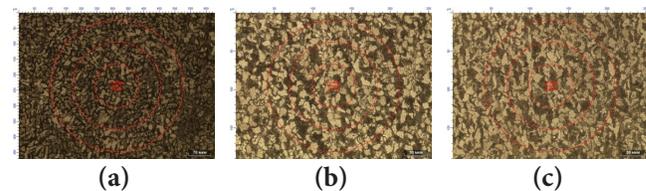


Figure 5. Microstructure of samples upon deformation: a) sample No.1 ($\times 250$); b) sample No.2 ($\times 650$); c) sample No.3 ($\times 650$).

radius. While investigating the following designations were assumed: the first digit is the number of the sample; the second digit is the number of the place (described above) of the hardness measurement location in the sample. Based on the cast samples hardness measurement results (Table 3) a clear correlation between the hardness increase and the amount of the introduced particles with the areas of their distribution and with the grain grade alteration is observed: the smaller the grain grade, the better hardness the samples obtain.

The alteration of hardness upon deformation showed considerable increase in hardness of sample No.1 up to 207 HB. In sample No.2, notwithstanding the averaging of the grain grade over the area of the sample, the difference in hardness is observed at different edges of the sample: at the edge with wolfram carbide particles the hardness increased up to 310 HB, and at the edge with titanium carbide up to 270HB. In sample No.3 the values over all the area of the sample are practically the same and amount to 380-390HB.

While investigating the wear-resistance three pieces were cut off from each cast sample with dimensions (10×10×10mm): 1 – at the outer radius; 2 – 1/2 of the billet radius; 3 – at the inner radius. The marking of the samples for measuring the wear-resistance quality was the same as the marking for measuring the hardness: the first digit is the number of the sample; the second digit is the number of the place (described above) of cutting the sample. The wear-resistance of the obtained samples was determined by method of abrasion. The investigation of wear-resistance of the obtained samples showed that the wear-resistance characteristics of different billet sections

Table 3. Results of investigating the hardness of the cast samples

Sample code N	Hardness HB
11	167
12	164
13	163
21	218
22	187
23	174
31	255
32	217
33	207

Table 4. Results of wear-resistance measurements at the cast samples

No	m ₀ , g.	m ₁ , g.	m ₂ , g.	Δm ₁ , g.	Δm ₂ , g.	Δm _{cp} , g.
11	2.068	1.955	1.843	0.113	0.112	0.113
12	2.642	2.536	2.437	0.106	0.099	0.103
13	2.241	2.130	2.019	0.111	0.111	0.111
21	1.72	1.628	1.545	0.092	0.083	0.088
22	1.823	1.718	1.621	0.105	0.097	0.101
23	1.99	1.889	1.794	0.101	0.095	0.098
31	2.384	2.303	2.23	0.081	0.073	0.077
32	3.35	3.277	3.209	0.073	0.068	0.071
33	3.744	3.66	3.578	0.084	0.082	0.083

are not the same. The highest degree of wear-resistance have the samples, obtained from the outer part of the cast billets, this being characteristic both for the samples with the introduced carbides and for the samples with no introductions (Table 4). This fact is explained by more dense structure at the outer side of the billet. The highest wear-resistance characteristics are observed in the samples with maximum carbide phase content.

Having analyzed the data obtained for wear-resistance of the samples, a conclusion can be drawn that introducing the disperse particles in the structure improves the wear-resistance characteristics by value from 10 to 34%.

4. Conclusion

Thus, accomplishing the study, the following conclusions can be made: introducing the disperse particles of carbides does not affect the occurrence of any kind of defects in crystal structure: no pockets, looseness, delamination or ruptures were observed in any of the samples; at increasing the amount of introduced disperse particles the dispersion of the billet structure takes place, and a considerable one; the introduced particles seriously increase hardness and wear-resistance of the hardened metal both in cast and in forged conditions; such method of improving mechanical characteristics is practically feasible and less expensive, as compared to other methods.

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