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Nanostructure Changes in Iron-Carbon Alloys as a Result of Impulse Deformation Wave Action

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The paper discusses possibilities and conditions needed to obtain a super small grain and nanocrystal structures by means of deformation shock waves that are displaced in relation to each other in time and space. Investigations demonstrated that with shock wave loading plastic deformation can spread over a bigger material volume as compared with other hardening methods and can be classified as an intensive plastic deformation method and as a gradient hardening method that are both applied to homogeneous metals and alloys to obtain micro- and nanocrystal structures characterized by improved mechanical properties. Deformation shock wave hardening used to create super small grain and nanocrystal structures in metal alloys is able to facilitate a wider introduction of nanostructured materials into industry.

Keywords: Surface layer, Gradient hardening, Nanocrystal structure, Nanostructuring, Strain wave, Surface plastic deformation, Iron-carbon alloys.

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1. INTRODUCTION

Steel and cast iron are still the most widely spread structural materials. Developing technologies ask for new methods of hardening iron-carbon alloys capable of giving them extended physical and mechanical properties. Intended formation of micro- and nanocrystal structures is an up-to-date trend in the area of improving properties of metal materials [1]. Here an increase in the strength and hardness alongside with a decrease of the grain size at micro level can be explained by the appearance of additional boundaries that prevent dislocation motions, or, with small nanosize grains (less than 100 nm), by a low density of already existing dislocations and unfavored conditions for new ones to develop. So nanostructuring in structural steels is a way to increase their hardness significantly up to 9 GPa, and up to 12-14 GPa in surfaces layers, which is by 2-7 times more than the hardness of similar coarse-grain materials [2]. Moreover, when nanocrystal structure is formed, a higher strength of a metal is accompanied by a higher plasticity, which is 1.5-2 times more compared with coarse-grain prototypes (Fig. 1) [3].

A very promising way to make the grains of metal materials smaller is to apply strain effect, and that is three-dimensional or gradient (varied within a component range) hardening. Conventional deformation methods (like rolling, drawing, pressing, etc) for three-dimensional hardening decrease the cross-section of a workpiece and prevent grains from being sufficiently reduced. There are special methods of intensive plastic deformation (IPD), such as hydrostatic pressure twisting, equal channel angular pressing, reversed bending, etc., that are used to deform a workpiece without changing its cross-section and shape, and enable the needed high rates of deformation and grain reduction. (down to 20…80 nm) [4, 5]. However the final nanostructured product can be shaped only as a foil or a small-diameter bar (up to 10 mm). So far IPD has been used to obtain

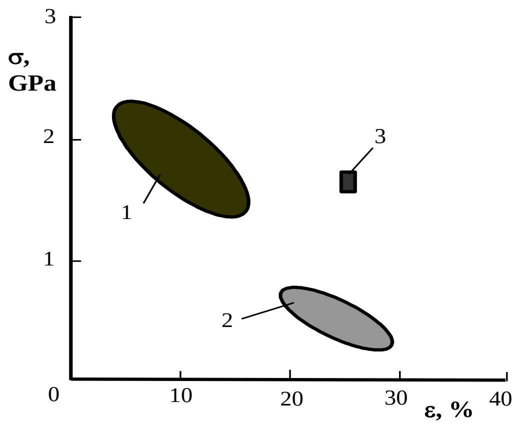

Fig. 1 – Correlation between steel hardness and plasticity shown by the curve of relationship of ultimate strength σ and percentage extension ε: 1 – high-strength steels, 2 – low-carbon steels, 3 – nanocrystal steel [3]

nano- and submicrocrystal structures in aluminum, iron, magnesium, wolfram, nickel, titanium and their alloys.

One of well-known methods of gradient hardening used to get super small grain and nanocrystal structures is supersonic final polishing, which permits to obtain nanosize crystals at a depth of up to 0.5 μm with the deformed layer thickness up to 0.2 mm maximum. In specific operation conditions such structures are able to increase the durability by almost 2.8 times [5]. However in complex-strained products meant to operate in heavy-duty or extreme conditions the most strained point is located as a rule at a certain depth in the subsurface layer of the material, that is why in order to obtain better performance characteristics there is a need to form a deeper hardened layer with a thickness of 1…3 mm, and even up to 6 mm in specific cases. The majority of known methods of gradient hardening by surface plastic deformation (reeling, smoothing or burnishing) are able to form the hardened layer of up to 0.5…1 mm thick and are not efficient enough to make a desired product.

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2. EXPERIMENTAL SECTION

To obtain a deep hardened surface layer it is suggested to use deformation hardening by shock-and-pulse method [6].

As is known from global science and engineering practice considerable deformations with a relatively small power applied can be well produced by shock loading that can be equally efficient both in material destruction and material hardening. However different impactor systems can yield different results with one and the same impact energy applied.

Depending on the relationship between the materials and geometric parameters of impactor system elements, as well as on the resistance of the loaded medium, the impact energy can be distributed among the impactor system components and the medium in a variety of ways. The impact itself is viewed as plane acoustic waves that propagate in the colliding bodies and are characterized by the law of variation of strains (forces) overtime, a maximal force value (wave amplitude), time period of wave action (wave duration) and wave energy. The period of such wave is called the shock pulse. Pulse shape reflects the law of variation of force amplitude over time. The efficiency of impact action directly depends on the shape of pulse generated by the impactor system [7].

Experimental investigations of loading a material surface by shock pulses having same energy but generated by different impactor systems (Fig. 2), (Table 1) [8, 9] showed that a sphere impact formed a delta pulse with a high amplitude and short-time duration (with energy transfer less than 12 %), the impact made by the butt-end of a metal rod (a striker) produced trapezoidal pulse with a smaller amplitude, but a longer duration (energy transfer raised up to 26 %); the impact made by the striker via an interim element statically pre-pressed to the loaded surface (a waveguide) caused a prolonged pulse having head and tail sections. The assessment of pulses demonstrated that the pulse generated by the impact of the striker via the waveguide was characterized by the biggest energy transfer (40 % and more).

To improve material strength by elastic-plastic strain in the process of surface plastic deformation of metals mechanical engineering has always used only big-amplitude short-duration pulses that are generated by primitive impactor systems having no intermediate links.

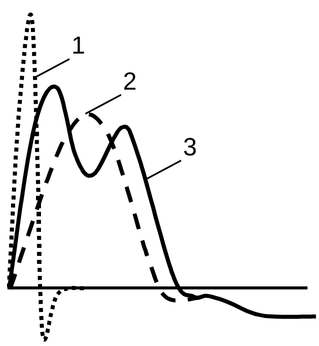
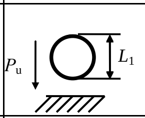
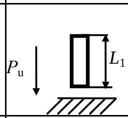
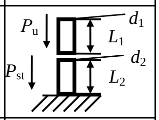


Fig. 2 – Dependency of the shape of the pulse generated in the deformation zone on the type of the shock system (Table 1)

Table 1 – Impact energy feed into deformation zone

	by the impact of a tool	by the striker impact onto the waveguide	
tool	sphere	striker	waveguide butt-end
mode diagram			
energy transfer, %	12	26	40
curve number	1	2	3

where P_u – is impulsive load, P_{st} – static load , L_1, L_2 – the length of the striker and the waveguide correspondingly, d_1, d_2 – cross-section diameter of the striker and the waveguide correspondingly

In wave terms the problem of pulse impact on metals and alloys was solved only in [10]. Research results demonstrated that with an impact via an intermediate link the tail section of the pulse is formed by the energy of reflected deformation waves and depends on the impactor system geometrics and properties of the loaded medium. By utilizing the pulse tail section it is possible to prolongate the effect of impulse momentum in the loaded media, to intensify plastoelastic deformation and increase the process efficiency. Prolonged impulse momentums have to be formed with the waveguide prepressed to the strained material and retained in this position during the total period of its loading by deformation waves.

Material hardening by deformation wave is characterized by a variety of governing factors, which provides a good potential to control pulse parameters, offers wider deformation treatment options and makes it possible to produce a deeper layer with a preset hardening uniformity [11-13]. Thanks to high (acoustic) speed of deformation wave propagation in a material (about 5000 m/sec) and the possibility to control the intensity and duration of force action onto surface layer fragments this treatment method can be classified as a means of intensive plastic deformation of materials.

The hardened layer is formed as a result of multiple pulse actions with relatively displaced deformation zones (Fig. 3).

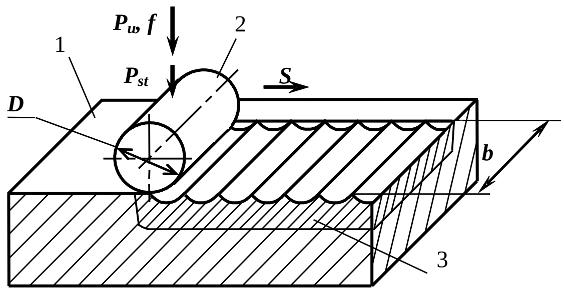


Fig. 3 – Diagram showing making impressions on a workpiece plane surface by a core roller in the process of static-pulse treatment (1 – specimen, 2 – core roller, 3 – hardened area): P_u – impulsive load, f – impulse frequency, P_{st} – static load, S – workpiece feeding speed relative to the roller , D – roller diameter, b – roller width

Shock action ratio and force, deformation zone dimensions, that are defined according to a specific task, the pattern of changing material properties through the surface layer depth as a result of a single pulse impact will determine the type of the distribution diagram of the properties of the gradient hardened surface layer.

3. RESULTS AND DISCUSSION

Deformation wave hardening was applied to metal pieces with different shapes and sizes. If needed, the impulse energy can be chosen in the range of 5…200 J. The static load value before the impact shall not be less than 10 % of the impact load.

When plane surfaces were hardened, the depth of the hardened surface layer reached 6…10 mm, while that of internal cylindrical surfaces amounted 20 mm. In the process of geometry generation with simultaneous hardening of the tread with 1…5 mm pitch the hardening depth was 2,5…3 mm and even more [14-16].

Investigations of the structure of metal specimen hardened by deformation waves (Fig. 4) revealed that there were nano-structure zones similar to those developed by IPD with their sizes varying from 30 to 90 nm. It is worth noting that the alternation uniformity of nano-structure zones can be regulated by the energy of deformation shock waves, the size and geometry of the contact area between the tool and deformed surface, as well as by the ratio and the displacement rate of developing deformation zones.

On one hand the obtained results permit us to classify this hardening mode as an intensive plastic deformation method, because the rate of deformation wave propagation in the material can be as high as 5000 m/sec, but on the other hand, it is a gradient hardening technique, because only the surface material layer gets deformed.

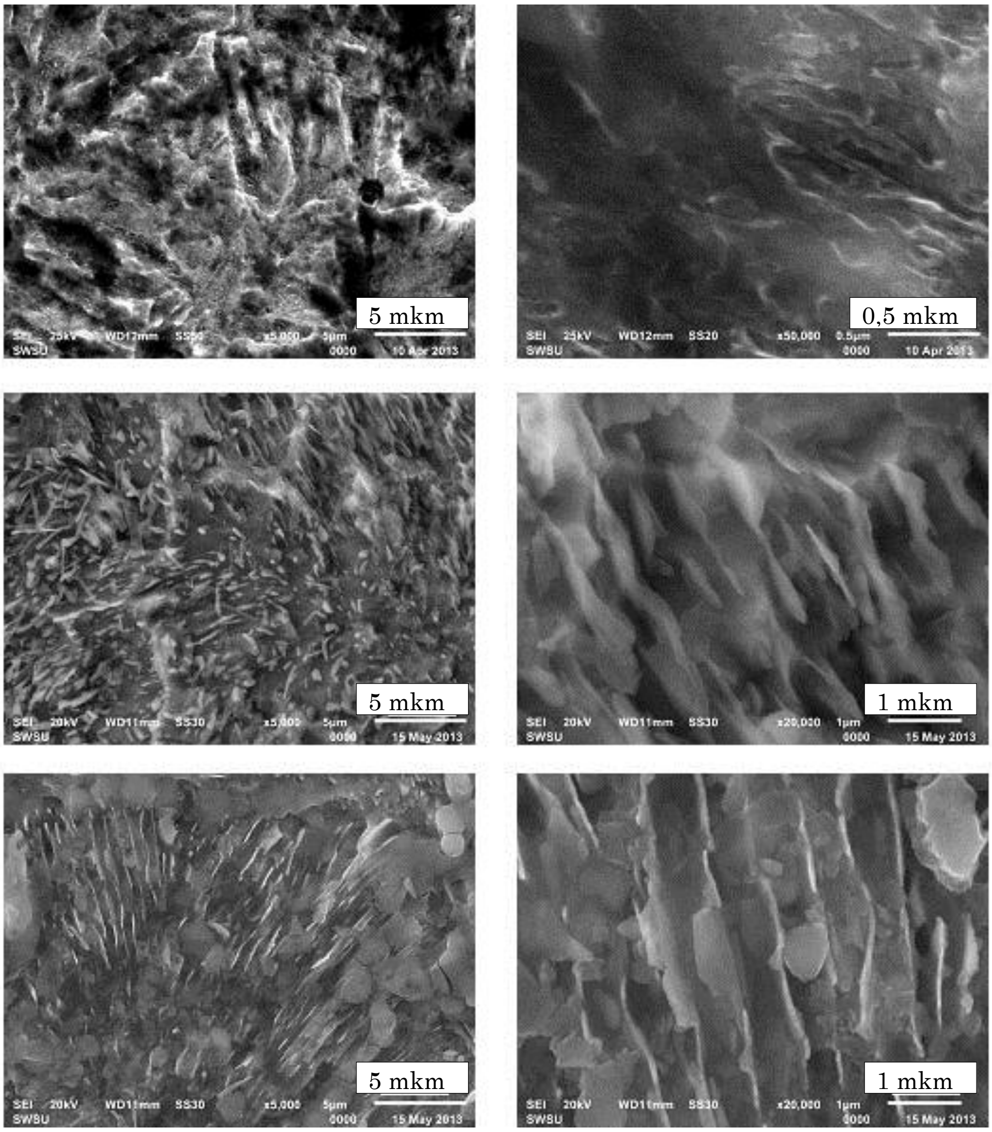


Fig. 4 – SEM images of specimen surfaces (steel 45) after an impact made by deformation shock waves with decreasing displacement in relation to each other (top-down)

4. CONCLUSIONS

Intentional formation of micro- and nanocrystal structures by plastic deformation method is a means to obtain materials with unique physical and mechanical properties, very strong, but at the same time with good plasticity.

Proposed is a new method of making nanostructure changes in the surface layer by plastic deformation action when a material is loaded by a controlled action of deformation shock waves.

Material hardening by deformation shock waves used to create super small-grain and nanocrystal structures in metal alloys is able to facilitate a more extensive introduction of nanostructure materials into industrial use and significantly improve the performance of home-made machines and mechanisms, increasing their durability and reliability under heavy-duty operation conditions.

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