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Production of Quasicomposite Surface Layer of a Metal Material by Shock Wave Strain Hardening

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Quite often in order to improve the performance of a product it is necessary to form a strengthened structure that will be extremely hard and have good plasticity at the same time. One way to meet this challenge is to apply shock wave mechanical hardening to produce micro- or nanocrystalline heterogeneous structures in homogeneous metals or alloys. A peculiar feature of such structure is its layer-by-layer formation with smooth transition between hard and plastic areas, which improves the performance of the strengthened item significantly

Keywords: Surface layer, Trengthening, Deformation wave, Surface plastic deformation, Multi-layer organization, Metal material, Heterogeneous structure, Hardness, Striker, Waveguide.

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1. INTRODUCTION

Today machine-building is facing one of its biggest challenges, which is how to ensure the design life-time and bearing strength of critical parts in high-tech machines. In operation machine parts are subjected to a multivariate impact, but as a rule their surface layer is the mostly loaded area, so its condition seriously determines the performance of a part.

Many scientific schools have been developing surface engineering methods and technical means that are able to change physical and mechanical properties of the surface layer, its structure and phase composition cardinally. First classical studies devoted to the influence of surface layers of solid bodies onto their mechanical properties were done in the 20-ties of the last century and are described in Academician Ioffe's well-known works. During the past two decades the following scientific school have been conducting research in this area: I.R. Kramera (USA), V.P. Alyokhin-M.H. Shorshov, V.F. Terentiev-V.S. Ivanova and Academician V.E. Panin [1]. Research outcomes show that strengthening treatment results in changes at nano- micro-, meso- and macroscale levels, while the desired properties have to be guaranteed everywhere. Just to ensure the strengthening of a thin surface layer is not enough, it is also necessary to form a deeper gradient transition sublayer with such properties that will take an intermediate position between the properties of the thin surface layer and the base. Usually multilayer composite coatings are applied for these purposes. They are made of heterogeneous materials with different properties and have a sharp transition boundary between the layers, which diminishes positive effect of strengthening treatment.

2. SUBJECT OF INQUIRY AND RESEARCH METHODS

Surface plastic deformation techniques are considered to be the most promising for the production of a gradient-strengthened structure in the surface layer. Simply mechanical hardening of a material may be sufficient to get a gliding microhardness distribution diagram with a diffuse boundary between the strengthened and non-strengthened areas, which reduces the risk of additional concentration of stresses and subsequent formation of fatigue cracks in the places where hard areas transit into plastic sections abruptly.

Recently mechanical hardening of metal material surface layers by shock waves has proved to be very efficient. This technology is characterized by a specific method of shock energy transfer onto the deformed material [2-4]. Strengthening agents are plane acoustic waves that are generated in the striker-waveguide shock system. Aggregate shock waves resulting from a single strike of the striker onto the waveguide are transferred to the contact point between the tool installed on the waveguide and the deformed material to form shock pulse the shape of which will determine the efficiency of shock loading. In order to regenerate the reflected shock waves and use them with maximal effect for the purposes of plastic deforming of a material the striker impacts the waveguide that has been statically pre-pressed against the loaded surface. The rate of static load has to be not less than 10 % of the pulse load value. The profile of deformation shock waves can be adjusted by changing the geometry of the colliding striker and waveguide, their material properties, impact velocity and deformed material properties and are chosen so that the shape of shock pulses matches the properties of the material and its loading conditions in order to increase the process efficiency and extend processing potential.

High (acoustic) velocity of deformation wave propagation in a material (about 5000 m/sec), the possibility to control strength and duration of force effect in surface layer areas allow us to classify the method of shock wave strengthening as a material severe plastic deformation technique that can yield a high rate of grain size refinement in a metal material. Nanocrystal structure obtained by means of severe plastic deformation is specifically characterized by multiple increase of its strength without any loss in good plasticity, which offers unique opportunities to improve the performance

The article was reported at the International Conference «The Advanced Technology, Equipment and Analytical Systems for Materials», Kursk, 13-14 May, 2014 of strengthened components [5, 6].

To make the performance of the nano-structured layer especially efficient it is necessary to form a sublayer with needed physical-and-mechanical features. Deformation shock wave strengthening is able to create a deep strengthened layer up to 6…10 mm thick, which is quite often a must for important components that operate in extreme operation conditions. Moreover, deformation shock wave strengthening technology makes it possible to control strengthening uniformity due to the overlapping of plastic marks in the material that result from shock wave impact that is rated by contact ratio

$$K = 1 - \frac{S}{\delta f 60},$$

where δ – is the mark size, mm, S – the tool feeding speed of a rough part, mm/min; f – impact frequency, Hz.

If $K = 0$, then the edge of one mark will border on the edge of another one; if $0 < K < 1$, the marks will overlap; when $K = 1$ the tool will be repeatedly impressed into one and the same place.

As a result a heterogeneously modified material structure can be obtained where hard and plastic areas will alternate with a preset depth according to a desired pattern, which makes this structure more durable. During operation ductile material in such structures will hinder the development of a brittle microcrack that may form in the supporting hard material and that will increase resistance to cyclic loads [7, 8].

To describe the obtained heterogeneous structure, that is variable both along and through the surface layer, it is suggested to apply such variables as relative reference hardness $L^h_{\Delta H}$ and relative number of local strengthened areas taken over a reference length $N^h_{\Delta H}$.

Relative reference hardness $L^h_{\Delta H}$ is the relationship of the sum of the lengths of areas having the same specific strengthening rate taken at a certain depth and the reference length taken for measurements (Fig. 1)

$$L^h_{\Delta H} = \frac{\sum_{j=1}^{N^h_{\Delta H}} L^h_{\Delta Hj}}{L} 100\%, \qquad (1)$$

where h – is the depth of the level taken to measure relative reference hardness, mm; ΔH – strengthening rate in the areas taken to measure relative reference hardness, %; $L^h_{\Delta Hj}$ – length of j- th area with strengthening rate ΔH taken at the level in question, mm; L – reference length, i.e. the distance taken along the strengthened surface to find the relative reference strengthening, mm; $n^h_{\Delta H}$ – number of local strengthened areas; pieces; j – ordinal number of the area having the strengthening rate ΔH, ($j = 1\ldots n^h_{\Delta H}$).

Relative number of local strengthened areas along the reference length $N^h_{\Delta H}$ is the relationship between the number of strengthened areas $n^h_{\Delta H}$ having strengthening rate ΔH and the reference length L taken for measurement purposes

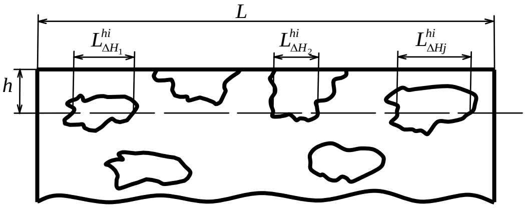


Fig. 1 – Distribution diagram of relative reference strengthening $L^h_{\Delta H}$

$$N^h_{\Delta H} = \frac{n^h_{\Delta H}}{L}. \qquad (2)$$

Heterogeneity parameters specify quantitative and qualitative alteration pattern for hard and soft areas of an unevenly strengthened structure. Parameter $L^h_{\Delta H}$ is used to estimate the relative length of all hard areas at a certain depth level in the strengthened layer, while parameter $N^h_{\Delta H}$ is used to define their number per length unit.

Strengthening non-uniformity described with the help of $L^h_{\Delta H}$ and $N^h_{\Delta H}$ parameters will be as follows. If at a certain $L^h_{\Delta H}$ value the variable $N^h_{\Delta H}$ increases, it indicates an increase in the number of smaller areas with a given hardness at a given level of the strengthened surface layer with such areas located closer to each other, which increases strengthening non-uniformity of such structure. If with constant $N^h_{\Delta H}$ value the variable $L^h_{\Delta H}$ increases, it means that the size of the areas having a given hardness increases at a given level of the strengthened surface layer, while the distances between them decrease and the strengthened structure becomes more uniform.

Here is an example how to find parameters $L^h_{\Delta H}$ and $N^h_{\Delta H}$. It is necessary to find relative reference hardness for the strengthened areas with strengthening rate $\Delta H = 40\ldots50$ % as of the reference length $L = 9.45$ mm at a depth of $h = 0.4$ mm (Fig. 2).

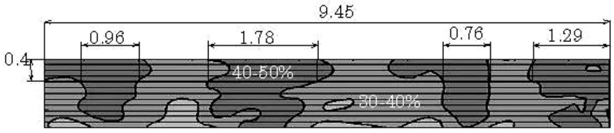


Fig. 2 – Evaluation of relative reference hardness for the areas with strengthening rate $\Delta H = 40\ldots50$ % at a depth of $h = 0.4$ mm along the reference length $L = 9.45$ mm

At this level of the strengthened surface layer the number of areas having strengthening rate $\Delta H = 40\ldots50$ % will equal $n^h_{\Delta H} = 4$ pcs. The length of the areas with the given strengthening rate is $L^h_{\Delta H1} = 0.96$ mm, $L^h_{\Delta H2} = 1.78$ mm, $L^h_{\Delta H3} = 0.76$ mm, and $L^h_{\Delta H4} = 1.29$ mm. The sum of area lengths will be

$\sum_{j=1}^{N^h_{\Delta H}} L^h_{\Delta Hj} = (0.96 + 1.78 + 0.76 + 1.29) = 4.79$ mm. According to Fig. 1 and 2 we'll get the values of $L^h_{\Delta H} = 51$ % and $N^h_{\Delta H} = 0.42$ pcs per mm.

3. DESCRIPTION AND ANALYSIS OF RESULTS

After shock wave strengthening the surface layer was examined through its thickness of up to 0.5 mm with the help of a scanning electronic microscope, and its microhardness was measured through its thickness of up to 5.5 mm. As a result nanostructure areas with sizes from 30 to 90 nm were found in the strengthened surface layer (Fig. 3). Their shape and location were determined by the energy of deformation shock waves, the size and shape of the tool-metal contact point and the displacement of shock waves in relation to each other, which is described by the contact ratio.

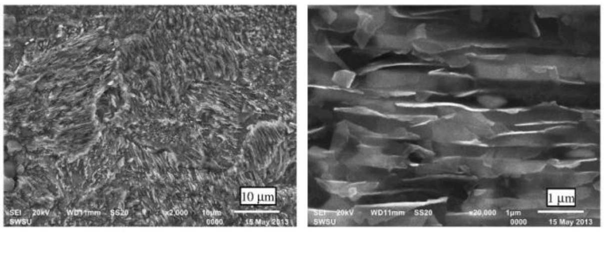
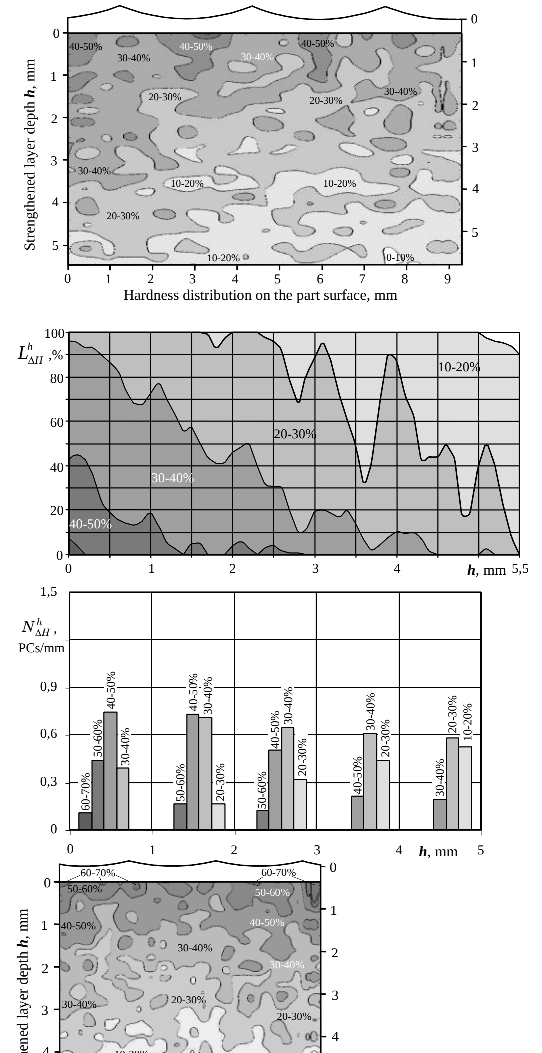


Fig. 3 – Scanning electronic microscope images of the surface layers of samples (steel 45) after deformation shock wave treatment

Based on the measurements of strengthened surface layer microhardness we plotted the diagrams of hardness distribution over the layer thickness and along its surface (Fig. 4). It was found that the resulting structure had heterogeneous composition with multilayer organization. The hardness of alternating areas located along the layer surface was gradually decreasing starting from the upper part of the strengthened layer and down to non-strengthened metal. Thus with contact ratio $K = 0$ at least three layers were present: the first one at a depth of up to 1 mm with alternation of hard areas having the strengthening rate $\Delta H = 40$-50 %; the second one lying at a depth of up to 1-3 mm with hard areas of $\Delta H = 30$-40 % and the third layer at a depth of 3-5.5 mm with hard areas of $\Delta H = 20$-30 %. When contact ratio is $K = 0.375$ at least four layers are formed: the first one at a depth of up to 0.8 mm with alternation of hard areas having the strengthening rate $\Delta H = 50$-60 %; the second one lying at a depth of up to 0.8-2 mm with hard areas of $\Delta H = 40$-50%; the third layer at a depth of 2-3 mm with hard areas of $\Delta H = 30$-40 % and the fourth one at a depth of 3-5 mm with hard areas of $\Delta H = 20$-30 %. It was also found that when the contact ratio increases, it results not only in an increase of strengthened layer levels, but also in the reduction of the sizes of alternating areas. Thus when $K = 0$ the average value of the relative number of local strengthened areas over the total thickness of the strengthened layers is 0.35 pcs/mm, while with $K = 0.375$ it is 0.63 pcs/mm.



contact ratio $K = 0$ contact ratio $K = 0{,}375$

Fig. 4 – Strengthening rate variation (given in %) in the surface layer formed by deformation shock wave processing

Operation testing of the obtained structure for cycle contact load effects has shown significant increase in its durability (up to 7 times) [9].

4. CONCLUSION

Production of a multilevel strengthened structure with smooth transition between its layers is a good opportunity to improve product performance. It is important that each layer should have adequate strengthening uniformity.

It has been found that when a homogeneous metal material is strengthened by deformation shock waves, a multilevel structure is formed with smooth transition between hard and plastic areas. In the upper part of the strengthened surface layer there are nanostructure areas, below them there is a sublayer with a heterogeneously strengthened structure with alternating hard and plastic areas and this sublayer gradually transits into non-strengthened metal.

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