

## Properties and Technology for Quasi-Composite Blanket Using Natural Reinforcement of the Metal by Strain Affected Areas

A. Kirichek<sup>1</sup>, D. Soloviev<sup>2</sup>

<sup>1</sup> Southwest State University, 94, 50 Let Oktyabrya Str., 305040 Kursk, Russia

<sup>2</sup> Murom Institute (Branch) of Vladimir State University, 23, Orlovskaya Str., 602264 Murom, Russia

(Received 14 October 2013; published online 10 December 2013)

Techniques for making materials with advanced performance attributes at the expense of blanket heterogeneous strengthening are considered. A new trend is defined in a multiple increase of performance attributes in metal materials by natural reinforcement with nanostructural and ultra-fine-grained fragments. The application of a wave strain hardening technique is substantiated for obtaining a heterogeneous structure in wide-area listed full-size products including bulky ones. A high carrying capacity of heavily loaded material with a deep-strengthened blanket is determined.

**Keyword:** Blanket, Performance attributes, Heterogeneous gradient strengthening, Multilevel, Reinforced material, Nanostructural fragment, Strain wave.

PACS numbers: 62.20.fq, 62.20.Qp

### 1. INTRODUCTION

Making non-uniform-heterogeneous materials, the integration of various materials having properties corresponding to either these, or those service conditions opens up large possibilities to increase engineering and economic characteristics of products, contributes to a considerable increase of their reliability, durability, weight reduction, cutting down expenses for manufacturing and operation.

Usually, a “heterogeneity” term is used for the designation of physically non-uniform systems comprising some phases separated from each other by surfaces on which one or several properties of the system change by leaps and bounds. There is every reason to speak of the universality of a heterogeneous-dispersed state which can be considered as a stage in a material structure following atoms and molecules. Many engineering and constructional materials: metal and hard alloys, reinforced concrete, brick, wood, plywood, reinforced plastics are heterogeneous and have anisotropy of physico-stress-strain properties.

One of the most successful historical examples of man’s application of volumetric structural heterogeneous composites can serve Damascus steel manufactured first by Old-Indian blacksmiths. Hardness and durability of Damascus steel were combined with high elasticity and viscosity and blades made of Damascus steel were able to cut asunder nails, bend bow-shaped and cut a kerchief in the air.

During the last decades there were developed many heterogeneous materials. The well-known structural composite materials are divided into reinforced with fiber and particles structured in a volumetry and surface way. Laminated gradient materials (including materials with one- or multilayer coatings, bimetal), hybrid materials and structures, dispersion systems are emphasized.

Modern volumetry structural composite materials possess a strength-to-weight ratio and rigidity in the direction of reinforcement four-five and more times increasing the strength-to-weight and specific stiffness of steel, aluminum and titanium alloys. Reinforcing

elements in the form of thin fibers, threads, bunches or cloths provide outstanding physico-mechanical properties of material, in particular, high strength and rigidity in the direction of fiber orientation and a binding agent (matrix) ensures its solidity.

The overwhelming majority of heterogeneous material classes have vivid inner boundaries of the heterogeneous blankets separation that adversely affect the operation properties of products. Microcracks appear on the boundaries that results in material failure.

One of the most promising modern directions of the development is the formation of a heterogeneous structure in a modified blanket of solid non-gradient material which on the one hand has no vivid boundaries of areas with changed properties, and on the other hand it is analogous by the properties to composite materials with a soft matrix and hard inclusions.

A heterogeneously modified surface of solid material possesses a priori a higher carrying capacity. A ductile material prevents from the development of a brittle microcrack formed in a carrying solid component resisting well to cyclic loads. There are very few technologies proving a formation of non-gradient heterogeneous structure in solid material with fuzzy, low-strained boundaries of areas with changed properties. At the same time, the depth of a modified blanket, as a rule, makes less than 100μm that is insufficient in order to provide high carrying capacity at the operation under hard conditions of a power load.

### 2. TECHNOLOGICAL METHODS FOR HETEROGENEOUS STRUCTURES FORMATION

From the directional search of progressive technologies for the creation of gradient heterogeneous material with increased design and operational properties reinforced with particles (areas) of a high-strength phase which are surrounded with plastic and viscous strata hinders an existing stereotype of necessity in blanket uniform strengthening. The existing concepts are explained by ambiguous effect of plastic strata upon strength properties of heterogeneous material.

It is well-known that the properties of heterogeneous materials to a considerable degree are defined not only by the properties of every component, but also by a correlation of components in the composition, by a form, a spatial location, orientation of particles of a more strengthened phase in a plastic matrix. The stress-strain properties of heterogeneous materials with a multilevel structure alongside with a free surface and layered inner boundaries are affected by inner grain and interphase boundaries, the existence of interlayer and interphase diffusion areas. The irrational choice of a multilevel structure can result in the decrease of stress-strain properties in comparison with a heterogeneous gradient or layer-based structure of material.

Nevertheless, at present more and more prevalence obtain multilayer heterogeneous materials both with homogeneous, and with composite layers made of solid inclusions in a plastic phase.

It should be pointed out that the most loaded point of a product complex-stressed in the course of operation and operated under heavy and extremal conditions of loading is situated, as a rule, at a certain depth in a subsurface layer of the material. In this case a material carrying capacity is defined not only by the hardness of a thin modified surface layer, but by properties of the subsurface layer, to be more exact, by a correlation of surface layer properties and a carrying subsurface layer (often by hardness correlation). To increase performance attributes a deeper strengthened layer should be necessary a thickness of which makes more than 1mm and up to 6mm under extreme conditions.

There are various technologies for the formation of a blanket heterogeneous structure. A method of blanket local strengthening by chemical-thermal working (CTW) through a protective mask essential for the division of a surface into strengthened areas and non-strengthened ones is known. A technique developed under the leadership of Prof. Ivanov comprises cementation at 930 °C, normalization, hardening at 770-780 °C in water and low tempering. It is defined that a breaking point at a bend of material with such a heterogeneous macro-structure drops only by 6...10 %, and elasticity increases 3...3.5 times as compared with solid cementation of a blanket. It results in the increase of fracture toughness 2.5 times and a bend angle to destruction by 50-60°. Inner friction increases 3...4 times promoting material endurance increase.

The technique is approved both in tools meant for nonmetal material working and in machinery. The durability of heterogeneous wood-working saws increased 2.5...3 times, heterogeneous blades of hack-saws - 2.6 times, heterogeneous knives of scooters for meat industry 5...6 times. The effect is achieved at the expense of modified hardness increase at the simultaneous increase or preservation of material initial plasticity. The mechanical tests have shown that at the tooth hardness HRC 64-65 heterogeneous blades hack-saws withstand a bend up to 55°, whereas common ones - only 30-35°, and the best foreign ones - up to 42-45°. At the same time the tooth durability increases up to 2.6 times, and the durability of the blade itself increases 2-2.5 times under conditions of low-cycle fatigue.

Heterogeneous structure making by chemical-thermal working with the aid of varnish masks finishing

on work surface of cog-wheels allowed increasing their contact durability 2-3 times (Ivanov G.P. et al., 1997).

It is well-known a work by L.A. Kirel, O.M. Mikhailova, S.A. Zhuravlev on the creation of a CTW heterogeneous structure in metal plates of body armours made of low-alloy steel. Their right sides were strengthened up to hardness HRC 62-67 and back ones up to HRC 46-51 to the depth of 20-40 % of the whole armour thickness. Heterogeneous structure making allowed a body armour weight to decrease 1.4 times at its durability properties preservation. [Patent RF No. 2090828].

More and more effective technologies for the creation of a heterogeneous structure with regular gradient areas on a blanket appear. To the basis of the heterogeneous structure formation by a thermal impact is laid a principle of a blanket local heating providing a creation of alternating areas with different hardness.

For example, at the expense of the laser hardening modes variation, it is possible to provide thread peaks and roots that promotes fatigue life increase by 30...50 % [Patent RF No. 2047661]. By the dimension variation in heating areas at thermal treatment is possible to make a heterogeneous structure with a different correlation of strength and plastic properties for the thickness of about 0.5 mm that is followed by the breaking point increase for 30 MPa [Patent RF No. 2219271].

At the electromechanical work by S.N. Parshev and N.Yu. Polozenko there was obtained a wear-proof blanket at the expense of current periodic transmission through a roller moving under load and a specified speed [Patent RF No. 2203173].

In such a way, there are open wide possibilities for a technological support of high performance attributes of critical parts at the expense of the creation of heterogeneous surface strengthened materials with the use of well-known working modes. For this purpose give the best fit not only technologies of chemical-thermal (nitration, cementation) and surface thermal strengthening (high-frequency current hardening, laser strengthening, plasma working, thermo-mill machining), but also electro-mechanical machining, working modes with surface plastic forming (SPF), micro-arc oxidation, a mode of coatings electro-erosion synthesis.

For the creation of a heterogeneous structure the most promising technologies are those which concern *plastic deformation*. Only by material surface strengthening with plastic deformation is possible with obtaining a smooth character of micro-harness distribution diagrams with a fuzzy boundary of strengthened and non-strengthened areas. Surface plastic deformation methods go well together with other strengthening impacts allowing the formation of combined strengthening technologies.

A plastic deformation serves as an effective tool for the formation of a laminated anisotropic structure in which a longitudinal or transverse fiber location exercises a cardinal effect upon products properties. The plastic deformation application at heterogeneous material machining besides proper product shaping allows effective controlling a form, location, orientation of inclusions in a matrix phase, changing a stress of phase separation boundaries which affect considerably product performance attributes.

For instance, the researches of A.P. Laskovnev,

A.I. Pokrovsky, I.N. Khrol concerning interrelations between chemistry, structure and properties of cast iron in a cast and deformed states with a different graphite form and metal matrix have shown the increase of cast iron performance attributes complex after deformation 1.5...2 times. The most vivid peculiarity of a deformed cast iron structure appeared to be a formation of graphite inclusions with an unusual fibrous form, the degree of the oblongness depends on a deformation degree. It is determined that for various parts it should be expedient to have a special location and a form of graphite inclusions. For a example, for seal rings on a friction surface it expedient to have a cross location of round graphite inclusions and on the friction surface of piston rings – a longitudinal elongated one.

There is a well-known method of obtaining structurally heterogeneous materials based on steel of austenitic and transitional classes at which one carries out first a local plastic deformation with the deformation degree  $\delta$  more than 40 %, and then a general plastic deformation with  $\delta$  less 30 %. In the area of deformation there is formed martensite and a matrix remains austenite. In such a way, it is possible to create a martensite grid with any specified profile consisting of areas with different hardness and plasticity of structural components.

The most effective deformation strengthening is achieved in the course of intensive plastic deformation. The intensive plastic deformation allows developing the whole complex of metals and alloys stress-strain properties, simultaneously increasing both strength and plasticity of material that is a consequence of the formation of ultra-fine-grained, submicro- and nanocrystalline structure. To the methods of intensive plastic deformation allowing the obtaining of a grain dimension 60...80 nm belongs equal-channel angular pressing at which the material is subjected to a torsion under a hydro-static pressure and also an effect upon material under working by a strain wave.

The technologies of a structure directed formation in metal alloys including the ultra-fine-grained structure formation by methods of intensive plastic deformation are described in the papers written by R.Z. Valiev, A.M. Glezer, Yu.R. Kolobov, S.A. Firstov and also Bridgeman, Thomson, Longford, Koen, Moiseyev, Trefilov, V. Rybin, V. Likhachyov and others. In engineering literature on plastic deformation resulting in the creation of an ultra-fine-grained, submicro- and nanocrystalline structure there are used such terms as: large deformations, developed deformations, mega-deformations. At the same time by the well-known at present methods of intensive plastic deformation commodity nanostructural output can be obtained only as samples of foil, small-diameter rods.

### 3. METAL MATERIAL STRENGTHENING BY STRAIN WAVE

It is known from world scientific and engineering practice that because of considerable deformation obtained due to high pressure creation in a contact area at comparatively small capacity spent the material ramp loading is rather effective both as with the purpose of destruction and with the purpose of strengthening. But,

at the application of different impact systems at one and the same blow energy different results are obtained.

The reason of this consists in that at the impact methods of surface plastic deformation (SPD) there was not taken into account the shock pulse duration defining time spent for elasto-plastic deformation, and also blow force changes during its effect upon material (blow pulse form) defining the character of material plastic yielding, there were no mechanisms for their control.

On blow pulse parameter controlling with the aid of strain waves arising at a blow it is possible to spread load impact more rationally at material elasto-plastic deformation, increase considerably procedure efficiency and with a higher accuracy create strengthened blanket characteristics required for specified conditions of the part operation (Kirichek A.V. and Soloviev D.L., 2005; Kirichek A.V. and Soloviev D.L., 2003).

A blow is considered as spreading through concussed bodies flat acoustic waves which are characterized by the law of deformation variation or efforts during time, a maximum value of efforts (wave amplitude), effort operation time (wave duration) and wave energy. These characteristics depend on geometry of colliding elements, properties of their material and concussion speed. The period of such a wave is called a shock pulse. The form of a shock pulse coming to a deformation center – the area of a tool contact with load-bearing medium will define the effectiveness of dynamic loading as a whole.

In one-dimensional variation the simulation of a longitudinal impact for perfectly elastic frameworks on condition that colliding sections are completely flat was created still in the XIX-th century by Saint -Venant (Alexandrov E.V. and Sokolinsky V.B., 1969). Analyzing the motion of an infinitesimal element of rod  $dz$  (Fig. 1) under the influence of forces caused by the interaction of the element with adjacent sections we can write

$$m \left( \frac{\partial^2 x}{\partial t^2} \right) = \left( \frac{\partial P}{\partial z} \right) dz, \quad (1)$$

where  $m = \rho F dz$  is the mass of the element  $dz$ ,  $\rho$  is the density of rod material,  $F$  is the cross-section area of the rod,  $x(z, t)$  is the longitudinal displacement of the infinitesimal element (section) of the rod,  $z$  is the section coordinate,  $t$  is the time coordinate,  $P$  is the longitudinal force.

Depending on the concussion diagram concerned the wave equation is supplemented with the corresponding initial and boundary conditions. With the aid of d'Alembert's method its solution could be presented as a sum of two functions

$$x(z, t) = f(at - z) + \phi(at + z), \quad (2)$$

where  $f(at - z)$  is the function describes sections displacement conditioned by a strain wave moving through a rod in the positive direction of the axis  $z$  (direct wave),  $\phi(at + z)$  is the function of sections displacement caused by the wave moving in the negative direction of the axis  $z$  (backward wave),  $a$  is the speed of strain wave transmission in the rod.

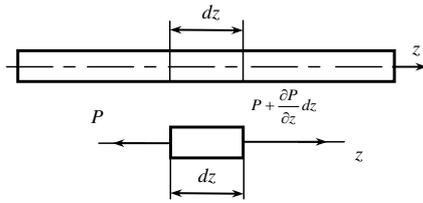


Fig. 1 – The diagram of the longitudinal force impact upon the rod element at strain wave dissemination through it

In such a way, a blow computation on the wave theory is based on the application of equations presented and boundary conditions corresponding to the concussion diagram under consideration.

A different form of shock pulses obtained at a blow with the same energy by different shock systems is confirmed by experimental oscillograms (Fig. 2), (Table 1).

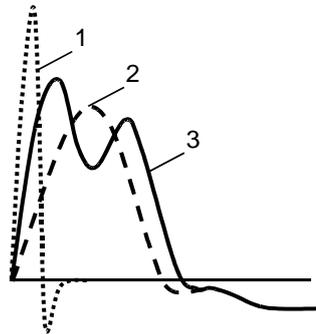


Fig. 2 – Dependence of the pulse form generated in the deformation center upon a shock system kind (Tabl 1)

Thus, at a ball blow there was formed a delta pulse with a high amplitude, small duration and low energy. At the end blow of a cylindrical rod (by a face) appears a trapezoidal pulse of lesser amplitude, but higher duration and more energy. At the face blow through an intermediate (waveguide) previously statically drawn in to a load-bearing face we have a prolonged pulse comprising a head and a tail. The pulse assessment has shown that a pulse obtained as a result of a face blow through a waveguide is noted for the most energy.

At the loading diagram face-waveguide upon a shock pulse formation in a contact patch a great influence perform: material and geometry of a shock system; correlation of mass, cross-section areas, lengths of a head and a waveguide.

To obtain different variants of energy states of a head and a waveguide after a blow one can use metals with different speeds of wave propagation. At considerable blow energy it should be expedient to make elements of the shock system (a head and a waveguide) of tool or pressed steel possessing high strength and used widely at engineering plants. Most often a waveguide has the form of a smooth cylindrical rod. A head has also a cylindrical form with small projections the dimensions of which depend upon a drive type used in the blow device.

Therefore, the deformation wave propagation control in a blow system is usually carried out by changing the correlation of cross-section areas  $r$  and the correlation of the lengths  $n$  of the head and the waveguide. The researches carried out have shown that the recommended range of geometrical and acoustic parameters of the blow system a – a waveguide used for loading with a wave deformation can be defined as  $n = 3...5$ ,  $r = 1...3$ .

Table 1 – Energy supply to the deformation center

tool	by tool blow		by head blow on waveguide
	ball	head	waveguide end
method diagram			
curve number	1	2	3

where  $P_u$  – pulse load,  $P_{st}$  – static load,  $L_1, L_2$  – head and waveguide, accordingly  $d_1, d_2$  – cross-section diameter of head and waveguide, accordingly.

The material loading procedure with a strain wave theory differs in the expanded control factor set that gives widespread possibilities for pulse parameters control, expands possibilities for deformation working allows creating a layer with a specified evenness of strengthening. A modified layer is formed as a result of multiple pulse actions the centers of which have a relative displacement. Overlapping deformation centers will define a strengthening evenness which is characterized by a contact ratio wave influence.

$$K = 1 - \frac{X}{\delta}; \quad X = \frac{s}{f60}, \quad (3)$$

where  $X$  – distance between centers of imprints, mm;  $\delta$  – imprint size measured in the direction of deformation center displacement, mm;  $s$  – billet supply speed with regard to a tool, mm/min;  $f$  – frequency of blows, Hz

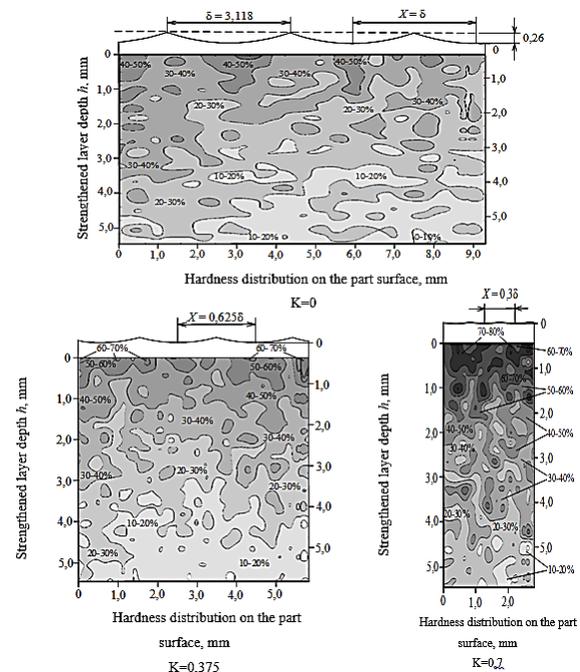


Fig. 3 – The strengthened areas distribution (strengthening degree value  $\Delta HV$  is shown in %) in the blanket after PPW by shock pulses with energy 56 J and frequency 8 Hz by a rod roller with diameter 10 mm and width 15 mm (steel 45, initial hardness HVO = 2000 MP)

The range of change  $K$  makes from 0 to 1: at  $K=0$  the imprints are not interrupted, the imprint edges verge on each other; at  $K=1$  occurs a complete overlapping of imprints, blows are delivered to the same place.

A modern level of strengthening techniques allows ensuring a strengthened layer depth up to 1 mm by dynamic working methods with a surface plastic deformation, and a strengthened layer depth up to 3 mm by static methods. The layer thickness as a result of a static-pulse impact with a strain wave is 3...4 times higher and makes 10 mm. The possibility appears to create a composite heterogeneously strengthened layer by means of a strain wave impact which is different in the presence of regular macroscopic gradient areas (fragments) with a modified structurally-phase state (Fig. 3).

With the exception of (Kirichek A.V. et al., 2004; Kirichek A.V. and Soloviev D.L., 2005; Kirichek A.V. and Soloviev D.L., 2008; Kirichek A.V. et al., 2008) and other publications of the same authors there are no recommendations for obtaining by means of surface plastic deformation a heterogeneously strengthened blanket of material reinforced fragmentary by regular macroscopic gradients of a structurally-phase state.

The contact endurance increase of a surface strengthened heterogeneously by a strain wave 2-7 times is defined.

## REFERENCES

1. E.V. Alexandrov, V.B. Sokolinsky, *Applied Theory and Computations of Impact Systems* (M.: Nauka: 1969).
2. G.P. Ivanov, L.V. Kartonova, A.A. Khudoshin, *Construction Site Engines and Road Building Machinery* 33 (1997).
3. A.V. Kirichek, D.L. Soloviev, *Strengthening Techniques and Coatings* No4, 6 (2005).
4. A.V. Kirichek, D.L. Soloviev, S.A. Silantiev, *Press-Forging Production Material Shaping* No2, 13 (2004).
5. A.V. Kirichek, D.L. Soloviev, *Strengthening Techniques and Coatings* No8, 3 (2005).
6. A.V. Kirichek, D.L. Soloviev, *Mechanical Engineering, Instrument-Making Industry* No1-2, 30 (2003) [in Russian].
7. A.V. Kirichek, D.L. Soloviev, *Russ. Eng. Res.* 28 No3, 277 (2008).
8. A.V. Kirichek, D.L. Soloviev, S.V. Barinov, S.A. Silantiev, *Strengthening Techniques and Coatings* No7 (43), 9 (2008) [in Russian].

A high (acoustic) speed of strain wave propagation in material, a possibility for the control of intensity and duration of power influence upon fragments of the blanket allow referring this working method to the methods of material intensive plastic deformation. This, in its turn, allows supposing the formation in the blanket not only a fine-grained structure of material, but also nano-structural areas as a result of the strain.

## 4. CONCLUSION

The techniques for obtaining heterogeneous materials with solid basis reinforced fragmentary with regular macroscopic gradients of a structurally-phase state allows the creation of products with high (advanced) level of stress-strain properties: high strength and carrying capacity at the simultaneous high viscosity and plasticity, high fatigue life and contact endurance.

Many enumerated techniques still waiting for their own researcher are studied either superficially, or not studied at all. Their mastering will be a main component in the basis of the creation of a gradient strengthened layer with the essential depth to provide a required carrying capacity of material under extreme operation conditions.