Effect of the structure heterogeneously hardened by impact deformation waves upon impact strength of the material

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Abstract. This work demonstrates possibilities of development of a heterogeneous hardened structure with alternating hard and plastic areas using impact deformation waves. There is a possibility of preserving impact strength of the metal material during formation process of heterogeneous hardened structure.

1. Introduction

A heterogeneous system is a system consisting of phases with different physical or chemical properties separated by surfaces, where one or several system’s properties change rapidly in a step-like manner. If such separation surfaces do not exist, the system is considered to be uniform or homogeneous.

All metal alloys used in machine engineering possess a non-homogeneous polycrystalline structure, and therefore they belong to heterogeneous materials with anisotropic physical and mechanical properties [1, 2]. To meet the requirements of “ideal” metal, the heterogeneous metallic material should have high yield strength and tensile strength together with high fatigue limit. It also should be strong and have plastic and sticky properties at the same time. So, when the material is formed and processed, the heterogeneous properties of the material must be specified.

In general, uniformity of the structure of the metallic material is controlled by introduction of alloying additives at a production stage. Thus, the material obtains required working properties.

In recent times, the heterogeneous hardened structure was successfully formed by gradient hardening treatment, such as coating, surface heat treatment, laser hardening and chemical heat treatment that form hard and plastic areas with a specified alternation in the surface layer.

The purposeful development of advanced technologies on creation of the gradient heterogeneous material with improved structural and functional properties reinforced with areas of high-strength phase surrounded by plastic and viscous layers is discouraged by the stereotype view related to necessity of uniform hardening of the surface layer. Such perception is explained by the complex effect of plastic interlayers on mechanical properties of the heterogeneous material. The transition regions from the solid material to the plastic one formed during the hardening process can become additional stress concentrators and develop fatigue micro cracks and premature failure under the action of cyclic loads.
Therefore, the use of strain hardening, which provides a smooth transition from the high-strength phase with the hardness of 6500 MPa to a plastic interlayer of the hardened material, is quite promising for the development of the heterogeneous gradient hardened structure.

In addition, hardening by surface plastic deformation (SPD) has other advantages, such as machining of parts of any size and configuration, production effectiveness, ease of implementation, mechanization and automation of the process, the possibility of local hardening in a given component representing structural stress concentrators [3-6].

For the first time ever, a strain hardened heterogeneous structure was created by using impulse waves; the method was named as static-pulse treatment [7, 8]. In case of hardening with the static-pulse treatment method, periodic impact force applies the load upon the surface using a striker via a statically loaded waveguide. When the striker hits the waveguide it forms an impulse wave which is transferred to the treated material. Static pre-loading of the waveguide with a tool does not allow the tool to leave the contact with the loaded surface after impact, providing recovery of reflected deformation waves. A geometry of the striker and waveguide is selected in such a way that the impulse waves would transfer maximum energy to the hardened metallic material. This has provided a better way to create a deeper hardened surface layer, than using well-known techniques of strain hardening, such as rolling, flattening or shot peening.

A mechanism that controls the uniformity of the hardened surface layer, depending on the parameters of the hardening with deformation impulse waves is as follows. Impulse waves form plastic impressions on the surface with a shape and a size according to specified numbering determine the depth, extent and uniformity of the surface layer hardening. A coefficient of plastic overlapping impressions is a generalized characteristic that links the size of the impression and numbering of the deformation action.

\[
K = 1 - \frac{S}{\delta f/60},
\]

where \( S \) – conveying speed of the work piece relative to the tool, mm/min; \( \delta \) – typical size of the impression measured towards a conveying direction, mm; \( f \) – impact impulse frequency, Hz.

With \( K = 0 \), the edge of one impression is adjacent to the edge of the other one; with \( 0 < K < 1 \), the impressions overlap; with \( K = 1 \) the tool indents into the same place several times [9, 10].

Such heterogeneous hardened structure works under contact cyclic loads quite effectively. As a result, the study has shown an increase of its durability up to 7 times [11, 12].

Often, machine components (gears, cams, tappets, etc) working under different types of loads at the same time, require an increase of the impact strength in addition to contact fatigue strength. However, it has been established that the hardening with increasing hardness forces the material to reduce its capabilities to withstand impact loads. No studies have been carried out on the effect of the heterogeneous hardened structure upon the change of impact toughness.

2. Results and Discussion

An experimental investigation was undertaken to establish the effect of uniformity of the steel hardened structure created by surface plastic deformation with the use of impulse waves upon impact strength.

The investigation involved a plane sample made of 30HGSA steel (initial hardness of 2800 MPa) of 6 mm thick. The sample was hardened with rod-shaped rolls: roll diameter was 10 mm and width of the roll was \( b_r = 20 \) mm, 30 mm and 40 mm. The energy of the deformation wave was \( A = 150 \) J, impact frequency was \( f = 10 \) Hz. Specific energy of blow \( a = A/b_r \) was 7.5 J/mm, 5 J/mm and 3.75 J/mm, accordingly. The heterogeneous structure was formed in the conveying direction with overlapping of plastic impressions (Figure 1). For the purpose of investigation of the impact strength, the sample was cut out across plastic impressions created on the hardened surface (section A-A) and along the impressions (section B-B). This is obvious that the hardened structure in section A-A has greater non-uniformity than in section B-B.
Figure 1. Pattern of impressions made at the flat surface of the work piece carried out with rod-shape roll at hardening with deformation wave:

1 – sample, 2 – rod-shaped roll, 3 – hardened region

$A$ – energy of impulse deformation waves, $f$ – impact frequency, $P_{st}$ – static load, $S$ – conveying speed of the work piece relative the roll, $D_r$ – roll diameter, $b_r$ – roll width, $\delta$ – typical size of the impression, mm

It has been established that with the increase in the specific energy of the impulse wave deformation used for hardening, the hardness of the hardened samples is increased and the impact strength is decreased. The maximum value of hardness for solid regions located at the top of the hardened surface layer was recorded in operation mode $a=7.5$ J/mm, $K=0.66$, the measured value was 4100-4200 MPa. The minimum value for solid regions was obtained in operation mode $a=3.75$ J/mm, $K=0.48$ the measured value was 3900-4000 MPa, size and number of solid regions are significantly less than those in the soft plastic interlayer. The hardness changed throughout the whole thickness of the hardened samples.

It has been established that with the increase of the overlap ratio, the impact strength is virtually the same. Thus, with $a=3.75$ J/mm, $K=0.48$ the impact strength measured across the plastic impressions (section A-A, Figure 1) was $117$ J/cm$^2$, and for $K=0.8$ it was $116$ J/cm$^2$. With $a=7.5$ J/mm the impact strength measured across the plastic impressions (section A-A, Figure 1) equals $108$ J/cm$^2$ as it is when $K=0.39$ and $K=0.66$ (Figure 2). The explanation implies that the impact strength is more affected by the structure of the hardened material located below the surface, in a subsurface layer at a certain depth. Hardening with overlap factor $K=0.48$ leads to development of the highly heterogeneous hardened surface layer throughout the depth of the material. Hardening with $K=0.8$ in the upper part leads to development of the hardened highly uniform surface layer. This layer has little effect on the impact strength as it is supported by the heterogeneous hardened underlayer.

It has been established that a hardened surface has larger impact strength in direction with the heterogeneous structure rather than in direction with a more uniform hardening. Thus, with $a=3.75$ J/mm, $K=0.48$ the impact strength measured across plastic impressions (section A-A, Figure 1) was $117$ J/cm$^2$, and the impact strength measured along plastic impressions (section B-B, Figure 1) was $102$ J/cm$^2$. With $a=5$ J/mm, $K=0.6$ the impact strength measured across plastic impressions (section A-A, Figure 1) was $108$ J/cm$^2$, and the impact strength measured along plastic impressions (section B-B, Figure 1) was $102$ J/cm$^2$. With $a=7.5$ J/mm, $K=0.39$ the impact strength measured across plastic impressions on the hardened surface (section A-A, Figure 1) was $108$ J/cm$^2$, and the impact strength measured along plastic impressions (section B-B, Figure 1) was $94$ J/cm$^2$. 

It has been established that with the increase in the specific energy of the impulse wave deformation used for hardening, the hardness of the hardened samples is increased and the impact strength is decreased. The maximum value of hardness for solid regions located at the top of the hardened surface layer was recorded in operation mode $a=7.5$ J/mm, $K=0.66$, the measured value was 4100-4200 MPa. The minimum value for solid regions was obtained in operation mode $a=3.75$ J/mm, $K=0.48$ the measured value was 3900-4000 MPa, size and number of solid regions are significantly less than those in the soft plastic interlayer. The hardness changed throughout the whole thickness of the hardened samples.

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3. Conclusion

Hardening with impulse deformation waves develops a heterogeneous hardened structure in metallic materials; this structure is characterized by high hardness and plasticity.

Hardening of metallic materials by impulse deformation waves contributes to an increase in hardness and size of solid areas related to the heterogeneous hardened structure of the hardened surface layer, and reduces the impact strength as well.

The increase of the impression overlap ratio within investigated range \( K = 0.39-0.8 \) virtually has no effect upon the impact strength change.

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