Strain hardening of metal parts with use of impulse wave

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Abstract. This work describes a strain hardening method with the use of impulse waves. This method increases energy transfer to the strained material extending its technological capabilities with development of a deep strengthened layer and allowing formation of a heterogeneous hardened structure using plastic deformation. This structure has specified distribution of the hard and soft (visco-plastic) areas. Due to development of the heterogeneous structure in the surface layer created by strain hardening with impulse wave, durability of parts that suffer contact fatigue loading is significantly increased.

1. Introduction

The current technology progress requires development of new methods that can strengthen metal materials as this helps to provide high physical and mechanical properties.

A hardening process involving surface plastic deformation (SPD) is successfully used for machine components, which operate under severe conditions and mainly under fatigue loads. The following SPD methods are widely used in industry: bead-blasting treatment, knurling and levelling as they form a hardened surface layer of 0.5-2 mm deep [1-3].

However, for the products operating under complicated stress in hard and extreme conditions, the point with the highest load is located at a certain depth under the surface layer and, therefore, a deeper hardened layer is needed to improve its operating properties. This layer should be more than 1-3 mm, and in extreme conditions it should be up to 6 mm deep. Therefore, new process engineering solutions are required to advance capabilities of the cold-work strengthening.

One of the directions for the development of the strain hardening technologies practices is the hardening process with the use of controlled impulse waves. The world scientific and engineering practice shows that due to significant deformations developed by the high pressure in the contact area at relatively low power, the shock loading is very effective for structural damage or a hardening purpose. However, when different impact systems with the same blow kinetic energy are involved, the result can differ. This happens because the impact effect depends on the method how the power is delivered to the deformation region.

The hardening process involving SPD in machine industry uses only short impulses with the high amplitude generated in primitive impact systems without an intermediate member.

A different shape of the impact momentum obtained in various impact systems with the same energy is described by experimental oscilloscope pictures (figure 1), (table 1) [4]. Thus, in case of the ball, the impulse had a triangle shape with the high amplitude, short duration and low energy. When
the object was hit with the flat end of the cylinder rod (striker) the impulse was of a trapezoid shape with the lesser amplitude, greater duration and greater energy. When the object was hit with the striker through an intermediate member statically pressed to the loaded surface (a wave guide), the impulse was extended, e.g. it had a leading and a trailing edge. The trailing edge is formed by the energy of deformation reflected waves and it depends on the loaded material properties. Impulse study showed that the impulse formed in case of the striker and the wave guide had the highest energy as the trailing edge prolongs the shock effect upon the loaded material and it intensifies elastoplastic strain and rises up the performance factor of the process.

**Figure 1.** Dependence of the impulse shape formed in a deformation region from the impact system

**Table 1.** Delivery of hit energy to a deformation region

| Curve number | Hit with tool | Hit wave guide with a striker |
|--------------|---------------|------------------------------|
| 1            | Hit with tool | Method                        |
| 2            | Hit with tool | Hit wave guide with a striker |
| 3            | Hit with tool | Method                        |

\[ P_u \text{ – impulse load, } P_{st} \text{ – static load, } L_1, L_2 \text{ – lengths of a striker and a wave guide, accordingly, } d_1, d_2 \text{ – cross sections of a striker and a wave guide, accordingly} \]

2. Results and Discussion

Based on the aforesaid, the gradient toughening method was developed. This method implies static and impulse treatment (SIT) that uses impulse waves [5] to develop plastic deformation. In SIT hardening the striker and the wave guide system is used, which generates a plane acoustic wave characterized by the law of the force variation (the deformation wave amplitude) in the course of time, the maximum value of the force, duration of the force (deformation wave duration) and energy of the deformation wave. These features depend on the striker geometry and the wave guide, material properties and impact speed. This wave period is called impact impulse. The form of the impact impulse delivered into the deformation region, for example, a tool contact area with the hardened material, shall define effectiveness of dynamic loading. Static pre-pressing of the wave guide and the tool does not allow the striker to lose contact with the loaded surface after impact providing recuperation of the reflected deformation waves. During hardening, the impulse shape is adapted to the maximum extent to the properties of the material and loading conditions. This adaptation increases a performance factor and extends treatment capabilities providing a deep 6–10 mm hardened layer.

Design facilities for the hardening with impact deformation waves are: an impact impulse generator and production tooling that provides implementation of the treatment process [6].
Design and process-dependent parameters for the hardening with impact deformation waves are: a form and measurements of the deforming tooling and new SPD parameters – a form and measurements of impact system components.

An impact system incorporates a striker and a smooth cylinder wave guide. The system can generate singular square-wave pulses; the amplitude of such pulse defines the force of impact.

The strain hardening tool is fixed at the free end of the wave guide, or the wave guide end is inserted into the required form and works as a tool. The tool can be of a spherical (ball) or roll (rod, disk or profiled rolls) shape. Depending on deformation regions generated at the same time the tool can be a single-contact or multi-contact tool. The tool represents a link transmitting the impact impulse to the loaded metal piece, therefore, the tool shape and measurements define a degree of the pulse distortion delivered through such tool. The shape and measurements of the tool will have an effect upon the configuration and the size of the single plastic impressions.

In the process of hardening with impulse deformation waves the form of the impulse can be adapted to physical and mechanical properties of the loaded material, tool’s curvature and the loaded surface, when maximum kinetic energy of the impulse is transferred to the material. For this purpose they use characteristic of structural resistance of the material, which is subjected to indentation of the tool and expressed in terms of the multiplying factor determined by a “force – impression” dependence in the range of \((2.5…7.5) \times 10^8\) N/m, which is taken in account in calculation of geometrical relationship of the striker and the wave guide [7].

Basic process parameters of the deformation wave hardening technique include energy and frequency of impulses, static pre-pressure of the tool applied to the hardened surface and the depth of advance.

A static part of the loading force should provide the effective use of reflected deformation waves when the tool is impressed into the material; it should equal more than 10% of the impact loading.

The energy of the impact wave is one of the main parameters that defines a plastic flow value. Usually, SPD consumes the energy for plasto-elastic deformation, rubbing friction between tool and a contact spot and the energy of the wave. The energy used for the wave processes can be controlled by changing of the form and measurements of the impact system. Directional deformation waves, generated in the impact system at the moment of impact, develop the best form of the impulse for a given condition. Kinetic energy of the impulse (up to 200 J), determined by striker’s speed and weight and its shape and size, determine the amplitude, duration and the form of deformation wave generated in the impact system. These factors define an impulse waveform in the deformation region.

Impulse frequency (5-40 Hz) controls the pulse ratio and a number of the deformation action. The pulse ratio couples the duration of the impact deformation waves and impulse frequency. It represents an important characteristic of impulse systems. A high pulse ratio is used mainly in systems with high frequency and short duration of the impact; and a low pulse ratio is used mainly in systems with low frequency and long duration of the impulse.

Along with impact frequency and the geometry of the impression, the advance controls the amount of the dynamic loading. To increase the hardening performance factor these parameters increase the impact power of the impulse generator to a maximum value and treat the material with maximum possible frequency delivering the required energy. In this case the number is controlled by the change of advance; in general, the advance does not exceed 2000 mm/min.

The above mentioned parameters of hardening with deformation waves shall be regarded as one system that controls surface layer quality characteristics.

The energy of the impact waves spent for plastic deformation of the hardened material is determined by design parameters: the form and measurements of the striker and the wave guide; and process parameters, such as impact kinetic energy and static pre-pressure of the tool applied to the surface to be hardened. The change in these parameters leads to microdisplacement of the tool and development of the impression of a definite size, e.g. – a singular trace of the tool. The shape and the size of the impression determine the pattern of change of material properties along the depth of the surface layer.
The size of single impressions and their relative displacement are determined by the process parameters: impact frequency and advance, adjust overlap of impressions. This overlapping defines uniformity of hardening providing a significant effect upon performance characteristics of the hardened surface layer [8, 9].

Specified deformation wave hardening parameters offer wide technological capabilities to create a hardened surface layer. The obtained results include the following:

- the surface layer with maximum hardness up to 6500 MPa and depth of hardening of 6-10 mm; to ensure specified accuracy and to reduce roughness of the material, subsequent fine machining can be used (a fine or finish turn operation, milling, abrasive machining, SPD finishing and hardening processing); a deep depth of the hardened layer allows selecting the allowance for machining for non-treated steel up to 1-1.5 mm, and for heat-treated steel – up to 0.5 mm;
- the surface layer with maximum hardness up to 6500 MPa and depth of hardening of 2-3 mm and low surface roughness up to Ra = 0.08-0.1 µm.

Adjusting the uniformity of hardening it becomes possible to form [10, 11]:

- a complete unevenly hardened surface layer with a specified change of alternating hard and malleable areas in depth and along the surface as well;
- a complete uniformly hardened surface layer similar to the layer obtained by using known SPD methods (e.g. knurling, levelling, etc);
- a uniformly hardened thin upper layer (up to 1-1.5 mm) and an unevenly hardened layer located under the upper one;
- a uniformly hardened thick upper layer (1.5-3 mm) and an unevenly hardened layer located under the upper one.

High (acoustic) speed of propagation of the wave deformation in the material, the ability to control the intensity and duration of forces acting on fragments of the surface layer suggests this method of treatment to be a method of intensive plastic deformation of the material [12-15]. The study of the metal samples’ structure hardened by deformation waves, revealed the presence of nanostructured areas similar to that obtained by intensive plastic deformation. The size of such areas varies from 30 nm to 90 nm. The uniformity of their interchange can be adjusted by the energy of impulse deformation wave, size and the geometry of the tool’s contact spot and the deformed surface, the number and a displacement level of emerging deformation regions [16].

Field investigation of the heterogeneous hardened structure obtained by impulse wave deformation showed its durability increase under the contacting fatigue loads up to 7 times.

3. Conclusion

The method of gradient hardening, which uses impulse waves to create plastic deformation, has been developed. This method is characterized by high energy efficiency and it generates a greater depth of the hardened surface layer up to 6-10 mm.

With plastic deformation it becomes possible to form a heterogeneous hardened structure in the surface layer as a result of the multiple action of deformation waves shifted in space and time in relation to each other.

There is determined high efficiency of use of hardening by impulse deformation waves forming a heterogeneous hardened structure to improve performance characteristics of machines’ parts experiencing contact fatigue loads.

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References

[1] Odintsov L G 1987 Strengthening and Parts Finishing by Surface Plastic Forming: Reference Book (Moscow: Mechanical Engineering) p 328
[2] Smelyansky V M 2002 Mechanics of Parts Strengthening by Surface Plastic Forming (Moscow: Mechanical Engineering) p 300
[3] Schneider Yu G 1998 Techniques for Pressure Finishing: Reference Book (St. Petersburg: Polytechnic)
[4] Kirichek A V and Soloviev D L 2013 Properties and Technology for Quasi-Composite Blanket Using Natural Reinforcement of the Metal by Strain Affected Areas Journal of Nano and Electronic Physics 5(4) 04010(5pp)
[5] Kirichek A V and Solov’ev D L 2001 The methods of dynamic surface strengthening by plastic deformation Kuznechno-Shtampovochnoe Proizvodstvo (Obrabotka Metallov Davleniem) 7 28-32
[6] Kirichek A V, Solov’ev D L and Silant’ev S A 2002 Impact device for static-pulse deformation working Kuznechno-Shtampovochnoe Proizvodstvo (Obrabotka Metallov Davleniem) 10 35-40
[7] Kirichek A V, Soloviev D L and Altuhov A Yu 2014 Deformation Wave Hardening of Metallic Materials Journal of Nano and Electronic Physics 6(3) 03069(4pp)
[8] Panin V E and Deryugin E E 2003 Mesomechanics of the formation of banded structures at mesoscopic and macroscopic levels The Physics of Metals and Metallography 96 2-15
[9] Kirichek A V, Solov’ev D L and Silant’ev S A 2004 Influence of regimes of static-pulse processing on uniformity of superficial layer hardening Kuznechno-Shtampovochnoe Proizvodstvo (Obrabotka Metallov Davleniem) 2 13-17
[10] Kirichek A V and Solov’ev D L 2008 Creating heterogeneous surface structures by static-pulsed treatment Russian Engineering Research 28(3) 277-279
[11] Kirichek A V, Soloviev D L and Altuhov A Yu 2014 Production of Quasicomposite Surface Layer of a Metal Material by Shock Wave Strain Hardening Journal of Nano and Electronic Physics 6(3) 03070(4pp)
[12] Zhu Y T, Huang J Y, Gubicza J, Ungár T, Wang Y M, Ma E and Valiev R Z 2003 Nanostructures in Ti processed by severe plastic deformation Journal of Materials Research 18(8) 1908-1917
[13] Valiev R Z, Krasilnikov N A and Tsenev N K Plastic 1991 Deformation of Alloys with Submicro-Grained Structure Materials Science and Engineering 137 35-40
[14] Valiev R Z, Korznikov A V and Mulyukov R R 1993 Structure and Properties of Ultrafine-Grained Materials Produced by Severe Plastic Deformation Materials Science and Engineering 168 141-148
[15] Siegel R W and Fougere G E 1995 Mechanical properties of nanophase metals Nanostr. Mat. 6 1-4
[16] Kirichek A V and Soloviev D L 2013 Nanostructure Changes in Iron-Carbon Alloys as a Result of Impulse Deformation Wave Action Journal of Nano and Electronic Physics 5(4) 04009(4pp)