STUDY OF COMPARATIVE CHARACTERISTICS OF ULTRASONIC IMPACT AND OPTIMIZATION OF DEFORMATION TREATMENT PROCESSES

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Abstract
Over the last few years, great benefits of ultrasonic impact treatment (UIT) have attracted considerable attention of many researchers and technologists to the application of this method. The paper presents the methodology, a dynamic model and the results of the study on the effectiveness of single (random) impacts and ultrasonic (random) impact that are currently used in deformation technologies. This type of work was performed and is published for the first time.

Introduction

Ultrasonic impact treatment originated in Russia in the early 70s [1] was further developed at Kvant, NSTC and Applied Ultrasonics [2] and currently attracts the attention of researches and technologists in many countries.

Since plastic deformation is one of effects accompanying this method, interest in UIT caused drawing analogies between UIT and other conventional deformation treatment methods such as shot peening (SP), hammer peening (HP) and ultrasonic peening (UP).

The authors, drawing the analogies, in particular those of [3] and [4], are right in their suggestion that the impact is the basic deformation energy carrier. However, they do not account in full measure for the features of the mechanism and characteristics of the ultrasonic impact described in [1] and [2], as well as for the results obtained in a number of projects carried out in accordance with procedures of the International Institute of Welding [5].

This work presents the results of experimental research on the efficiency of random impacts caused by a single impulse of force [3] with boundary conditions of hammer peening, and the impact with boundary conditions of ultrasonic peening as defined in [4] and ultrasonic impact as defined in [1]. The paper also presents a dynamic model of the ultrasonic impact as defined in [1] and the impact as defined in [4].

Comparison method

Let us first define that the ultrasonic impact upon the impact object in accordance with [1] and [2] occurs under the action of the impulse of force (generated by ultrasonic transducer vibrations) at the rear end of a freely axially moving pin indenter with a normalized wave length directly contacting the transducer tip and the impact surface. At this impact phase, the indenter vibrates synchronously and in-phase with ultrasonic transducer vibrations at its resonance frequency that defines the carrier frequency in the impact spectrum and causes impact surface vibrations adequate to this frequency in the impact area without indenter rebounding from the transducer tip and impact surface.

Thus, the ultrasonic impact, along with plastic deformation of the surface material and stress impulse generation in the subsurface material, is accompanied by ultrasonic plastic deformation of the surface material and ultrasonic stress wave generation in the subsurface material.

At the same time, the impact caused by a single impulse of force creates the area of plastic deformations on the impact surface and provides for stress impulse propagation in the subsurface material.

The experimental conditions of acoustic energy transfer from the transducer to the impact surface were the same, while different types of indenters were used.

Table 1 : Indenter dimensions

No.	Type	Radius of work surface, mm	Length, mm
1.	Pin ∅6.35mm	4	25
2.		4	9.2
3.		5	17.1
4.		6	29.0
5.	Ball	4	-
6.		5	-
7.		6	-

The impact efficiency using indenters given in Table 1 was evaluated under the following initial conditions:

- preset pressing force of the tool movable mass against the impact surface – 0, 5, 10, 15 and 25 kg;
- before impacting the tool movable mass is withdrawn from the surface by 2 and 10mm;
- vibrational amplitude of the waveguide tip under no-load conditions – 0 and 50 µm.

Nos. 2-7 are indenters having equal masses and work surface radiuses (see Table above). Specimens were made of aluminum alloy AMg5 and steel 20.

The scatter of results obtained from measuring and calculation of the indentation area and volume did not exceed one percent.

The following was controlled during testing:

- indentation diameter;
- length of double-side impact;
- length of single impact upon the impact surface.

The indentation diameter was evaluated using measuring microscope to the three-place accuracy.

A sample estimate was made for indentation volume using the weight method. The results obtained have confirmed the calculation data.

The length of impact was controlled using an oscilloscope connected to the contact sensor.

Results

The results are presented in diagrams, showing the relationship between the impact efficiency in terms of the area and volume of indentations made by different indenters and initial impact conditions mentioned above.

Ultrasonic vibrations of indenter create plastic deformation at the instant of impact. This is confirmed by a respective increase of the area and volume of indentation. Figure 1 shows that when the concentrator tip is withdrawn from the rear end of indenter at a distance close to the actual impact amplitude during UIT or HP, being equal to 2 µm, the ultrasonic impact, as compared to the single impact adequate to hammer peening, increases the indentation area by up to seven times over the entire range of initial experimental conditions.

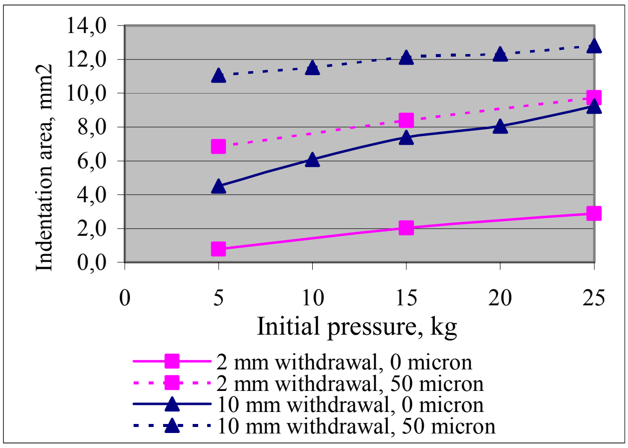


Figure 1 : Indentation area on ultrasonic and ultrasonic-free impacting upon aluminum specimen using pin indenter ∅6.35x25mm with working surface radius of 4mm when the movable mass is withdrawn from the surface by 2 and 10mm.

The analysis of the impact efficiency by different indenters in terms of microhardness magnitude and distribution has shown that the ultrasonic impact by pin indenter increased the microhardness of the aluminum specimens from HV_{20} 64 to HV_{20} 80, while impacting by the ball indenter up to HV_{20} 72. In the former case the depth of hardening is 0.4mm, and in the latter case this is 0.3mm. It should be considered that the results were obtained by a single impact and that these determine the treatment effectiveness and performance in depth in the non-linear proportion to the impact length and treatment time. We have already demonstrated that UIT hardens the materials of this sort to the depth of not less than 2mm.

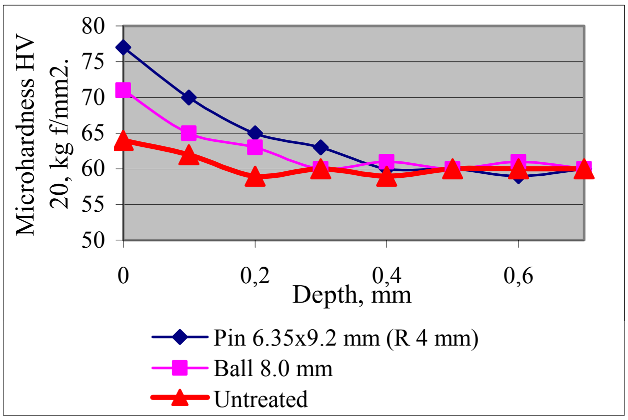


Figure 2 : Microhardness distribution across the thickness of aluminum specimen on impacting using indenter with working surface radius of 4mm when the movable mass is withdrawn from the surface by 2mm (vibrational amplitude 50 µm).

As can be seen, the efficiency of a single ultrasonic impact by the pin indenter is by 20 to 40% greater than that of the ball indenter. Since each subsequent impact will be accompanied by the accumulation of this difference, the actual impact efficiency will be determined by the impact length.

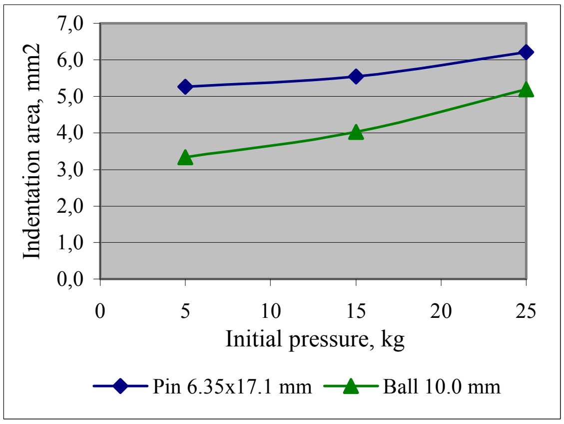


Figure 3 : Indentation area on impacting steel specimen using indenter with working surface radius of 5mm when the movable mass is withdrawn from the surface by 10mm (vibrational amplitude 50 µm).

Thus, of particular interest in this study is the comparison of time characteristics of impacts transformed at the impact surface via pin and ball indenters.

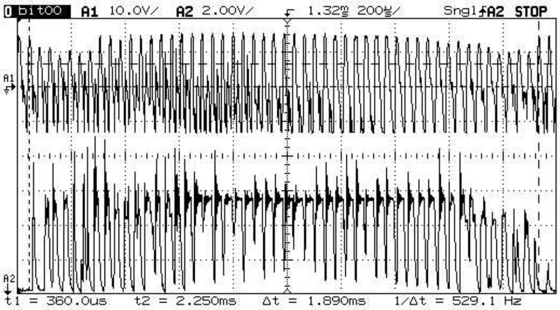


Figure 4 : Oscilloscope picture of transducer excitation (top) and ultrasonic impact excitation (bottom) using pin indenter with working surface radius of 5mm, pressure of 50 kg and movable mass withdrawal of 2mm.

From oscilloscope pictures shown in Figure 4 it can be seen that the pin indenter impact is accompanied by its distinct ultrasonic vibrations in the material of impact surface. At the same time, from the oscilloscope picture shown in Figure 5 it can be seen that the excess freedom of motion of the ball indenter causes single rebounds from the impact surface even with higher pressure.

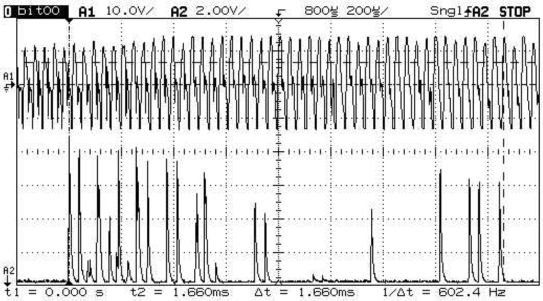


Figure 5 : Oscilloscope picture of transducer and impact excitation using ball indenter with working surface radius of 5mm, pressure 50 kg and movable mass withdrawal of 2mm.

It should also be taken into account that when the ball is impacted the compressive stresses cause distribution of recovery elastic force through the entire area of diametral section that is generally much greater than the indentation diameter. Moreover, the pin indenter produces the indentation with diameter much closer to that of the indenter as compared to the ball of equal mass. Thus, additional elasticity occurs in the ball indenter (relative to the pin indenter), which causes the indenter to rebound earlier.

Dynamic model of impact

Calculation of a stressed state at any instant of time is done using the global stiffness matrix $\sum_{i=1}^{k}\left[K^{(e)}\right]$, where K = the number of finite elements in the model; *(e)* = the total number of degrees of freedom of points of the finite elements. The variation of the model state with time is described by direct calculation of discrete values of stress-strain function in the oscillating system with lumped parameters (OSLP), as well as by taking into account the effect of external harmonic force on the elements of the oscillating system with distributed parameters (OSDP) coupled by this force. It was found that OSLP corresponds to the movable mass with a spring and OSDP to the indenter rigidly attached to the impact object by the external harmonic force.

Model design is accomplished provided that each finite element is in equilibrium. The summary stiffness matrix of the finite element is as follows:

$$\left[K^{(e)}\right] = \int [\beta]^T [E][\beta] dV ,$$

where:

dV = increment (or decrease) of the finite element volume;

$[\beta]$ = deformation matrix of finite element;

$\left[K^{(e)}\right]$ = stiffness matrix of finite element;

$\xi\eta\zeta$ = space of non-dimensional coordinates;

$\vec{U}^{(e)}$ = resultant vector of free displacements of finite element points;

$\vec{u}(\vec{r})$ = displacement field of all finite element points;

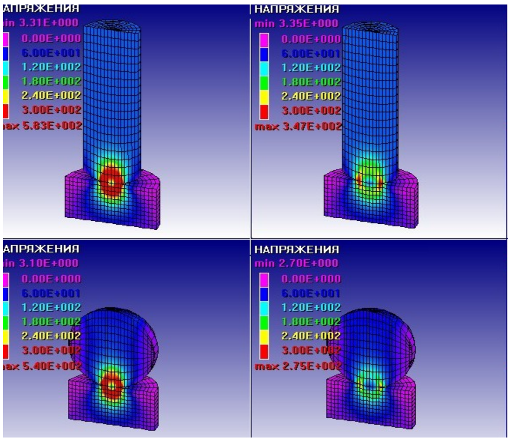
Ψ_r = finite element geometry function;

$\vec{\varepsilon}(\vec{r})$ = strain field between all points of finite element;

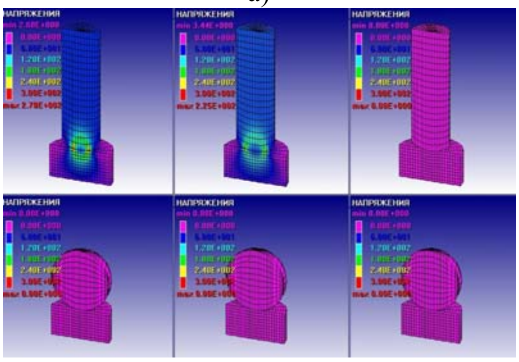
$\vec{\sigma}(\vec{r})$ = stress field between all points of finite element;

$[E]$ = matrix notation of the coefficient of elasticity, allowing for all types of deformation (compression, tension, shearing, torsion).

The model makes it possible to analyze and show the change of the stress field in the indenter and impact object during impact under the effect of external forces and initial conditions specified above. Discrete modes of deformation for pairs indenter-impact object are shown in Figure 6.



a)



b)

Figure 6 : Discrete representation of ultrasonic impact by pin indenter and impact by ball indenter.
a) "Parallel operation" of indenters
b) Early rebound of ball indenter and continuing "operation" of pin indenter

The result of the analysis of the impact efficiency based on the impact length made by dynamic model is shown in Figure 7. By comparing the dynamics of embedding indenters into the material being impacted it can be seen that the ball indenter displacement ceases as the impact force, expressed using contact stresses, decreases. At the same time, the embedding of the pin indenter continues. The flatter portion of the curve shows the effect of ultrasonic plastic deformation.

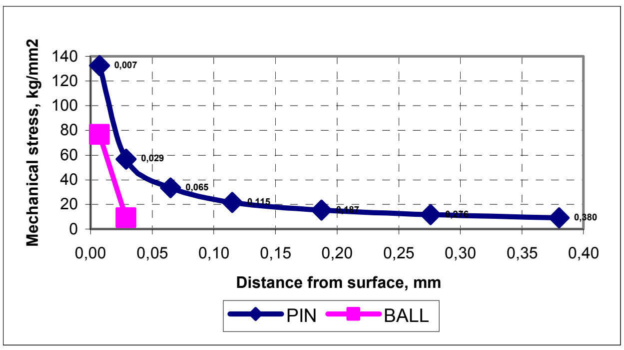


Figure 7 : Comparison of efficiency between ultrasonic impact by pin indenter and single impacts by ball indenter.

Thus, it is shown that the greater efficiency of the impact by pin indenter is due to the following advantages of the pin indenter over the ball indenter: localization of the impact energy, the impact length and the ultrasonic phase synchronous to the sought-for impact.

Conclusion

1. Along with impulse deformation of impact surface, the ultrasonic impact is accompanied by ultrasonic deformation of the surface, modification of material properties and generation of ultrasonic wave in the material of the object.
2. These properties of the ultrasonic impact define its greater efficiency as compared to other methods of surface strain hardening.
3. The ultrasonic impact by pin indenter fundamentally changes the nature of the interface and relationships in the system ultrasonic transducer – indenter – impact object.

References

[1] E.S. Statnikov et al., "Ultrasonic head for deformation strengthening", Author's certificate No.472782. "(Priority from April 1972), Inventions Bulletin, No.21, Moscow, 1975.
[2] E.S. Statnikov, "Guide for application of ultrasonic impact treatment for improving fatigue life of welded structures", IIW Doc. XIII-1757-99.
[3] P.J. Haagensen, "Weld Improvement Methods – Applications and Implementations in Design Codes", invited paper at the Conference on Fatigue of Welded Structures, Senlis, Paris, France, 12-14 June 1996.
[4] G.I. Prokopenko, T.A. Lyatun, "Study of surface hardening conditions by means of ultrasound", Physics and Chemistry of Material Processing, No. 3, pp. 91-95, 1977.
[5] E.S. Statnikov, V.O. Muktepavel, V.I. Trufyakov, P.P. Mikheev, A.Z. Kuzmenko and A. Blomqvist, "Comparison of ultrasonic impact treatment (UIT) and other fatigue life improvement methods", IIW Doc. XIII-1817-00.