Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Ultrasonics 44 (2006) e533–e538
Ultrasonics
www.elsevier.com/locate/ultras

Physics and mechanism of ultrasonic impact

Efim Sh. Statnikov [a,b,*,1], Oleg V. Korolkov [b,1], Vladimir N. Vityazev [b,1]

[a] *Applied Ultrasonics, 5871 Old Leeds Rd., Irondale, Birmingham, AL 35210, USA*
[b] *Northern Scientific and Technology Company, 6, Voronin St. Severodvinsk, Arkhangelsk Region, 164500, Russia*

Available online 6 June 2006

Abstract

More and more experts and researchers in industry express their interest in the application of deformation effects of various peening techniques on the metal surface. This is primarily due to a relatively simple directional change in condition at the surface and in subsurface layers of the material as a result of plastic deformation due to impulses of force caused, among other things, by converting ultrasonic oscillations of various impacting elements (indenters) at the treated surface.

These effects are of a stochastic nature and their duration (or the time of impact) is generally measured in units of microseconds. To obtain relatively uniform coverage, an operator may use several treatment passes. However, a stochastic nature of single impacts makes it difficult to obtain a uniform distribution of deformations and hence surface characteristics as specified, in particular, by the engineering standards.

We have developed the methods and means of implementing the ultrasonic impact and controlling its parameters. A fundamental distinction of the ultrasonic impact is that its duration is measured in the range from hundreds of microseconds to units of milliseconds, while the parameters responsible for the effects upon the surface may be adjusted according to the task.

It is important to note that in the frequency range of processing ultrasound of up to 80 kHz this feature of the ultrasonic impact allows utilizing the plastic deformation region as a matched membrane to transmit ultrasonic oscillations and excite ultrasonic stress waves in the material being treated. These phenomena, in turn, initiate highly effective relaxation processes, plastic deformation and, as a result thereof, effects upon the structure and properties of the material, which are adequate to the task.

This paper describes the theory and the results of the experimental investigations into the physics of the ultrasonic impact. Also, the mechanism of the ultrasonic impact implementation based on high-power ultrasonic transducers is addressed. The paper is aimed at engineers and researchers in the area of industrial application of high-power ultrasonics.

Keywords: Surface; Deformation treatment; Peening; Ultrasonic impact; Duration of impact

1. Introduction

Improvement techniques, specifically post-weld processing of joints made of various steels and alloys, have been extensively investigated and used in practice over the past few years. The International Institute of Welding (IIW) gives much attention to such treatment techniques [1]. Ultrasonic impact treatment (UIT), which was originally developed in Russia for the shipbuilding industry in the early 1970 s [2], has been acknowledged by experts and engineers in various countries and beginning in 1998 this technique under the trademark *Esonix* UIT has gained great momentum for commercial development in the USA, in particular, on sites and under programs of the Federal Highway Administration (FHWA).

The UIT technique belongs to deformation methods affecting the surface and has certain common features with well-known surface plastic deformation methods (peening methods) such as hammer peening (HP), shot peening

* Corresponding author. Address: Applied Ultrasonics, 5871 Old Leeds Rd., Irondale, Birmingham, AL 35210, USA. Tel.: +1 205 951 7747; fax: +1 205 951 7750.
E-mail addresses: estatnikov@appliedultrasonics.com, nstc@uit.arh.ru (E.Sh. Statnikov).
[1] Tel./fax: +7 8184 584318.

0041-624X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.ultras.2006.05.119

(SP) and ultrasonic peening (UP). However, in addition to safe and environmentally friendly operation, a different physical nature of UIT [3] is responsible for its higher effectiveness, possible fine adaptive control of the process parameters, automated in-process control of the treatment quality, and on-going monitoring of the treatment. The schematic diagram of *Esonix* UIT is shown in Fig. 1 [4]. The essential distinctive features of UIT are presented in many publications and official IIW papers, for example [5]. *Esonix* UIT is widely used in fabrication, maintenance and repair of welded metal structures [6] and provides the following: (a) creation of favorable compressive stresses in the treated zone; (b) reduction in residual welding tensile stresses in a welded joint; and (c) reduction in external stress concentration through the formation of a smooth transition at the weld toe due to ultrasonic plastic deformations. Comprehensive investigations of the *Esonix* UIT effectiveness have shown that this technique is absolutely more beneficial in comparison with the well-known methods of improving fatigue resistance of welded joints, which are based on using various peening treatments and heat effects [7].

It should be noted here that parameters of random events of the effect upon the treated surface that accompany well-known strain hardening methods, including ultrasonic peening (UP) [8], are virtually independent of the designer or operator performing the procedure and thus this limits the ability to select and control the process parameters that have substantial effect on the treatment effectiveness and quality. By contrast, *Esonix* UIT is characterized by a wide range of varying specified parameters and on this basis enables attaining the effects, which are adequate to a wide range of tasks being solved.

Investigations showed that the ultrasonic impact is the major factor responsible for intense plastic deformation during *Esonix* UIT [9]. A combined action of impact-induced plastic deformations and intense ultrasonic stress waves during reboundless phase of the impact creates necessary prerequisites to control properties and condition of the treated surface. In addition, it should be considered that *Esonix* UIT is characterized by possible fine adjustment of impact parameters such as amplitude, phase, frequency, duration and mass that are reduced to the impact point and responsible in the aggregate for the impact energy (work) and distribution thereof in time.

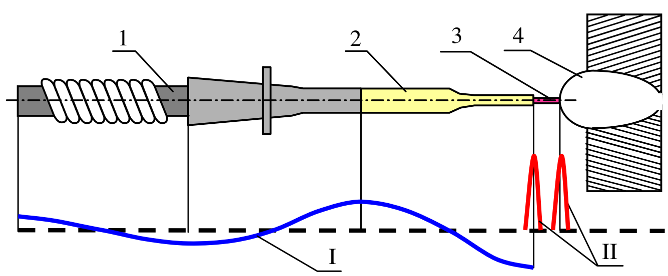

Fig. 1. Schematic diagram of *Esonix* UIT (1 – magnetostrictive transducer, 2 – waveguide, 3 – indenter, 4 – treated surface, I – ultrasonic oscillations, II – impact impulses).

2. Characteristics of impacts initiated by continuous and pulse excitation of ultrasonic transducer at its resonant frequency

The conversion of continuous energy flow (compressed air or electrical current in hammer peening, compressed air or rotating rotor in shot peening, electromagnetic or piezoelectric oscillations in ultrasonic peening) into random impulses of force at the treated surface may be considered to be the common feature of peening techniques.

One of major features of *Esonix* UIT is the pulse excitation of impulses of force at the treated surface.

The recording of random impacts under continuous excitation (peening) and the impacts generated under pulse excitation in accordance with *Esonix* UIT is shown in Figs. 2 and 3.

Analysis of the oscilloscope picture shown in Fig. 2 demonstrates that when a transducer is continuously excited the percentage of time during which the stochastic impacts occur, in the case of the "peening" variation, is not more than 25% of the total transducer operation time. It means that in the process of ultrasonic peening, for example, at least 75% of power, which is inherently small, is spent for unproductive processes. Also, under continuous excitation in accordance with the UP method the duration of each random impact event is no longer than units of microseconds.

Analysis of the oscilloscope picture shown in Fig. 3 demonstrates that under pulse excitation the total time of impacts is commensurable with the excitation time and at least 75% of its integral value.

3. Ultrasonic impact theory

To implement the stochastic and ultrasonic impacts the ball and the rod were respectively taken. This is validated by simple mathematical representation of the ball as a lumped mass, which works primarily during single random impacts, and the rod as an object with distributed mass, whose parameters directly affect the ultrasonic impact characteristics.

In such a model, the time parameters of the ultrasonic impact is assessed through the calculation of a stressed state of the rod with distributed parameters and of lumped mass (ball) at any instant of impact, which is done using the global stiffness matrix $\sum_{i=1}^{k}[K^{(e)}]$, where K is the number of finite elements in the design model (rod-ball) and (e) is the total number of degrees of freedom of the finite element points [9]. The variation of the model state with time was 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 the external harmonic force on the elements of the oscillating system with distributed parameters (OSDP) coupled by this force. It is agreed that for both OSLP and OSDP the validity of the initial conditions is verified by mathematical and physical experiments with

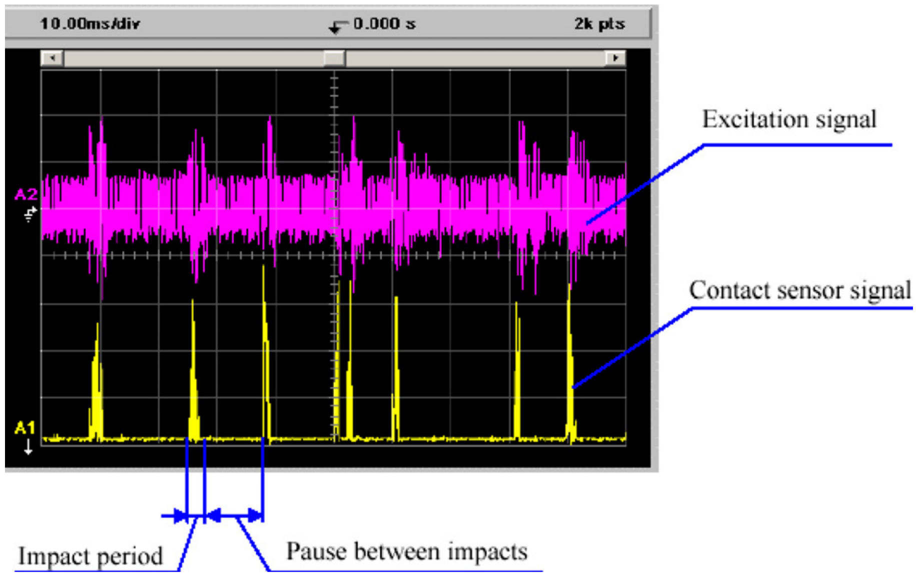

Fig. 2. Oscilloscope picture of impacts under continuous excitation (peening).

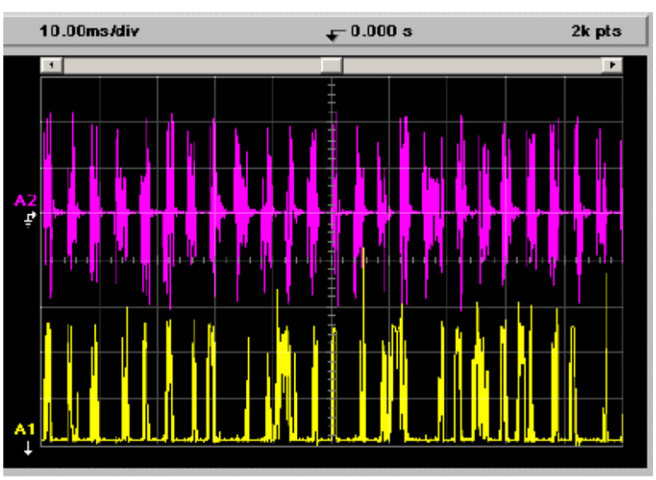

Fig. 3. Oscilloscope picture of impacts under pulse excitation in accordance with *Esonix* UIT.

the results presented in Figs. 4 and 5, respectively. OSLP is the movable mass (of the tool) with a spring and OSDP is

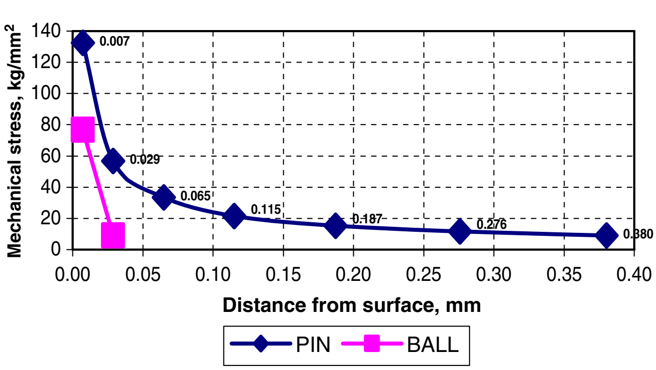

Fig. 4. Comparison of efficiency between ultrasonic impact by pin indenter and single impacts by ball indenter.

the indenter (impacting element) rigidly attached to the impacted object by the external harmonic force.

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

$$[K^{(e)}] = \int [\beta]^T [E][\beta]\, \mathrm{d}V,$$

where:

$\mathrm{d}V$ is the increment (or decrease) of the finite element volume;
$[\beta]$ is the deformation matrix of finite element;
$[K^{(e)}]$ is the stiffness matrix of finite element;
$\xi\eta\zeta$ is the space of non-dimensional coordinates;
$\vec{U}^{(e)}$ is the resultant vector of free displacements of finite element points;
$\vec{u}(\vec{r})$ is the displacement field of all finite element points;
Ψ_r is the finite element geometry function;
$\vec{\varepsilon}(\vec{r})$ is the strain field between all points of finite element;
$\vec{\sigma}(\vec{r})$ is the stress field between all points of finite element;
$[E]$ is the matrix notation of the coefficient of elasticity, allowing for all types of deformation (compression, tension, shearing, torsion).

The results of the analysis of the impact efficiency, which is adequate to the impact length, are shown in Fig. 4. By comparing the dynamics of indenter embedding into the material it can be seen that the indenter displacement at single impact of the lumped mass ceases as the impact force, expressed by contact stresses, decreases. At the same time, the embedding of the pin indenter continues at substantially smaller forces of impact and hence smaller accompanying contact stresses with ultrasonic oscillations included into the design model. Thus, the flatter portion of the design curve in Fig. 4 shows the effect of increased

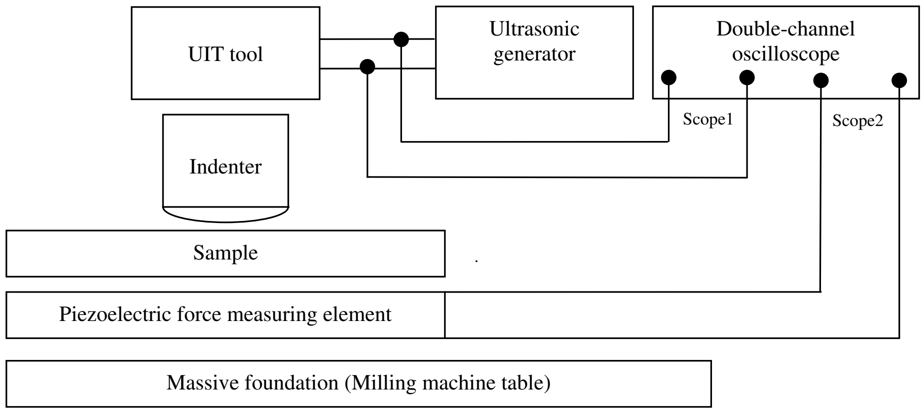

Fig. 5. Schematic diagram of experimental setup for evaluating ultrasonic impact effectiveness.

duration of the ultrasonic impact and ultrasonic plastic deformation at smaller deforming forces.

4. Experimental verification of ultrasonic impact

The schematic diagram of an experimental setup for evaluating ultrasonic impact effectiveness is shown in Fig. 5. The photograph of the setup is shown in Fig. 6 wherein the same components are designated. In a given experiment, a metallic sample is mounted on the milling machine table and ultrasonically impacted using an indenter of the UIT tool, as shown in Figs. 1 and 5. The ultrasonic transducer excitation signals and a signal from the force measuring element, installed under the sample, are synchronously recorded by a dual-channel oscilloscope. The excitation of the ultrasonic transducer of the UIT tool was terminated after each analyzed single rebound of the tool from the surface. The depth of the indentation from the impact was measured by means of a micrometer. In order to find the volume of the metal, displaced from the indentation due to plastic deformation, the sphere segment equivalent to the indentation diameter was calculated, the radius of the sphere being equal to the radius of the round end of the indenter. The scatter of the results did not exceed 5%. The development of plastic deformation in time (Fig. 7) was evaluated by calculating the movement of the indenter during plastic deformation of the treated material through double integration of the signal from the force measuring element under boundary conditions specified based on the indentation measurement results.

As follows from the analysis of the experimental diagram shown in Fig. 7 the maximum work of plastic deformation during ultrasonic impacts, lasting hundreds of microseconds during *Esonix* UIT, occurs during the phase of reboundless synchronous oscillations of the indenter.

The diagram shown in Fig. 7 demonstrates the influence of ultrasound (more precisely, the ultrasonic stress wave in the treated material, which are initiated by reboundless oscillations of the indenter during impact) on the plastic deformation efficiency. As can be seen from the diagram, with comparable duration of single impact impulses at the onset of the ultrasonic impact, the total percentage of

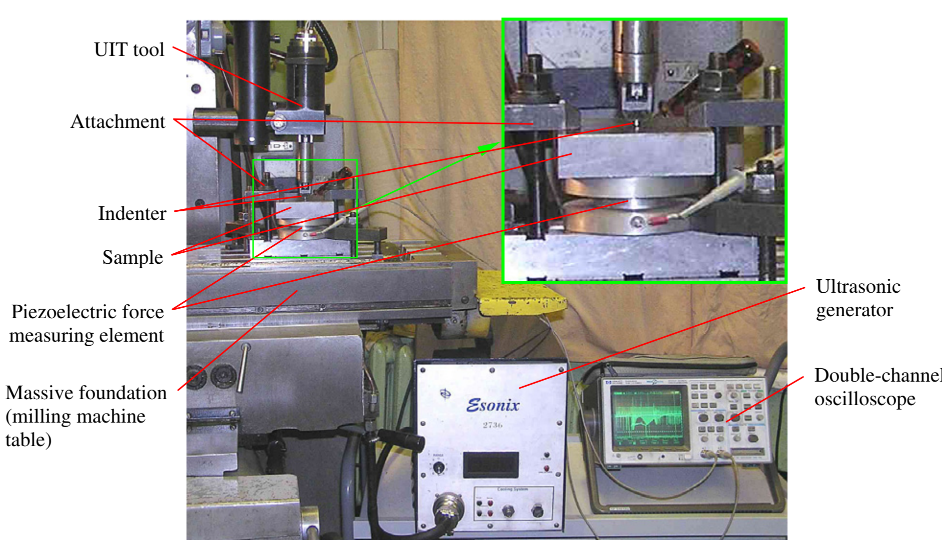

Fig. 6. Experimental setup for evaluating ultrasonic impact effectiveness.

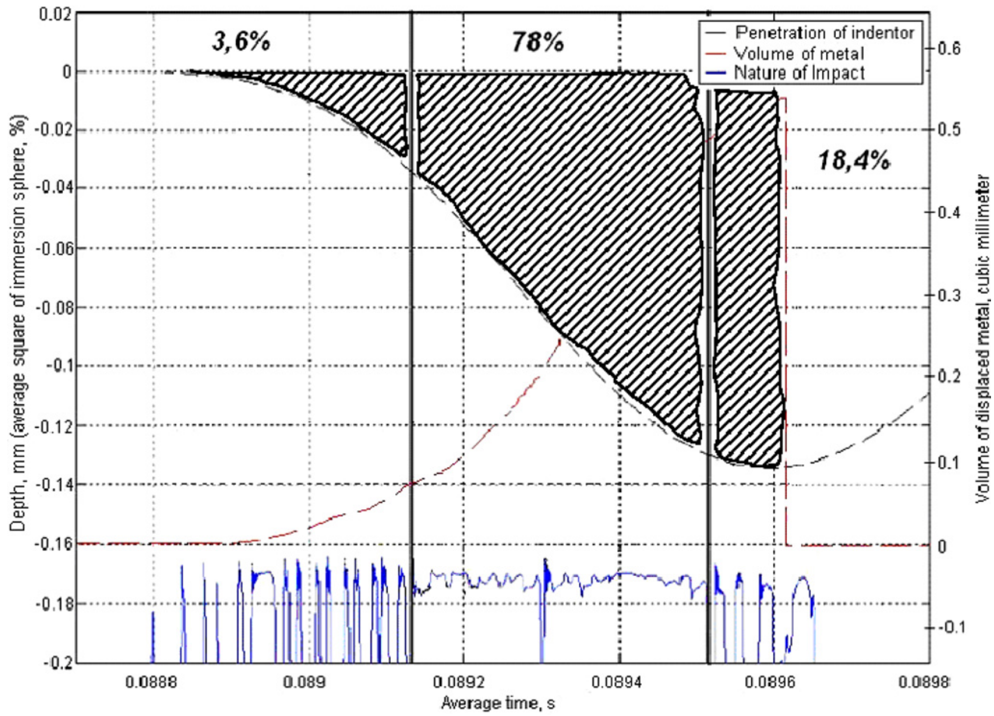

Fig. 7. Distribution of plastic deformation during ultrasonic impact.

plastic deformations is only 3.6% during forming the saturation region thereof, while during uninterrupted ultrasonic oscillations of the indenter for virtually the same period of time this is more than 78%.

5. Conclusions

Thus, the studies conducted demonstrate that *Esonix* UIT is a process comprising the ultrasonic impacts regulated in frequency and duration, which provides the maximum effectiveness of the strain hardening treatment. At the same time, any peening is a stochastic process comprising high-frequency impacts, wherein the use of the effects of high-power ultrasound is limited by the time parameters of single impacts and a random nature of their generation.

In addition to converting harmonic oscillations of the ultrasonic transducer into the impulses of force at the treated surface, the ultrasonic impact during *Esonix* UIT is accompanied by: (a) oscillations of indenters in a narrowing gap between the transducer and the surface, which grow in frequency and create plastic deformation saturation region and subsequently (b) transfer into reboundless oscillations of indenters, which are synchronous with oscillations of the transducer and the surface; thereafter (c) as the elastic force accumulates, these oscillations transform into a rebound with successive reduction in indenter oscillation frequency in a widening gap between the transducer end and the surface. For clarity sake, the oscillation period at a frequency of about 27 kHz is about 37 ms and will recur about 60 times within an ultrasonic impact reboundless phase when the duration of this phase is, for example, up to two milliseconds; in the case of 36 kHz the oscillation period will recur about 80 times.

That is, the ultrasonic impact comprises:

- Saturation of plastic deformations during narrowing gap phase.
- Ultrasonic plastic deformation and relaxation during reboundless impact phase, which is accompanied by the propagation of the intense ultrasonic stress wave in the product material.
- Continuing plastic deformation in a widening gap during rebound phase.

References

[1] P.J. Haagensen, S.J. Maddox, IIW Recommendations on post weld improvement of steel and aluminium structures, IIW Doc. XIII-1815-00, 2002.

[2] E.Sh. Statnikov, L.V. Zhuravlev, A.F. Alekseev , et al., Ultrasonic head for strain hardening and relaxation treatment (in Russian), USSR Inventor's Certificate No. 472782, Published in Byull. Izobret. No. 21, Priority of 1972, 1975.

[3] E.Sh. Statnikov, Physics and mechanism of ultrasonic impact treatment, IIW Doc. XIII-2004-04, 2004.

[4] E.Sh. Statnikov, Guide for application of ultrasonic impact treatment for improving fatigue life of welded structures, IIW Doc. XIII-1757-99, 1999.

[5] E.Sh. Statnikov, V.I. Trufyakov, P.P. Mikheev, Yu.F. Kudryavtsev, Specification for weld toe improvement by ultrasonic impact treatment, IIW Doc. XIII-1617-96, 1996.

[6] E.Sh. Statnikov, Applications of operational ultrasonic impact treatment (UIT) technologies in production of welded joints, IIW Doc. XIII-1667-97, 1997.
[7] E.Sh. Statnikov, V.O. Muktepavel, A. Blomqvist, Comparison of ultrasonic impact treatment (UIT) and other fatigue life improvement methods, IIW Doc. XIII-1817-00, 2000.
[8] E.Sh. Statnikov, V.N. Vityazev, O.V. Korolkov, Esonix ultrasonic impact treatment versus ultrasonic peening, IIW Doc. XIII-2050-05, 2005.
[9] E.Sh. Statnikov, V.N. Vityazev, O.V. Korolkov, Study of comparative characteristics of ultrasonic impact and optimization of deformation treatment processes, 5th World Congress on Ultrasonics, 2003.