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A double-gaussian waveguide for ultrasonic treatment of metals

A. A. Mukhametgalina†, A. A. Nazarov

†a.mukhametgalina@mail.ru

Institute for Metals Superplasticity Problems RAS, 39 S. Khalturin St., Ufa, 450001, Russia

Ultrasonic treatment (UST) of metals is based on the exciting of resonant high-frequency vibrations to induce oscillating elastic stresses in the bulk of materials, which result in the generation, motion and rearrangement of crystal lattice defects. Normally, the resonant vibrations are obtained by using cylindrical samples or ultrasonic instruments having the length equal to the half-wavelength of ultrasound. In such waveguides, however, the distribution of the stress amplitude is not uniform along their axis. Accordingly, changes in the structure and properties due to the UST are different along the sample. Here, a new type of ultrasonic waveguide based on the Gaussian (ampulla) horn is proposed and called a double-Gaussian waveguide. It is composed of two identical high-amplitude parts of a Gaussian waveguide joined at a node that allows one to achieve a uniform distribution of the amplitude of normal stresses in a significant region with a length equal to that of a doubled Gaussian region. Analytic results obtained by Eisner are used to calculate geometrical characteristics of the waveguide and the latter are refined by finite element modeling. Characteristics of double-Gaussian waveguides made of steel 45 and titanium alloy VT6 (Russian grades) are calculated. This type of waveguide can be used in the bulk ultrasonic treatment of materials to expose the samples to oscillating stresses of an equal amplitude.

Keywords: ultrasonic waveguide; ultrasonic treatment; finite-element simulations.

1. Introduction

One of the methods used to modify the structure and properties of metals is the ultrasonic treatment (UST), during which oscillating tension-compression stresses are excited in the bulk of a sample of material [1–4]. A number of studies have shown that during the bulk UST, depending on the amplitude of the wave, either a relaxation of a preliminarily deformed structure and related internal stresses occurs [2, 5] or dislocations are intensively generated and the substructure is formed [1, 6, 7]. Of a particular interest is the application of UST to metals and alloys with an ultrafine grained structure processed by severe plastic deformation. These materials commonly have a highly nonequilibrium structure caused by the defects accumulated during severe deformation and are often characterized by lowered thermal stability of microstructure, reduced ductility and impact toughness [8–10]. Recent studies on the influence of UST on these materials discovered a number of effects related to the relaxation of their highly nonequilibrium structure such as the reduction of internal stresses, refinement of the structure of grain boundaries, enhancement of the thermal stability of the microstructure, of ductility and impact toughness without a loss of the strength etc. [11–16].

For bulk UST, one needs to excite resonant elastic vibrations in the samples. Normally this is done by using cylindric samples with the length equal to the half-wave length of an oscillating system [5–7,13]. Then a standing wave is formed in the sample during UST, in which the amplitude of the normal stresses is distributed according to the relation

$$\sigma_m = \frac{2\pi E u_m}{\lambda}\sin\frac{2\pi}{\lambda}x, \qquad (1)$$

where E is the Young's modulus of the material, u_m the displacement amplitude at the end of the sample, x the coordinate along the sample axis and λ the wave length.

A disadvantage of this shape of the samples is that during the UST the stress amplitude is not uniform along the waveguide. Accordingly, changes in the structure and properties due to UST are different along the sample. In some cases, this makes a convenience, since allows one to study the effect of ultrasound in a wide range of stress amplitudes using a single half-wave sample. For example, using such samples the amplitude dependence of the dislocation density in sonicated metals [1] and of the strength and ductility of ultrafine grained nickel processed by equal-channel angular pressing (ECAP) followed by UST [13] were studied. In general, however, this disadvantage restricts a researcher in the choice of sample lengths and test methods for further studies. For example, in order to carry out rigorous tests of mechanical properties one needs samples in which the quantitative characteristics of any external influences would be the same on their whole gauge length. Choosing a specific shape of a waveguide for which the stress amplitude would be the same over its significant part one would expand the zone of a uniform action of the ultrasound of a given intensity and obtain samples of large sizes for the studies of mechanical properties.

Such a waveguide can be developed basing on the ampulla horn in the Gaussian region of which the amplitude of strain and stress are constant [17]. The idea is to join the high-amplitude part of the horn to its "mirror-image" instead of the low-amplitude part that will result in a waveguide with the double length of the Gaussian region. Such a waveguide will act not as a concentrator of displacements but will provide a uniform distribution of the normal stress amplitude over the significant part of its length.

In the present work we report on the calculations of geometrical parameters of such double-Gaussian waveguide and the results of its simulations using finite-elements method by means of the code ANSYS Workbench.

2. Analytic consideration

Consider a double-Gaussian waveguide of the length $2l$ schematically represented in Fig. 1.

Assume that there is no dissipation of the energy of oscillations so that the standing wave is perfectly symmetric with respect to the middle plane $x=0$. Then the displacement field can be calculated for one part of the system, i. e. $0<x<l$, exactly in the same way as it was done by Eisner [17]. Below we reproduce the key points of those calculations.

The equation for the displacement amplitude is written as follows:

$$\frac{d^2u}{dx^2}+\frac{d}{dx}(\ln A)\frac{du}{dx}+\frac{\omega^2}{c^2}u=0, \qquad (2)$$

where $u(x)$ is the oscillation amplitude at the section with a coordinate x, ω the circular frequency of ultrasound, $c=\sqrt{E/\rho}$ the sound velocity in the bar, ρ the density of material and $A=A(x)$ is the area of the cross section with a coordinate x.

The interval $[0, l]$ is divided into two parts with different solutions to Eq. (2):

$$U(X)=\begin{cases}\varepsilon_m X & \text{for } 0\le X\le X_t,\\ -\dfrac{\varepsilon_m(X-X_t)^3}{3(1-X_t)^2}+\varepsilon_m X & \text{for } X_t\le X\le 1,\end{cases} \qquad (3)$$

where ε_m is the maximum of strain, $X=x/l$, $U(X)=u(x)/l$ are dimensionless quantities.

As an independent dimensionless variable determining the characteristics of the waveguide, it is convenient to use the following quantity:

$$\varphi=\frac{\omega u(l)}{c\varepsilon_m}=\frac{\omega l U(1)}{c\varepsilon_m}, \qquad (4)$$

which determines other parameters:

$$\Omega=\frac{\omega l}{c}=\varphi+\frac{2}{3\varphi},\quad X_t=1-\frac{2}{\Omega\varphi} \qquad (5)$$

The shape of the waveguide is given by the following relation:

$$\frac{A(X)}{A(0)}=\begin{cases}\exp(-\frac{1}{2}\Omega^2X^2) & \text{for } 0\le X\le X_t,\\ \exp\left\{-\frac{1}{2}\Omega^2\left[X_t^2+\frac{1}{3}(X-X_t)^2\right]-2(1-\frac{4}{3\varphi^2})\ln(1+\frac{X-X_t}{1-X_t})\right\} & \text{for } X_t\le X\le 1\end{cases} \qquad (6)$$

Due to the symmetry, the same distribution of displacements will be valid for the left part of the double-Gaussian waveguide. The amplitudes of oscillations at the entry end, $u(-l)$, and at the exit end, $u(l)$, will be the same, while the amplitudes of strain, ε_m, and stress, σ_m, will be uniform over the interval $-x_t<x<x_t$. In other words, the part of the waveguide with the length $2x_t$ will be subjected to oscillating normal stresses with the same amplitude σ_m.

The length of the uniformly stressed region, $2x_t$, and the corresponding values of the stress amplitude are then determined by the following equations:

$$2x_t=2(1-\frac{6}{2+3\varphi^2})l, \qquad (7\,a)$$

$$\sigma_m=E\varepsilon_m=E(1+\frac{2}{3\varphi^2})\frac{u(l)}{l}. \qquad (7\,b)$$

3. Case calculations of a double-gaussian waveguide

Equations (7) show that with an increase of the parameter φ the length of the region with a uniform stress amplitude increases, but the maximum stress amplitude decreases. Therefore, a compromise choice of this parameter is needed in order to obtain optimal geometrical characteristics of the waveguide.

As examples, calculate the characteristics of the double-Gaussian waveguide for two materials: steel grade 45 (according to Russian classification) and titanium alloy VT6 (analog of Ti-6Al-4V). For steel 45 $\rho=7826$ kg/m^3 and $E=200$ GPa (Russian standard GOST 1050-88), and for VT6 $\rho=4430$ kg/m^3 and $E=115$ GPa (GOST 18807-91). The calculations are done for the frequency of $f=19.9$ kHz. The wave length $\lambda=(1/f)\sqrt{E/\rho}$ in bars of these materials for this frequency are equal to $\lambda=254$ mm and $\lambda=256$ mm, respectively. As independent variables, the parameter φ and the diameter of the waveguide at its ends, $d(l)=d(-l)$, are taken. The maximum diameter of the waveguide is calculated as $d(0)=d(l)\sqrt{A(0)/A(l)}$.

The values of the maximum diameter of waveguide, the length of uniformly stressed region, and maximum stress amplitude for the case of $d(\pm l)=20$ mm and $u(\pm l)=1$ μm for several values of φ are presented in the Table 1.

Let us compare the maximum stress amplitudes achieved in the double-Gaussian waveguide with the one obtained in the antinode of a cylindric waveguide with the length $2l=\lambda/2$ (see Eq. (1)) for the case of VT6 alloy. For $u(l)=1$ μm the maximum stress amplitude in the cylindric bar is equal to $\sigma_{m0}=2.82$ MPa. Then, for $\varphi=1.5$ one finds that $\sigma_m/\sigma_{m0}\approx 0.67$. That is, for the same amplitude of displacements, in the double-Gaussian waveguide an approximately 33 per cent less amplitude of stresses is achieved than in the cylindric waveguide for this case. The difference increases with an increase of the parameter φ, and for $\varphi=2$ one finds $\sigma_m/\sigma_{m0}\approx 0.5$.

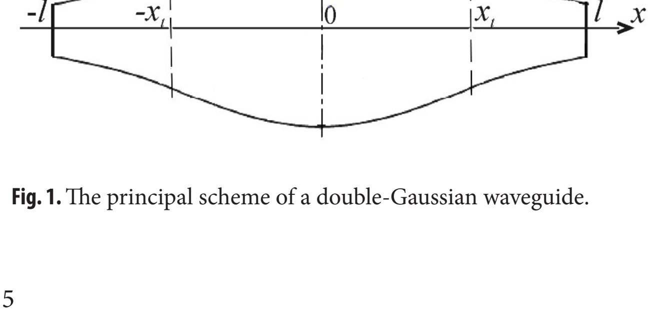

Fig. 1. The principal scheme of a double-Gaussian waveguide.

Table 1. Geometrical characteristics and achievable stress amplitudes at $u(\pm l)=1$ μm for double-Gaussian waveguides made of steel 45 and VT6 titanium alloy.

φ	$d(l)$, mm	$d(0)$, mm	Steel 45			VT6		
			l, mm	x_t, mm	σ_m, MPa	l, mm	x_t, mm	σ_m, MPa
1.5	20	33.77	78.64	24.72	3.30	79.26	24.91	1.88
1.7	20	40.21	84.62	37.04	2.91	85.29	37.33	1.66
2	20	53.82	94.37	53.93	2.47	95.12	54.35	1.41

4. Finite-element simulations

The analytical calculations presented above are approximate due to their one-dimensional character, since they do not take account for the finiteness of the lateral sizes of a waveguide. In order to refine the results, one can use finite element simulations.

To determine the resonance frequency, a modal analysis of the double-Gaussian waveguide has been carried out by finite-element method using ANSYS Workbench as follows.

Using the geometrical parameters obtained from analytic expressions for $\varphi=2$, a finite-element model of the waveguide was constructed. Materials constants for VT6 alloy given above and the Poisson's ratio $\nu=0.3$ were taken for simulations. The model was divided into 3654 elements and had 16636 nodes.

Modal analysis in the range of frequencies between 19 and 20 kHz resulted in the value of eigen-frequency of f_0=19.281 kHz. In order to fit the frequency of f=19.9 kHz, the geometrical parameters of the model were scaled by using the fitting factor of $f_0/f=0.969$. After this scaling, modal analysis was carried out once again which resulted in the desired eigenfrequency of f=19.9 kHz.

Using the model thus obtained, a harmonic analysis was carried out for a range of frequencies from 19 to 20 kHz. A harmonic force with an amplitude of 2 N was applied to one end of the waveguide for each frequency and the amplitude of oscillations of the ends was calculated. The resonant frequency was found to be equal to 19.9 kHz.

Presented in Fig. 2 are the displacement and stress distributions mapped on longitudinal sections of the finite-element models of the double-Gaussian waveguide with the values of φ parameter equal to 2 (Fig. 2a, b). For a comparison, the displacement and stress maps for a half-wave cylinder with a diameter of 20 mm of the same material are given in Fig. 2c, d. The symmetric distribution of the displacements and stresses along the acoustic axis with respect to the medium plane, the existence of an extended region of a uniform distribution of the stress amplitudes are clearly seen from Fig. 2a–d. The length of the region of uniform stress amplitude in the double-Gaussian waveguide is close to the value calculated from the analytical theory. At the same time, the simulations have revealed that the distribution of stresses is not perfectly uniform in the cross section of the Gaussian region of the waveguide with parameter φ equal to 2. Namely, the stress amplitude slightly decreases in the radial direction closer to the surface. According to the simulation results, with a decrease of the parameter φ and, correspondingly, the ratio of maximum

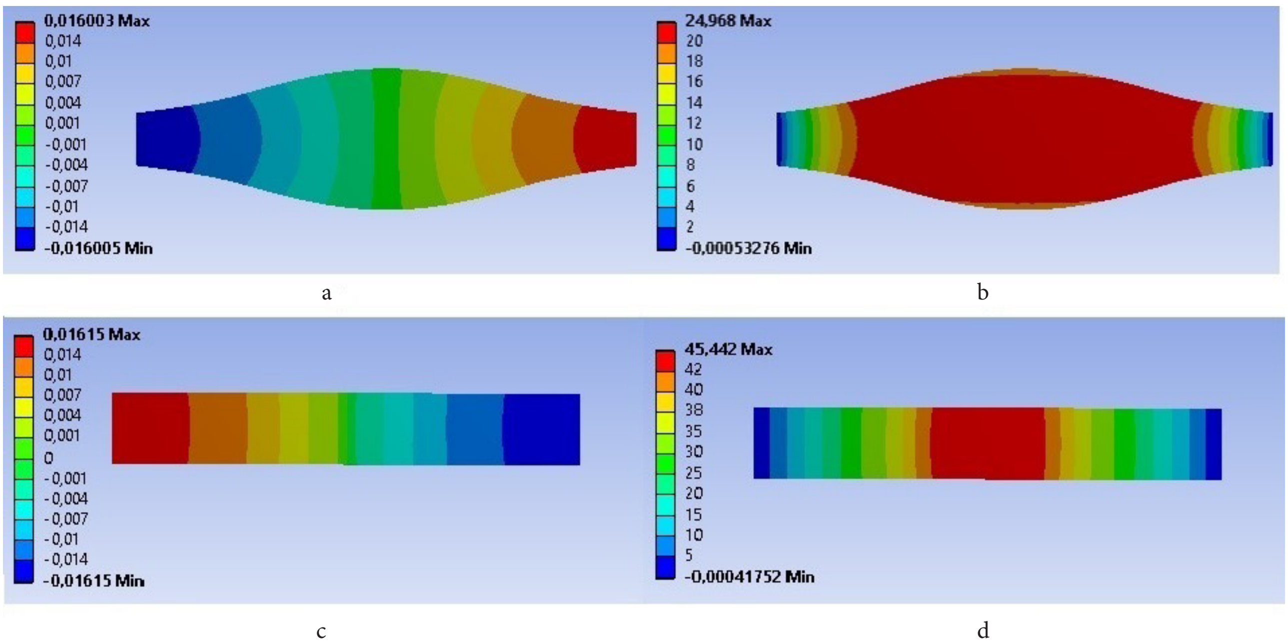

Fig. 2. (Color online) Distribution of displacements (a, c) and stresses (b, d) in a double-Gaussian waveguide with $\varphi=2$ (a, b) and in a uniform cylindric bar (c, d); the displacements are given in millimeters and stresses in megapascals.

and minimum diameters $d(0)/d(l)$, the distribution of the stresses over the cross section in the Gaussian region becomes more uniform.

The simulations confirm that at the same values of displacements at the waveguides' ends (Fig. 2 a, c), the stress values in the Gaussian regions of double-Gaussian waveguides are lower than those in the antinode of a cylindric bar (compare Fig. 2 b, d). From the results of harmonic analysis, at $u(l)=1$ μm the stress amplitude in the cylindric bar is $\sigma_{m0}=2.81$ MPa, while in the double-Gaussian waveguide with $\varphi=1.5$ $\sigma_m\approx 1.85$ MPa. These values are close to the ones obtained from the analytical calculations (see Table 1).

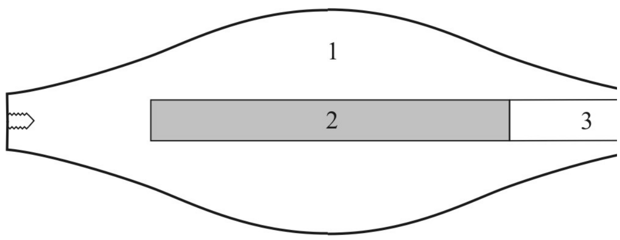

Fig. 3. An assembled double-Gaussian ultrasonic instrument for the UST of cylindric samples: waveguide body (1), sample under treatment (2) and clamping cylinder (3).

5. Discussion

Here, we have developed a new kind of waveguide the intended use of which is not an enhancement of the amplitude of displacements caused by ultrasonic vibrations as in traditional cases but an increase of the length of the region in which a uniform distribution of normal stress amplitudes can be achieved. For this, we used the high-amplitude part of the Gaussian waveguide whose symmetrical duplication resulted in a double-Gaussian waveguide. If a sample of material is given the shape of this waveguide, in a significant part of its length the normal stresses will have the same amplitude. This is important to carry out a uniform UST of the samples.

The analysis has shown that an increase of the parameter φ results in an increase of the length of the uniformly stressed region. At the same time, it leads to an increase of the diameter of the waveguide in its middle part and non-uniformity of the stress in the radial direction. Also, the amplitude of the stress in the Gaussian region decreases as compared to the one in the antinode of a uniform half-wave length cylinder.

A comparison of the results of analytical calculations and finite element modeling shows that the analytic relationships between the maximum displacement and stress amplitudes can be successfully used in the design of such waveguides. In order to measure the amplitude of stresses, one can measure the displacement amplitude at the end of waveguide and use Eq. (7 b). Geometrical parameters, however, should be updated using a fitting parameter, which can be obtained by finite element simulations.

In some cases, the length of samples subjected to deformation treatment before UST is not enough to make a whole double-Gaussian waveguide. For example, in the most cases severe plastic deformation by ECAP allows for a fabrication of cylinder of parallelepiped shaped samples with the length of about 100 mm. In these cases, the specimens cut from such samples can be treated in an instrument made as an assembled double-Gaussian waveguide (Fig. 3).

Inside the solid double-Gaussian waveguide calculated and fabricated as described above, a cylindric hole is made to insert a cylindric sample 2 of the length comparable to the length of the Gaussian region. This sample is tightly clamped inside the waveguide by a screwed clamping cylinder 3. Providing a good acoustic contact between the contacting parts by means of polishing their surfaces, one can obtain resonant vibrations in the system at frequencies close to the eigenfrequency of a solid waveguide.

To enhance the range of achievable stress amplitudes, a standard ultrasonic concentrator can be connected to the ultrasonic transducer prior to this waveguide. A similar instrument but with the simple cylindric form of the waveguide has recently been used in [18] to subject cylindric samples of VT6 alloy with the length of 40 mm with an ultrafine grained structure processed by ECAP. This scheme of treatment has proved its efficiency and resulted in a significant enhancement of the characteristics of superplastic deformation of the alloy as compared to the state just after ECAP.

6. Conclusions

The following conclusions can be made basing on the results of the present study.

1. In order to excite ultrasonic vibrations with a uniform distribution of normal stress amplitudes in a significant part of samples, samples in the shape of a double-Gaussian waveguide composed of symmetrically joined two high-amplitude parts of a Gaussian waveguide can be used.
2. Analytic expressions for the double-Gaussian waveguide obtained basing on Eisner's consideration [17] allow one to predict the relationship between the displacement amplitude at the waveguide's ends and the stress amplitude in the Gaussian region fairly well, but the geometrical parameters of the waveguide should be updated using a fitting ratio obtained from finite-element simulations.
3. Basing on the double-Gaussian waveguide, a composite-structure instrument can be made, in which a relatively long (up to 40 – 60 mm length) cylindric sample can be tightly clamped and subjected to uniform field of oscillating stresses.
4. The double-Gaussian solid waveguide or composite instrument can be useful for the bulk ultrasonic treatment of large samples designed for the studies, for example, of superplastic properties or impact toughness.

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