Effect of Sonic and Ultrasonic Radiation on Safety Factors of Rockets and Missiles

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In rocket motors, the combustion processes are sources of sonic and ultrasonic waves that penetrate all parts of the vehicle. Consequently, the construction materials are exposed to sonic and ultrasonic radiation of high intensity. It has been known for some time that a relation exists between certain lattice imperfections, applied stresses, and sonic or ultrasonic radiation. Sound energy is absorbed by lattice imperfections, whereas thermal energy is absorbed homogeneously in the material; and, accordingly, an ultrasonic energy input of only 10^{12} ev/unit causes the same large (nearly 40%) reduction in the steady stress of zinc as a thermal energy input of 10^{20} ev/unit. Similar measurements have been made on aluminum, beryllium, tungsten, low-carbon steel, and stainless steel. The results show clearly that the strength of the materials is reduced when exposed to intense sonic or ultrasonic radiation. Consequently, catastrophic effects may occur in those parts of the vehicle where the sonic and ultrasonic energy is concentrated by reflections to produce very high intensities.

Introduction

HIGH-THRUST jet and rocket engines are sources of high-intensity sound waves that penetrate all parts of the vehicle. Such sonic and ultrasonic radiation acts on the construction materials directly or indirectly through intermediate fluids or gases, influencing the physical properties. Therefore, it was believed that an effort should be made to investigate effects of interaction between sound waves and matter. This paper presents briefly results obtained from studies of basic phenomena of *direct* ultrasonic radiation of metals and points to some of the theoretical aspects involved.

The prototype of the direct effects was observed by Blaha and Langenecker[1] in 1956. A large (up to 40%) reduction in the steady stress required for plastic deformation of zinc crystals occurred when these crystals were radiated by low-amplitude vibrations of 800 kc/sec. The effect was believed indicative of an activation of dislocations such that the apparent stress necessary for yielding was reduced.

In addition, detailed studies[2] on this subject with quite similar results on cadmium and aluminum, at frequencies between 15 cps and 1.5 Mc/sec, were made in 1959. These studies showed that there is no dependence on frequency, but there is linear dependence on intensity of the applied sonic or ultrasonic irradiation.

Inspired by the forementioned report of the prototype effect, Nevill and Brotzen[3] investigated the effect of ultrasonic waves on the strength of low-carbon steel and drew quite similar conclusions. They also found that there is no dependence on the applied temperature between room temperature and 500°C.

In the past year, another step in the investigations on the interaction of sound waves with metals was completed in the Michelson Laboratory of the Naval Ordnance Test Station, China Lake, Calif. Several metals (zinc, aluminum, beryllium, stainless steel, and tungsten) were irradiated by much more intense sound waves, i.e., by high-amplitude ultrasonic waves, using equipment and instrumentation as described below.

Two properties of zinc and aluminum *single* crystals made these materials most useful for initial investigations: 1) they have low melting points; and 2) they have reasonably well-understood principle glide elements so that analysis of results is greatly simplified.

The polycrystalline materials (aluminum, beryllium, stainless steel, and tungsten) were chosen for the present investigation because of their importance as structural materials and their availability.

The measurements were made at room temperature and elevated temperatures, i.e., up to 800°C, except in the case of zinc and aluminum, where the lower melting points limited the temperatures applicable. Finally, it should be mentioned that the low kilocycle range of frequencies was chosen because of the relative ease of obtaining vibrations of adequate intensity.

Instrumentation and Material

High-precision measurements were made with an extension apparatus shown in Fig. 1 developed from a stepwise improved Polanyi-type[4] instrument. The specimens under test were fixed at their lower end to an ultrasonic transducer and at the

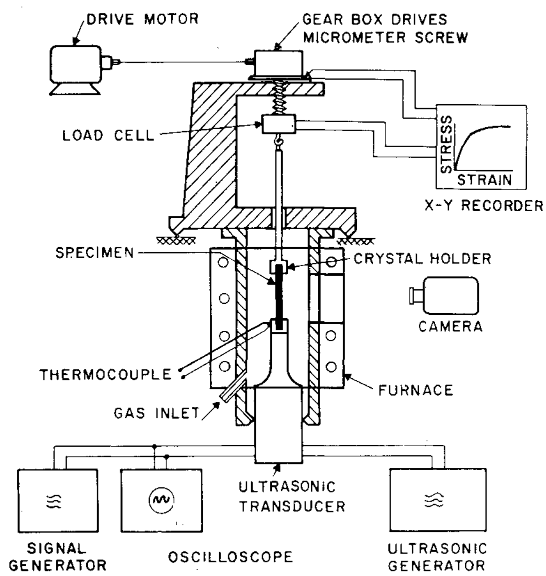

Fig. 1 Extension apparatus including instrumentation

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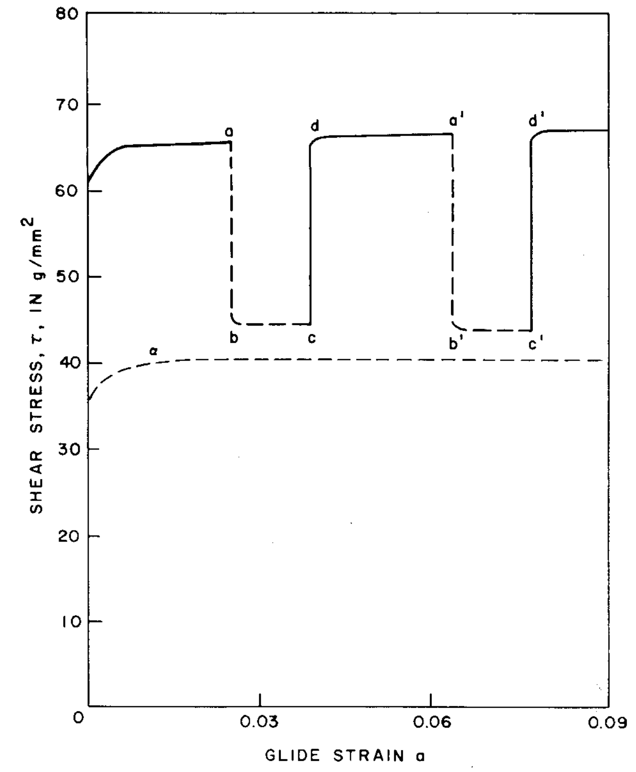

Fig. 2 Effect of low-amplitude ultrasonic radiation on the static yield stress of zinc; turn-on of radiation at *a* causes drop in static yield stress to *b*; after turn-off of the radiation at *c*, the stress returns to its original value ($d \simeq a$, etc.); curve α was obtained by straining with the ultrasonic radiation on from the beginning of the test

upper end to a load cell. The load cell is part of a highly sensitive electronic weighing and recording system. The specimens were stressed by the upward motion of the crystal holder. This motion was caused by a precision micrometer driven by a synchronous motor equipped with gear box of adjustable speed. The resulting strain rates were 6×10^{-5} up to 3×10^{-3}/sec.

Generation, regulation, and observation of amplitude and frequency of the sinusoidal ultrasonic waves originated at the ultrasonic transducer were accomplished, respectively, through the use of a Gulton ultrasonic generator and a Tektronix oscilloscope. A GR signal generator was used for calibration of the ultrasonic waves.

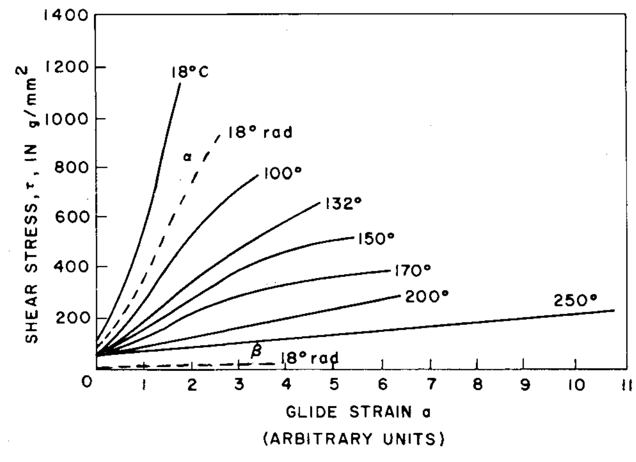

Fig. 3 Work-hardening curves of zinc in ultrasonic radiation (α, 2 w/cm^2; β, 30 w/cm^2) at room temperature compared with work-hardening curves of zinc at different temperatures (after Schmid and Boas, Ref. 5)

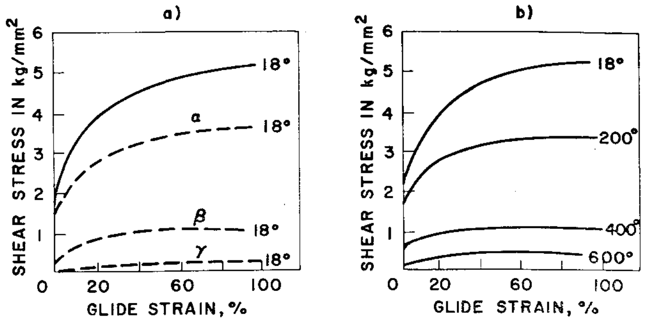

Fig. 4 Work-hardening curves of aluminum; a) at 18°C and ultrasonic radiation (α, 15 w/cm^2; β, 35 w/cm^2; γ, 60 w/cm^2); b) at different temperatures without radiation, Ref. 5

The measurements at elevated temperature (up to 800°C) were made by heating the specimens in the furnace attached to the extraction apparatus. During these tests, the specimens were enveloped by an atmosphere of a single gas (several types were used) that flowed through the furnace core surrounding the specimen at a rate of about 0.5 ft^3/hr.

In addition to the continuous recording of the elongation of the specimens, as described previously, the deformations of specimens were also recorded, using a 16-mm movie camera operating at 24 frames/sec; and high-speed deformations, as for instance kinking of specimens by ultrasonic waves, were filmed by a 16-mm Milliken camera operating at 400 frames/sec.

The specimens investigated were uniform single-crystal wires of zinc (purity 99.999%) and aluminum (purity 99.-993%); their crystallographic orientation was determined from x-ray photographs. Polycrystalline specimens were used in the shape of wires of aluminum (purity 99.993%), beryllium (drawn from S-200-B beryllium of the Brush Beryllium Company), stainless steel (type 302, i.e., the basic "18-8" chromium-nickel steel), and tungsten (no. 218, General Electric Company). The following sample experimental results have been selected from a large number of tests.

Experimental Results

Fig. 2 shows the prototype effect of low-amplitude sound waves on the static yield stress of zinc single crystals. Within 15 cps and 1.5 Mc/sec, these resulting stress-strain curves are independent of frequency.

The dashed lines in Fig. 2 indicate a decrease in stress occurring when the Zn crystal is exposed to the sonic or ultrasonic radiation with power amplitudes $W \simeq 2$ w/cm^2 during stressing. The stress is reduced markedly as soon as the sound waves pass through the crystal. If the generator is switched off, the stress returns to its original value. Curve α was obtained by straining a Zn specimen with the sound field on from the beginning of the test.

A larger reduction in the shear stress but no change in the slope of the stress-strain curve has been observed when the sound power amplitude was increased through values up to 7 w/cm^2.

Fig. 3 compares stress-strain curves of zinc crystals at room temperature in the sonic or ultrasonic field (dashed lines) with stress-strain curves of zinc crystals at different temperatures without radiation.[5] The dashed-line curve noted by β was obtained at room temperature by straining the specimen in sound field having power amplitudes of ~30 w/cm^2, so that the stress of the specimen was not noticeably above zero.

In Fig. 4 stress-strain curves of aluminum single crystals are shown. The diagram on the left has been obtained at sonic radiation of different sound power amplitudes. The diagram on the right shows the well-known temperature dependence of the stress of these crystals, without any radiation.[5]

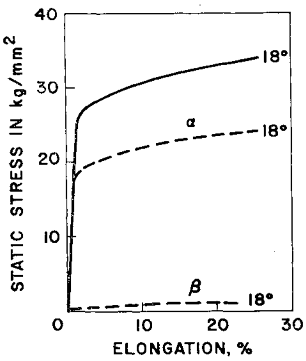

Fig. 5 Stress-strain curves of stainless steel at 18°C and ultrasonic radiation (α, 45 w/cm²; β, 95 w/cm²)

Figs. 5 and 6 show the effect of vibrations on the static yield strength of stainless steel and beryllium. Here again, the reduction in the static yield stress due to sonic irradiation is remarkable; at the noted power amplitudes of the irradiation, the strength is zero. Tungsten behaved like the other metals when subjected to ultrasonic radiation, and so a separate diagram is omitted.

Superimposition of radiation and elevated temperatures indicate that the final result is one of addition. For instance, at 400°C, low-amplitude radiation of $\sim$20 w/cm² reduces the strength of stainless steel to zero. Note that at room temperature much higher sound power amplitudes are necessary to reduce the strength to zero, as is shown in Fig. 5.

At "excessively high-amplitude" sound waves, zinc *single* crystals did deform by kinking, as shown in Fig. 7. When polycrystalline specimens were exposed to similar excessively high-amplitude sound waves, no kinking but sudden fracture, usually along grain boundaries, did occur.

Discussion

Attenuation (damping) of sound waves is known from various experiments to take place preferentially at lattice defects such as dislocations, grain boundaries, etc.[6,7] Thus, Blaha and Langenecker[2] explained the effect of sound waves on the static yield strength of zinc crystals on the basis of the activation of dislocations by sound energy absorption.

The principal mechanisms by which dislocations may absorb sound energy are the *thermoelastic effect*[8] and those mechanisms associated with the *motion of dislocations*.[9] The thermoelastic energy losses due to heat flow between regions of compression and rarefaction of a compressional wave have been computed by Lücke.[10] This mechanism, however, is not suited for an interpretation of the reported large decrease in yield strength.

Energy-absorption mechanisms due to the motion of dislocations may be broken down into three effects: damped resonance, relaxation, and hysteresis.

Because of the natural frequency of a dislocation loop, which is known to be in the order of 10^8/sec,[11] the resonance effect cannot be the mechanism involved in the observed effects.

A theoretical discussion of relaxation effects and the resulting Bordoni peaks has been given by Seeger.[12] To explain

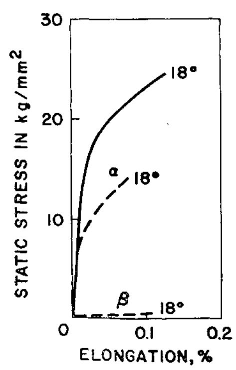

Fig. 6 Stress-strain curves of beryllium at 18°C and ultrasonic radiation (α, 40 w/cm²; β, 90 w/cm²)

the reported effects by a relaxation model, the existence of characteristic relaxation frequencies would be required. Since the experimental results showed no dependence on frequency or temperature, a relaxation effect must be discarded as a possible explanation.

Hysteresis mechanisms[9] are strain-amplitude dependent but independent of frequency for frequencies of the kilocycle range (quasi-static behavior).[11]

Here the strain amplitude has been estimated at $\epsilon_0 \simeq 3 \times 10^{-4}$, corresponding to a strain energy density of about 10^3 erg/cm³ which results if the conversion of electrical to mechanical energy in the piezoelectric sound source is about 90% efficient. Accordingly, even plastic deformation of completely unloaded metal specimens by intense sound waves may be the result of hysteresis.

Thus, the potential well model suggested by Blaha and Langenecker[2] remains valid. The passage of sound waves causes an increase in the elongations of the oscillations of dislocation lines until these lines break away from their equilibrium positions and move along their glide planes, causing the plastic deformation. (For details of theory and model of mechanical damping due to dislocations, see Ref. 11.)

A breakaway of dislocation lines requires a sufficiently high shear stress component p, acting in the glide plane, that

Fig. 7 Kinking of zinc by high-amplitude sound waves (amplitudes greater than 50 w/cm²)

can be estimated from $p = \sin\chi_0 \cos\lambda_0(\rho v W)^{1/2}$, where χ_0 and λ_0 are the angles formed by the longitudinal axis with the glide plane and the glide direction, respectively, ρ is the density, v is the velocity of sound in the wire shaped specimens, and W is the sound power amplitude of the applied ultrasonic field. In the case of zinc, ρ = 7 g/cm³ and $v \simeq 4.2 \times 10^5$ cm/sec. With $W \simeq 30$ w/cm² (and, regarding the factor of 10^7 for conversion into units of the cgs system), one obtains $p \simeq 4 \times 10^7$ dyne/cm², a value exceeding the critical shear stress τ_0 required to initiate migration of dislocations in the basal plane ($\tau_0 \simeq 100$ g/mm² $\simeq 10^7$ dyne/cm²). It then follows that the applied ultrasound indeed produced shear stress components in the basal plane adequate to break away dislocations from their pinned positions and drive them through the crystal.

The same statement also holds for aluminum single crystals, if the corresponding values are applied. Difficulties arise, however, when one tries to explain the decrease in the static yield strength of polycrystalline steel (and other high-strength polycrystalline metals) on the basis just described. A reduction in the static stress from above 30 kg/mm² to zero would require components of sound pressure amplitudes of about 3×10^9 dyne/cm² corresponding to sound power amplitudes $W \simeq 40$ kw/cm^2, which never have been approached in the present investigations. Thus, a more realistic model of interpretation, the deduction of which will be reported later, involves concepts of partial reflections of sound waves, their conversion from one wave type to another, and localized internal overheating; accordingly, plastic deformation may initiate in such regions.

Nevertheless, the reported reductions in the static strength—and even the fracture—of loaded and unloaded single and polycrystalline metals have been observed regardless of how the acting stress fields were originated: 1) by conventional stress (load or pressure) applied to the specimen; 2) as the result of conventional stress superimposed by the stress resulting from sound waves; or 3) produced by sufficiently intense sound waves only.

The disappearance of strength from cool, irradiated metals invites comparison with the effects of heating: in the case of zinc, sound energy of 10^{12} or 10^{13} ev/unit applied at room temperature causes a decrease in strength corresponding to a thermal energy input of some 10^{20} or 10^{21} ev/unit. An explanation may be that sound waves increase the potential energy at lattice defects (dislocations, grain boundaries, etc.) rather than in the undisturbed metal crystal, whereas temperature increases cause the amplitudes of atomic vibrations to increase in a statistically homogeneous manner over the whole specimen.

Conclusion

The reported reduction in the apparent static yield stress necessary for plastic deformation by sound waves has been observed on several metals, such as zinc, aluminum, beryllium, low-carbon steel, stainless steel, and tungsten. The effects observed proved to be independent of frequency (at least within the range applied, i.e., between 15 cps and 1.5 Mc/sec). Also, no dependence on temperature has been found. The dependence on amplitude of vibration, however, proved to be linear. A limit in the application of high amplitudes of the sound waves is given by the fact that at certain amplitudes the static yield stress goes to zero. Further increase in amplitude caused plastic deformation, as bending or kinking in the case of single crystals, or fracture in the case of polycrystalline specimens, respectively.

Obviously, the static load-carrying capacity of the metals is reduced when exposed to sound fields. This is particularly true for metals used in rocketry where the rocket engines emit sound waves of high amplitudes. Consequently, catastrophic effects may occur in those parts of the vehicle where the sonic and ultrasonic energy is concentrated by reflections to produce very high intensities.

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