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LASER GENERATION OF LONGITUDINAL AND SHEAR PULSES IN METALS

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ABSTRACT
A Q-switched Nd:YAG laser has been used to generate longitudinal and shear acoustic pulses in various metals over a wide range of incident laser power densities. Detection with piezoelectric transducers has allowed various generation mechanisms to be identified in both the non-plasma and plasma regimes. The effect of various modifications to the metal surface is discussed.

INTRODUCTION

Many papers have appeared in the literature which describe the generation of ultrasound by lasers. It is only recently, however, that generation in metals has been studied to any depth (1). Previous work, both theoretical (2,3) and experimental (4) tended to concentrate on liquids, where complications due to shear generation did not arise.

The work to be presented here extends the study of laser generated ultrasound in metals and concentrates principally on aluminium. Both longitudinal and shear pulse generation have been examined over a wide range of incident laser power densities and with various modifications to the metal surface. Two principal generation mechanisms have been identified; at low laser power densities, thermomechanical mechanisms operate, while at power densities sufficient to cause plasma formation, additional mechanisms due to momentum transfer become important.

GENERATION AT FREE METAL SURFACES

A Q-switched Nd:YAG laser was used, capable of supplying 17ns half-width pulses of up to 60mJ in energy; its' wavelength of operation, 1.06μm, was in the near infrared. Power densities of over $10^8 Wcm^{-2}$ could be achieved at the metal surface, allowing the study of ultrasonic generation in the plasma regime.

In a typical experiment, the laser pulse was incident normally onto one face of a parallel-sided metal specimen. Detection of the acoustic pulses was accomplished on the sample's far side with a range of piezoelectric ceramic transducers. Both longitudinal (1-10MHz) and shear (4MHz) transducers were used and their outputs were displayed on an oscilloscope which was triggered by the laser pulse via a beam splitter and photodiode.

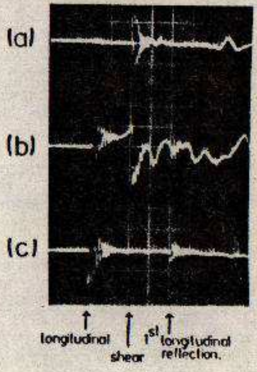

Fig.1 Typical oscilloscope traces

Figs. 1(a) and (b) show typical oscilloscope traces, obtained from both longitudinal and shear transducers, when an unfocused 40mJ laser pulse was incident on a free aluminium surface. In this case the resultant laser power density at the surface was insufficient to produce a plasma. The trace from the 4MHz shear transducer (Fig. 1(a)) contained, in general, a single shear pulse which arrived at the transducer at a time $t = x/c_s$ after the trigger pulse, x being the thickness of the sample and c_s the shear velocity. Signals from longitudinal transducers (Fig. 1(b)) indicated detection of both longitudinal and shear pulses, the longitudinal pulse arriving before the shear at $t = x/c_\ell$, c_ℓ being the longitudinal velocity. The fact that shear pulses were easily detected by longitudinal transducers suggested that the acoustic source created by the thermomechanical mechanisms contained a large shear component.

The amplitudes of longitudinal and shear pulses were found to be proportional to the incident laser power density, provided a plasma was not formed at the free metal surface. At higher power densities, such that a plasma was formed, a more complicated relationship was observed as shown in Fig. 2. In the case of the longitudinal pulse, Fig. 2(a), a substantial enhancement in generation efficiency was seen once the power density was sufficient to form a plasma. This enhancement was not shared by the shear pulse, Fig. 2(b), which suffered a decrease in generation efficiency on the formation of a plasma. A maximum in shear amplitude was seen at a certain power density; increasing the power density further caused a decrease in shear generation efficiency. Some subsequent slight increase in shear pulse amplitude was seen at very high laser power densities (above $10^8 Wcm^{-2}$).

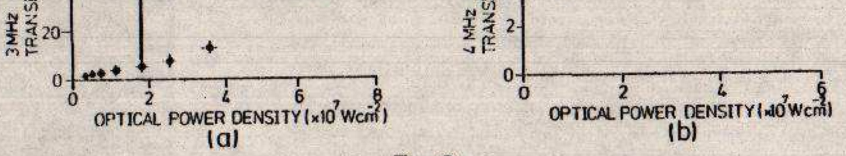

Fig. 2

The oscilloscope trace presented in Fig. 1(c) illustrates the phenomena observed in the plasma regime. The amplitude of the longitudinal pulse has been enhanced by the presence of the plasma to a much greater degree than that of the shear pulse. Comparison with Fig. 1(b) indicates that the amplitude of the detected shear pulse is now negligible when compared with that of the longitudinal pulse and that a clear longitudinal reflection is evident.

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PRELIMINARY DISCUSSION

In the non-plasma regime, the generation mechanisms are thermomechanical in nature. The incident laser pulse is absorbed rapidly in direction normal to the free metal surface. A thermal gradient into the metal is then established over a distance dependent on several factors as described in detail by Ready (5). In addition to this normal thermal gradient, a lateral gradient will be caused to exist parallel to the metal surface, due to the discontinuity at the edge of the laser beam. The resultant acoustic source will be in the shape of a thin disc, the width of the laser beam being much greater than the effective depth of penetration of the normal thermal gradient.

The thermal gradients create strains in the metal, launching the acoustic pulses. It appears that both gradients play a part in the generation process, but we have found experimentally that the lateral thermal gradient is a major shear source.

In the plasma regime additional mechanisms operate. Consider first the enhancement of the longitudinal pulse on the formation of a plasma; this is due to momentum transfer to the solid from both ablation of material from the target, and expansion of the plasma away from the surface. The lack of significant enhancement of the shear pulse in the plasma regime indicates that momentum effects are not a major shear generation mechanism; further, the observed efficiency decrease is evidence of plasma shielding effects. Momentum transfer would tend to mask plasma shielding effects in the case of the longitudinal pulse.

MODIFICATIONS TO THE METAL SURFACE

The results so far have been restricted to generation at free metal surfaces. Several workers (6,7) have indicated that modifications to the surface may provide an enhancement of the generation efficiency. Modifications include the application of various coatings and the use of constraining layers. The cited authors, however, did not distinguish between longitudinal and shear pulses; we have thus carried out an independent study which examines both acoustic modes.

Coatings provide enhancement by two mechanisms. Firstly, they may increase the total laser energy absorbed, by reducing the effective reflectivity of the surface (a polished aluminium surface reflects approximately 90% of an incident 1.06μm laser pulse). Secondly, they may enhance the longitudinal pulse in particular by their greater tendency for ablation or evaporation, especially at higher laser power densities.

Constraining layers, e.g. a glass slide cemented rigidly to the metal surface, again provide enhancement by two main mechanisms, the most important one being the imposition of a rigid boundary at the metal surface. At an unmodified free boundary, the resultant stress must be zero and displacements are allowed; however, at a constrained boundary, displacements are restricted and stresses are allowed to build up. The result is that greater strains are caused to exist in the constrained surface case for a given thermal gradient into the metal. The second mode of enhancement is plasma confinement at higher laser power densities. The plasma formed at the metal surface is confined to within a limited distance of the surface by the applied layer, increasing the momentum transfer to the surface.

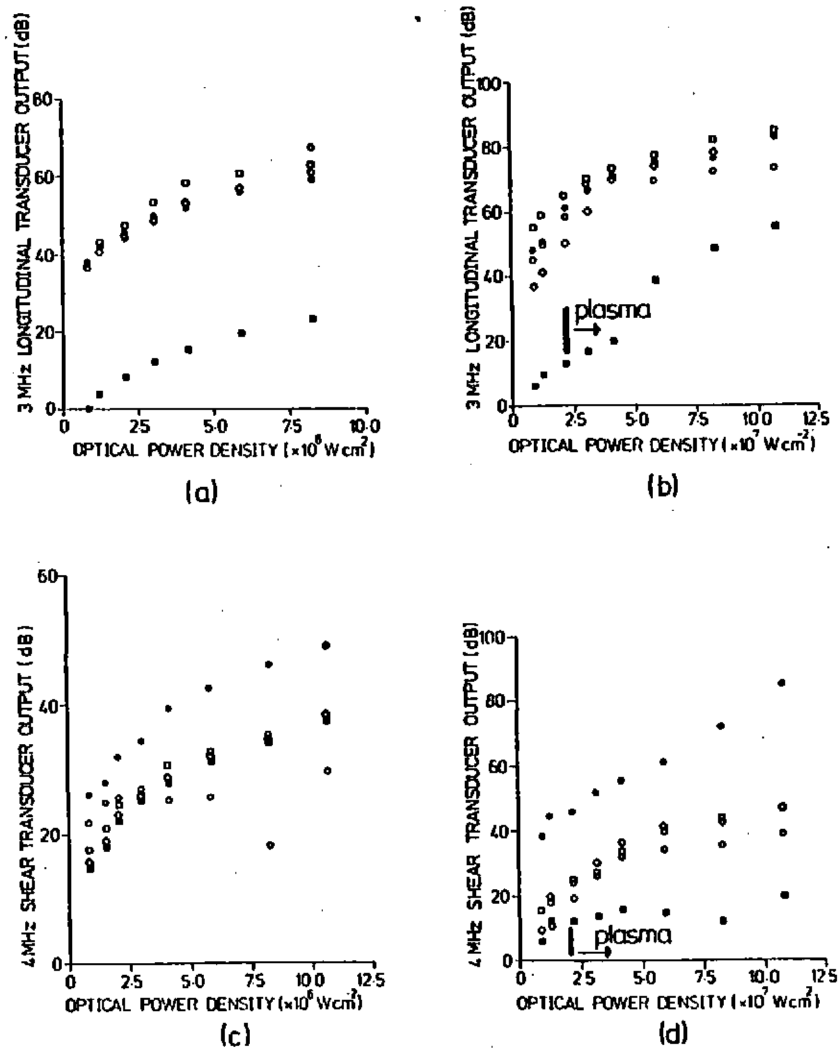

Fig. 3 Effect of various modifications to the metal surface.
■ unmodified metal surface ● constraining layer
○ black paint □ oil ◇ silicone resin (Dow Corning 276-V9)

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Fig. 3 illustrates, in graphical form, to what extent various modifications were found to enhance the generation process. Consider first the longitudinal pulse. In the non-plasma regime (Fig. 3(a), both a constraining layer and various coatings provided enhancement as expected, with an increase over free surface signals approaching 40dB. At higher laser power densities, such that a plasma was formed, these enhancements tended to be reduced somewhat (Fig. 3(b)). Enhancement of the shear pulse generation efficiency was found to be most effectively produced by a constraining layer over the range of power densities examined (Figs. 3(c) and (d)). The effect of coatings was minimal in the non-plasma regime, Fig. 3(c), and a decrease in shear generation efficiency was observed when an oil covering was used. On the formation of a plasma, Fig.3(d), coatings were found to provide an enhancement, but not to the same degree as the constraining layer.

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