174 Evaluating the fidelity of force measurement for characterising acoustoplasticity

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Motivation

The plastic deformation of metals is key in many industrial forming processes, from forging critical aerospace components to deep-drawing aluminium cans. It has been demonstrated that high-power ultrasonics can reduce the force required to cause and maintain yielding during plastic deformation of metals, offering opportunities for significant increases in process speed and reduction in demand on energy resources. The effect, which was first observed in the 1950's [1], is known as acoustoplasticity.

Even after decades of research, the fundamental nature of acoustoplasticity is still contested. Whilst many researchers link ultrasonic excitation with a real change in intrinsic material behaviour, a similar number refute conclusions of this nature and point to stress superposition, suggesting that the actual peak stress within the specimen has not been measured correctly. This is due in part to the inconsistency in experimental setups and instrumentation used, most of which rely on superimposing ultrasonic vibrations during a tensile or compressive test of a metal sample in a universal test machine. A paper by Daud and Lucas [2] measured both the quasi-static and oscillatory stress using a piezoelectric force transducer capable of resolving the high frequency dynamic force response signal. For the first time, this provided clear evidence of a drop in the flow stress which could not be wholly explained by the theory of stress superposition and has susequently been cited as evidence of acoustoplasticity being a true intrinsic material effect. Consequently, of fundamental importance is that the measurements made with piezoelectric force transducers are interpreted correctly.

Many researchers in this field continue to rely on load cells that cannot resolve the oscillatory stress. A number of promising theories of acoustoplasticity that relate the drop in flow stress, acoustic intensity and dislocation network evolution have been put forward which are well supported by evidence from microscopy techniques. However, in neglecting to measure the oscillatory force directly, the foundation of the resulting constitutive models is compromised (e.g. [3], [4]). Where research studies have measured the dynamic force response, it is not clear that the mounted resonance of the force transducer itself or the dynamic response of the test machine was considered [5].

To capture the dynamic stress from measurements using a piezoelectric force transducer it is necessary to account for the effect that embedding the transducer in the test structure has on the measurement. It is well known, for example, that the location of the transducer with respect to the nodes and anti-nodes in a steady-state vibrating structure affects the measurement [6]. In addition, mounting the force transducer within a structure will affect its dynamic response [7].

This study aims to define an experimental set-up that addresses the key issues necessary for subsequent characterisation of acoustoplasticity through tensile testing; how to establish the fidelity of the force measurement from a piezoelectric force transducer in an tensile test under superimposed ultrasonic excitation of the test specimen, and how that measurement relates to the force experienced by the test specimen.

Method

A second method of finding the force in the test specimen and test structure was used as a check to evaluate the force transducer measurements. Using a laser vibrometer, the vibration velocity response was measured on a grid across the surface of the whole vibrating structure to create an Operational Deflection Shape (ODS). The ODS was not used to predict force directly, but used to refine a numerical model in Finite Element Analysis (FEA). This model was then used to predict the force at any location, allowing a comparison with the experimental measurements from the piezoelectric force transducer mounted in the test machine.

A key consideration for the test methodology was to isolate the ultrasonically vibrating system from the cross-head (and therefore dynamics) of the test machine, as the compliance of the test machine has a significant effect on the velocity measurements. This was acheived using a mass-spring absorber [8] for a mass on the end of a rod, aiming to impose a boundary condition of an infinitely rigid mounting. This boundary condition is simple to implement in an FEA model and, additionally, the resulting isolation from the test machine compliance removes the need to quantify that compliance. The effectiveness of the absorber was evaluated by comparison of the measured and predicted ODS and also by measuring the frequency response of the absorber excited by a random input signal into the ultrasonic transducer.

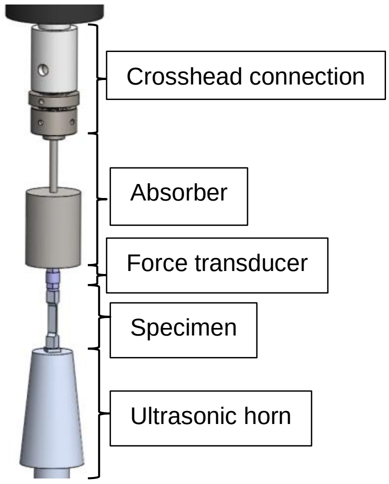

Fig 1. Test apparatus with absorber

The mounted resonance frequency of the force transducer also influences true measurement of the oscillatory force. The frequency range of operation for a piezoelectric force transducer is limited by its linear response range, and this is a challenge for using these transducers for meaurements at ultrasonic frequencies. As mounting the transducer on a structure additionally alters its frequency response this must also be taken into account [7]. In this study, the frequency response of the piezoelectric transducer was measured in its mounted location by exciting the whole test system with a random input signal into the ultrasonic transducer. Two force transducers were evaluated; a 5 kN Kistler force transducer with a nominal 70 kHz natural frequency and a 10 kN Kistler force transducer with a natural frequency of 55 kHz.

Key results

The ODS measured at 20 kHz showed that the velocity response of the absorber was negligible compared to the peak velocity within the specimen. The piezoelectric transducer is therefore mounted at a location in the test apparatus where it is not influenced by the test machine dynamics. This demonstrates the absorber's effectiveness in removing the influence of the compliance of the test machine, enabling agreement between the experiment and the FEA model that assumes an idealised rigid boundary condition. The force predicions, from the FEA model that relied on matching measured and predited ODS's, could then be used as a basis for evaluating force measuremets from a piezoelectric force transducer.

By comparing the measured frequency response of the mounted 5 kN transducer to its calibration curve provided by the manufacturer, it was demonstrated that measurements using this transducer, of the quasi-static and oscillatory force response of an ultrasonically excited tensile test, were unaffected by the mounted resonance response of the transducer itself. This was not the case for the 10 kN transducer, where the resulting errors meant it could not be used for characterising acoustoplaticity, at least with this apparatus and ultrasonic frequency. This limitation on measurable force significantly restricts the range of metals and specimen sizes that can be used for characterising acoustoplascicity using an experimental set-up that relies on a universal test machine.

Conclusions

To characterise acoustoplasticity, the true drop in flow stress must be measured and this relies on accurate measurement of the static and oscillatory force during ultrasonic excitation of the test specimen. In this study, the factors that affect the accuracy of this measurement were considered.

An FEA model, calibrated with experimental velocity measurements of the ODS, provided a method for evaluating force within the specimen and wider test apparatus, subsequently allowing assement of two piezoelectric force transducers. This approach was enabled by incorporating an absorber into the test configuration that negated the need to account for the compliance of the test machine by approaching an ideal rigidly fixed boundary condition at the location of the piezoelectric force transducer.

The frequency response measurements of two force transducers confirmed that measurements of the quasi-static and oscillatory force were unaffected by the transducer mounted resonance using the 5 kN transducer but were affected using the 10 kN transducer.

It has been shown that the modified test apparatus for an ultrasonically excited tensile test forms a basis for improved charaterisation of acoustoplasticity compared to the set-ups described in the literature that have used either the test machine load cell or a piezolelectric force transducer to evaluate the effects of acoustoplasticity.

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