

## The Effect of Ultrasonic Excitation in Metal Forming Tests

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**Abstract.** The use of ultrasonic excitation of tools and dies in metal forming operations has been the subject of ongoing research for many years. However, the lack of understanding about the effects of ultrasonic vibrations on the forming process has resulted in difficulties in maximising the benefits and applications of this technology. In particular, experimental characterisations of the effects of superimposing ultrasonic oscillations have largely relied on interpretations of measurements of the mean forming load and have ignored the oscillatory forces. Previous research [1] has shown that by applying ultrasonic vibrations to the lower platen in compression tests on pure aluminium specimens, the resulting stress-strain relationship can be characterised by a temporary effective softening of the material during intervals of ultrasonic excitation. The current research investigates this effect in a series of simple forming tests using a number of different metal specimens. In this research, the forming tests are conducted using a piezoelectric force transducer to measure the oscillatory force data during ultrasonic excitation of the die. It is shown that the benefits of superimposing ultrasonic excitation of the die are highly dependent on the material being formed and that, in many cases, the maximum oscillatory force exceeds the static forming load even where the mean forming load is reduced significantly during the interval of ultrasonic excitation.

### Introduction

Research in the use of ultrasonic vibration in metal forming and joining processes has been ongoing since the middle of the 20<sup>th</sup> century. In particular, for metal forming processes, extensive research has reported significant benefits of superimposing ultrasonic vibrations on the forming tools in terms of forming load reductions. In early studies [2] into the use of ultrasonic vibration, many researchers focussed on the influence of ultrasonic oscillations on the internal stresses during plastic flow of metal and also on interfacial friction effects, known as the volume and surface effects respectively. Many of these studies have been associated with the development of ultrasonic metalworking processes related to industrial applications such as die forming, wire drawing and extrusion [3]. In all of these studies, the evaluation of the benefits of ultrasonic excitation relied on measurements of the mean forming load only and not on measurement of the oscillatory force during ultrasonic excitation.

This paper presents the results of a simple forming test where a flat sheet sample of metal is forced into a shaped female die by a round nose male die on a test machine. The die forms part of a tuned ultrasonic horn, so that ultrasonic excitation can be applied during the tests and results can be compared with tests performed without ultrasonic excitation. The design and tuning of the ultrasonic horn is achieved using finite element modelling and experimental modal analysis using a 3D laser vibrometer. For the forming tests, the plunger is attached to the cross-head of the test machine and is also attached to a piezoelectric force transducer for measurement of the static-oscillatory forming force. The results of this study illustrate how ultrasonically assisted metal forming can result in a lowering of the mean forming load during ultrasonic excitation of the die and, further, investigates the oscillatory force during ultrasonic forming.

### Design of the Ultrasonic Die

The ultrasonic excitation system is shown in Fig. 1 and consists of a Langevin piezoelectric transducer, a booster and an ultrasonic horn, all tuned to their first longitudinal mode of vibration at 20 kHz. The tuned booster was included to allow a flange to be incorporated between the transducer and the die horn to provide a nodal mounting to the test machine. This ensures that the mounting rig does not affect the vibratory motion of the horn, booster or transducer.

The forming die in this study constituted the output end of the ultrasonic horn. The die horn and booster were designed using finite element (FE) analysis and the modal frequencies and associated mode shapes were subsequently confirmed using experimental modal analysis (EMA). The FE software Abaqus was used in these studies to determine the modal parameters of the horn and booster. The ultrasonic booster was designed using the five-element horn configuration as reported by Peshkovsky [4]. The transducer can only provide ultrasonic amplitudes up to 10  $\mu\text{m}$ , depending on the generator setting, therefore the profile of the booster and horn are designed to amplify the amplitude and allow a range of ultrasonic amplitudes to be excited.



Figure 1: Ultrasonic transducer, booster and die horn

The die horn and booster are manufactured from titanium (Ti-6Al-4V) and were modelled fully with 3D quadratic elements in Abaqus. The FE model predicted that the longitudinal mode of the booster plus die horn occurs at 20.7 kHz. The modal frequency determined experimentally from EMA was found to be 20.8 kHz for the longitudinal mode. Fig. 2 shows a comparison of the FE results and those obtained using EMA. The amplification achieved by profiling the booster and die horn, i.e. the ratio of amplitudes at the output and input faces of the booster/horn system, was measured and calculated to be a gain of four.

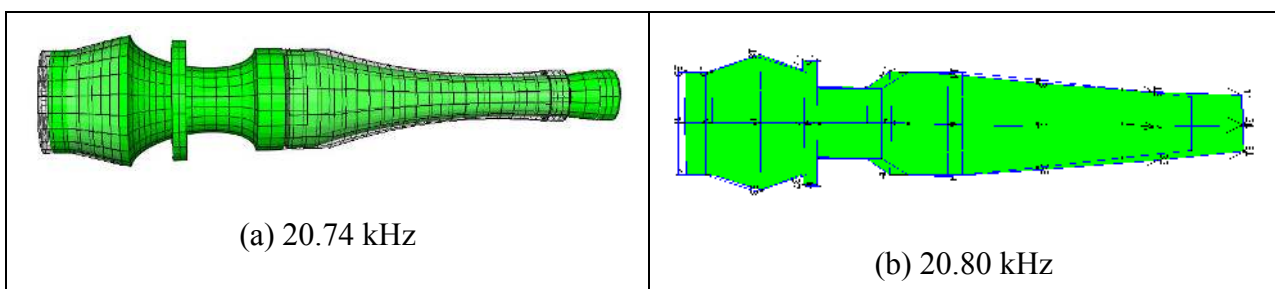


Figure 2: Comparison of (a) FE predicted and (b) EMA measured longitudinal mode and modal frequency.

### Experimental Procedure

In these experiments, flat sheet metal specimens were compressed between a bowl-shaped female die and a round-nosed male die. The female die constituted the tip of the ultrasonic horn tuned to a longitudinal mode at 20.8 kHz. The die horn was excited by a piezoelectric transducer driven by an ultrasonic generator. The male die was connected to the cross-head of a Zwick-Roell test machine which provided a constant cross-head speed of 10 mm/min for these experiments. A Kistler force transducer, mounted between the male die and the cross-head as shown in Fig. 3, was used to measure the static-oscillatory force response during each test. The oscillatory displacement

amplitude of the ultrasonic die was measured during each forming using a 3D laser Doppler vibrometer. The recorded signals were acquired using DataPhysics signal acquisition hardware and software for data processing.

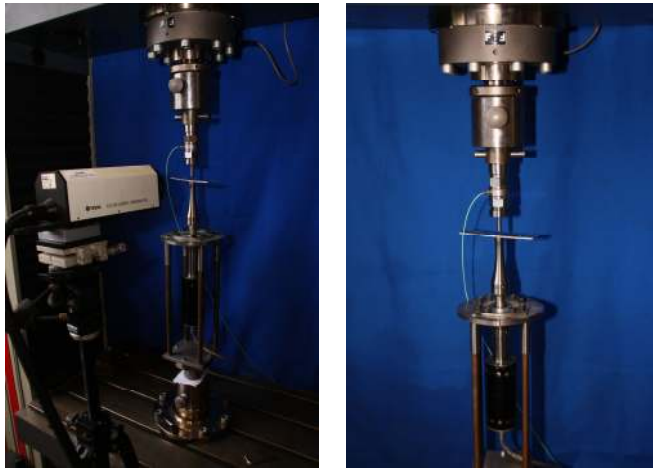


Figure 3: Ultrasonic metal forming test setup.

Forming tests on four different metals were conducted to measure the effects of ultrasonic excitation of the forming die; aluminium A1050, aluminium alloy 7075, die cast magnesium AC50, and austenitic stainless steel grade 304. The specimens were all flat 3 mm thick plates. A series of static and ultrasonic forming tests were performed at a constant cross-head speed of 5 or 10 mm/min under dry surface conditions. In the experiments reported here, the specimen was compressed to approximately 1 mm displacement as measured by the machine cross-head at which point the ultrasonic excitation was applied to the ultrasonic die horn. The first set of force data was recorded from the load cell in the cross-head of the machine and two ultrasonic amplitudes of the die horn were excited; 12  $\mu\text{m}$  and 20  $\mu\text{m}$ . The second set of data was recorded for an ultrasonic amplitude of 20  $\mu\text{m}$  and the force was measured using the piezoelectric force transducer mounted between the punch and the machine cross-head. For all tests reported here, the tests were stopped at a cross-head displacement of 3 mm. Table 1 shows the density and Young's modulus properties for the four metals.

Table 1: Materials used in the study.

Material	Density, $\rho$	Modulus of Elasticity, E
Aluminium A1050	2705 kg/m <sup>3</sup>	70 GPa
Die cast magnesium AC50	1740 kg/m <sup>3</sup>	44 GPa
Austenitic stainless steel 304	8030 kg/m <sup>3</sup>	193 GPa
Aluminium alloy 7075 T73	2810 kg/m <sup>3</sup>	73 GPa

### Comparison of Static and Ultrasonic Forming Tests on Metals

**Force measurement using the machine load cell.** Fig. 4 shows the force-displacement results measured for static and static-ultrasonic forming tests on the four different metal specimens, measured by the load cell in the machine cross-head. During ultrasonic excitation of the female die the mean force is recorded by the test machine and clearly exhibits a reduction in the forming load in all tests.

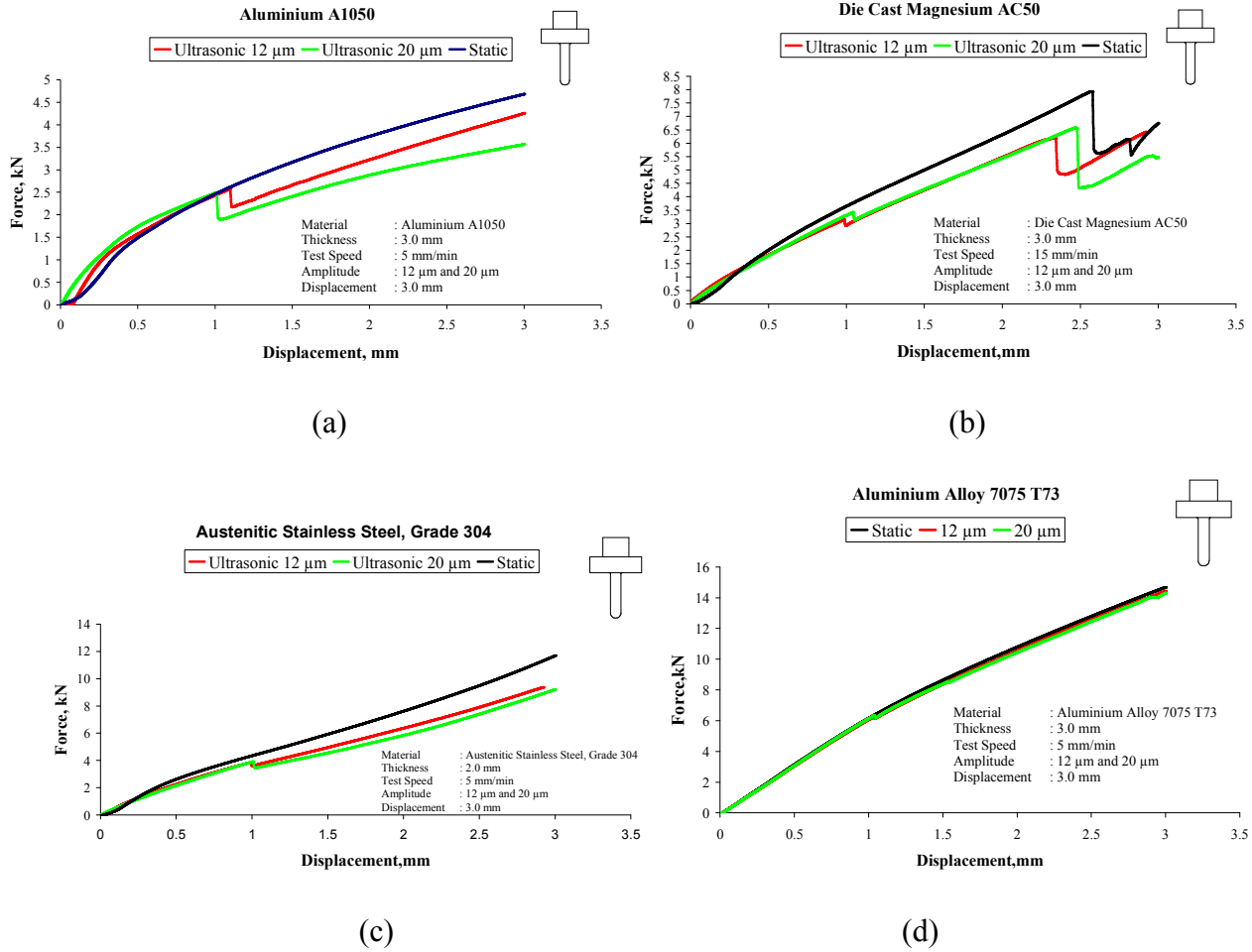


Figure 4: Die forming tests with and without ultrasonic excitation of the female die for (a) aluminium A1050 (b) die cast magnesium AC50 (c) austenitic stainless steel, grade 304 (d) aluminium alloy 7075 T73.

Table 2: Percentage reduction in the mean forming force.

Material	% Reduction in the forming force for 2 ultrasonic amplitudes	
	12 $\mu$ m	20 $\mu$ m
Aluminium A1050	16%	22%
Die cast magnesium AC50	7%	9%
Austenitic stainless steel, grade 304	7%	11%
Aluminium alloy 7075 T73	2%	3%

The results in terms of the percentage reduction in the forming force are summarised in Table 2. These results demonstrate that the effect of ultrasonic excitation of the die in metal forming is highly dependent on the material and its capacity to absorb ultrasonic energy. The soft aluminium specimens exhibited the largest reduction in the forming force which would indicate that the use of ultrasonic excitation is most beneficial in forming of this metal. The amplitude of the ultrasonic die horn is known to have a significant effect on the reduction in forming force [1] and this can be seen in Table 2. However, amplitude has little influence on force reduction in specimens where the reduction in forming force achieved is small.

If metals are heated to provide similar reductions in forming force, metal specimens generally benefit from improved ductility. However, the ultrasonic forming tests exhibit a reduction in the break force for the one specimen (die cast magnesium) that failed within the 3 mm cross-head displacement range of the tests. This result is consistent with previous findings that ultrasonic excitation leads to a reduction in the forming force and in the break force which can be explained by effective material softening due to the acoustoplastic effect [5] and dependency on factors such as acoustic impedance, internal friction, lattice imperfections, flow resistance, grain boundaries and impurities [6,7].

**Force measurement using the piezoelectric force transducer.** Measurement of the forming force without reference to the oscillatory force behaviour does not provide very meaningful interpretations of the effects of ultrasonic excitation because it relies on a reduction in mean load as being a direct measure of a beneficial effect. The measurement data presented in Fig. 5 superimposes the force measured from the piezoelectric force transducer on the force measured by the machine load cell. For all the tests shown in the figure, the ultrasonic amplitude of the die horn was 20  $\mu\text{m}$  and the cross-head speed was 10 mm/min. The tests were carried out for a 3 mm displacement of the machine cross-head as before.

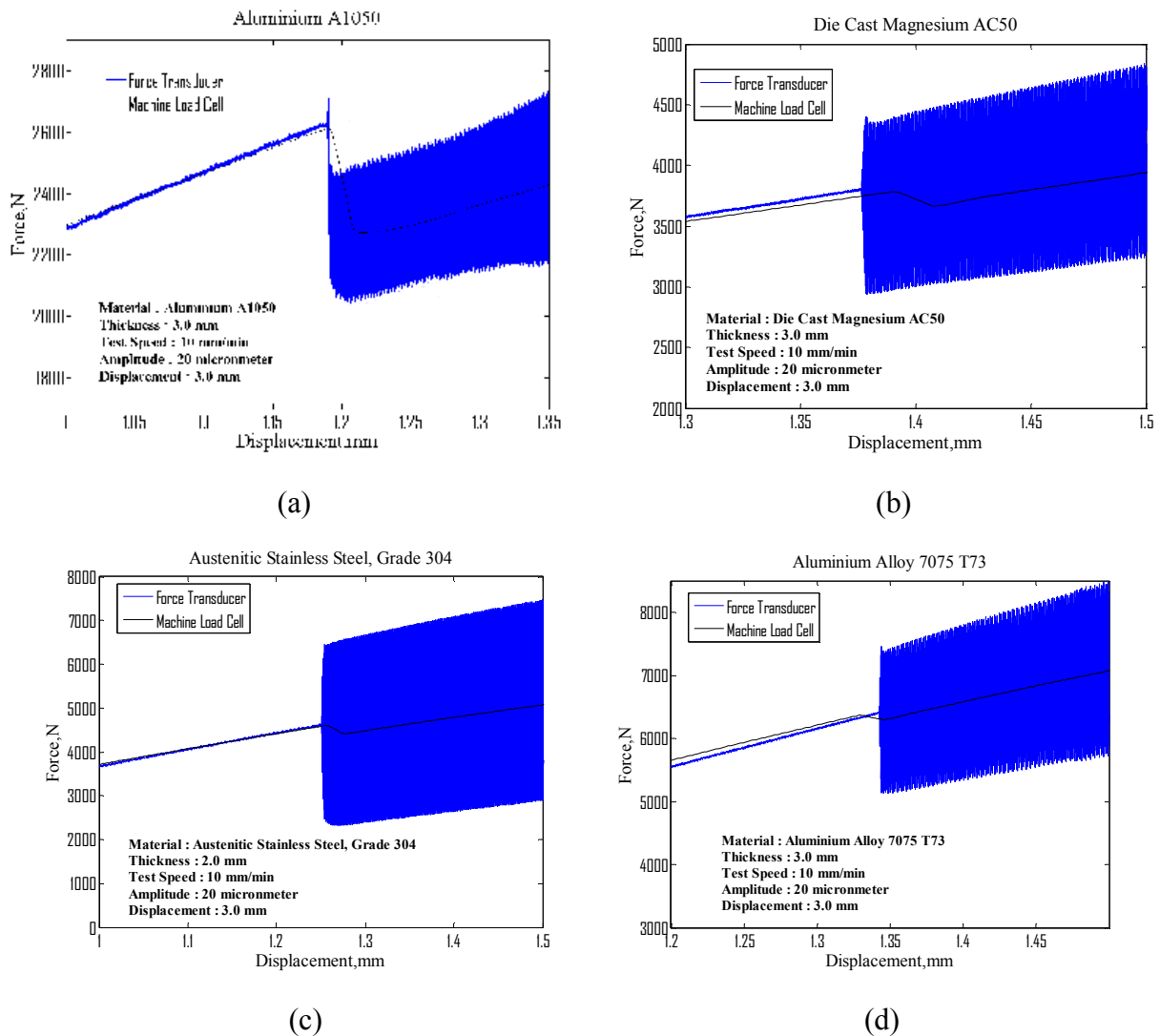


Figure 5: Die forming tests showing the measured oscillatory force for (a) aluminium A1050, (b) die cast magnesium AC50, (c) austenitic stainless steel grade 304, (d) aluminium alloy 7075 T73.

For each measurement, the peak-peak amplitude of the oscillatory force during ultrasonic excitation of the die horn is summarised in Table 3. The results for aluminium 1050 exhibit a path of maximum oscillatory force which is lower than the static load. These results are in good agreement with experimental results from cylindrical specimen compression tests reported by Daud [4]. For the other three metals, the maximum oscillatory force is larger than the static force even though, in all cases, there is a clear reduction in the mean load from the static load during the interval of ultrasonic excitation. Under the very high compressive loads required for compressive forming processes, it becomes difficult to achieve significant forming force reduction benefits from ultrasonic excitation of the forming tools for hard metal materials. For softer materials the benefits are significant.

Table 3: Amplitude of oscillatory force (pk-pk).

Material	Force amplitude (vibration amplitude 20 $\mu\text{m}$ )
Aluminium A1050	500 N
Die cast magnesium AC50	1300 N
Austenitic stainless steel, grade 304	4000 N
Aluminium alloy 7075 T73	1800 N

### Summary

The mean and oscillatory forces were measured during a simple ultrasonically assisted compressive forming test for four different metal specimens. The results agreed with previous studies of metal forming processes showing that the forming load is reduced by ultrasonic excitation of the forming tool. However, it was shown from measurements of the oscillatory force that a reduction in the mean forming force is not directly indicative of a benefit of ultrasonic excitation since, in many cases, the maximum oscillatory forming force can exceed the static forming force.

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