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Measurement of the acoustic softening effect in forming of metals

UIA Symposium 2010, Cambridge MA

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power ultrasonics in metal forming

Power ultrasonics: usually 20 – 100 kHz

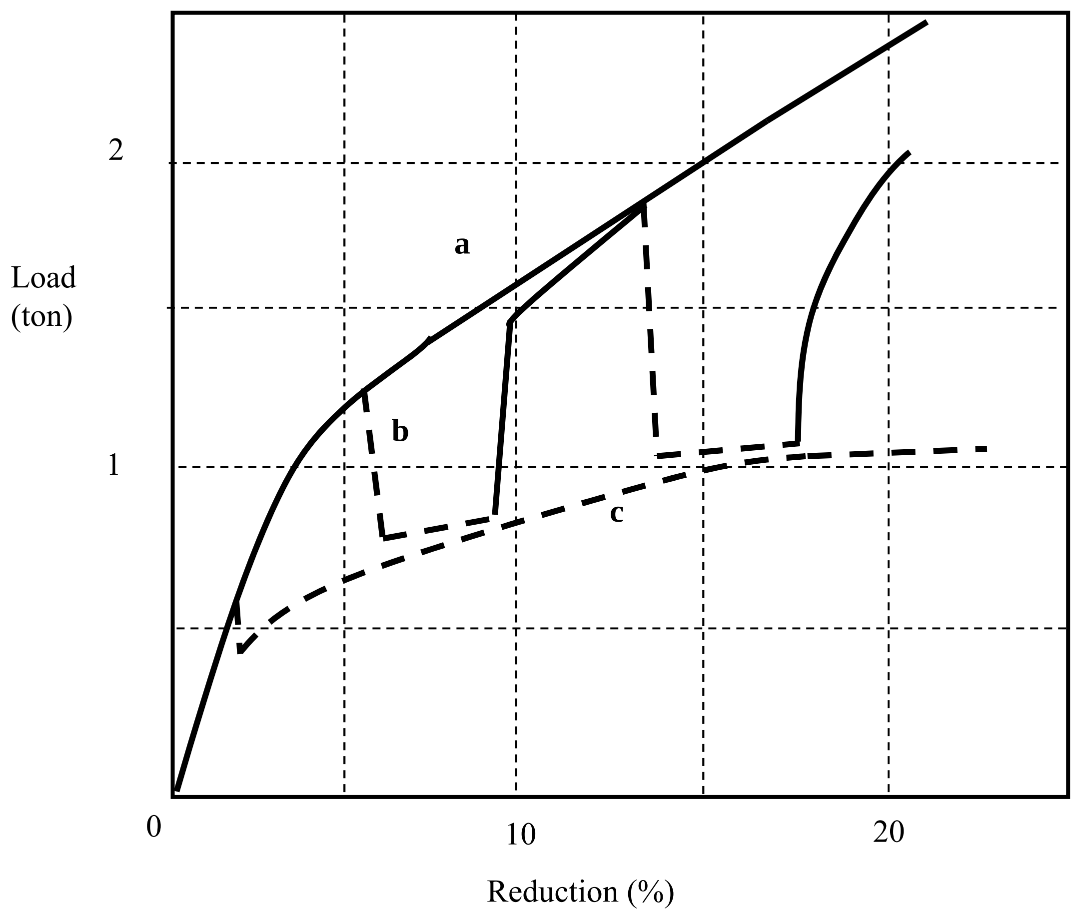
Applications where ultrasonics is used to effect an irreversible change in the target medium.

Early uses of power ultrasonics were in extrusion, wire drawing and metal can shaping (die forming) applications.

Claims were made that forming forces could be reduced by around 50% and that the main contributing factor was friction reduction.

There was considerable argument as to the existence of “acoustic softening” (or the “acoustoplastic effect”) as a mechanism of forming force reduction due to ultrasonic excitation in these processes.

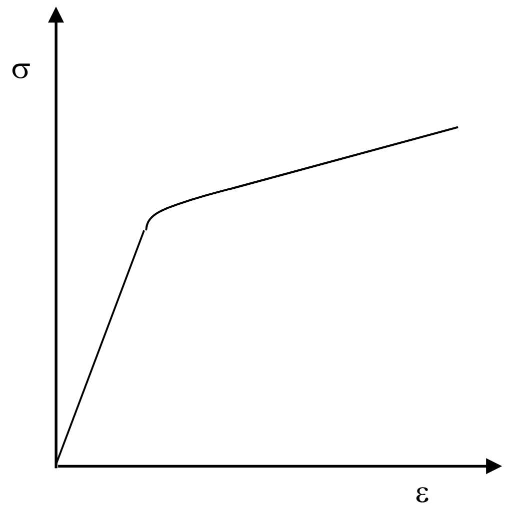
early measurements of compression tests



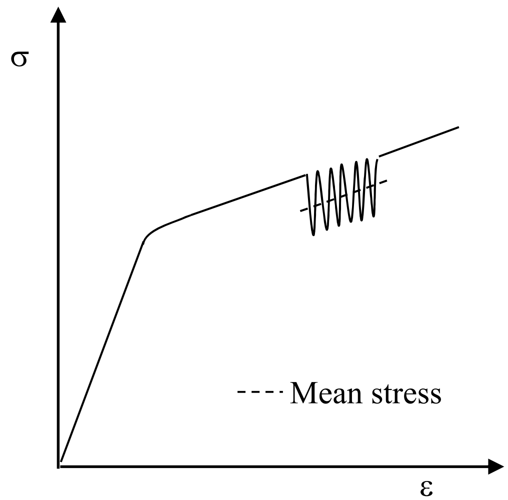
Measured compressive load due to superimposed ultrasonic vibration, (a) without ultrasonic vibration, (b) two intervals of superimposed ultrasonic vibration, (c) continuous ultrasonic vibration.

Izumi et al, On the superimposing of ultrasonic vibration during compressive deformation of metals, Trans. J. Inst. Metals, 7 (1966).

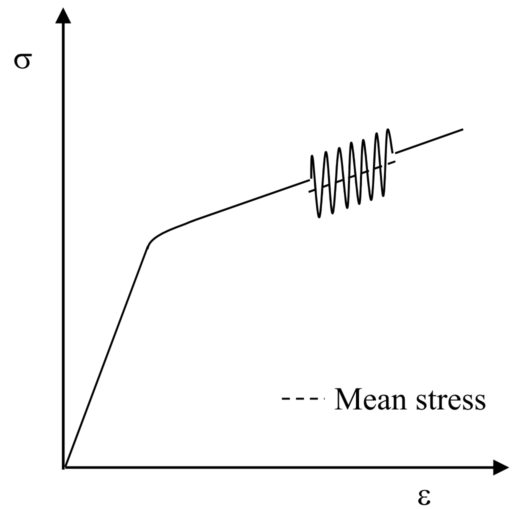
principle of oscillatory stress superposition



stress-strain curve for an elastic-plastic material

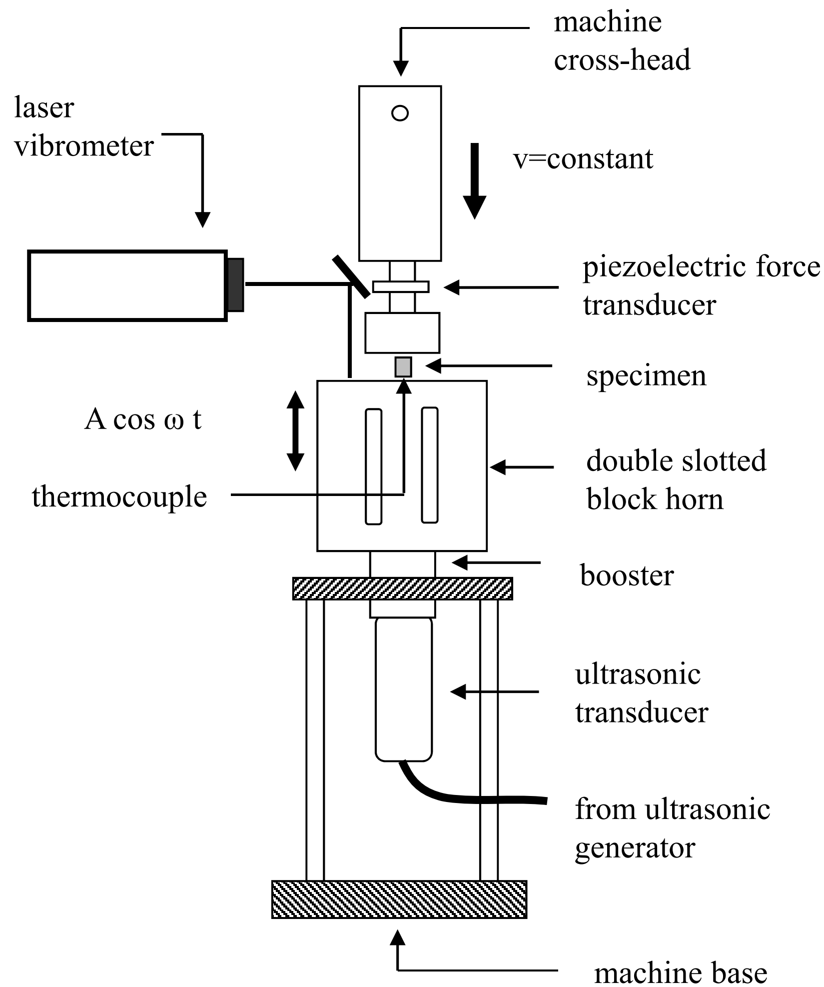


oscillatory stress superposition shown for a rate independent material



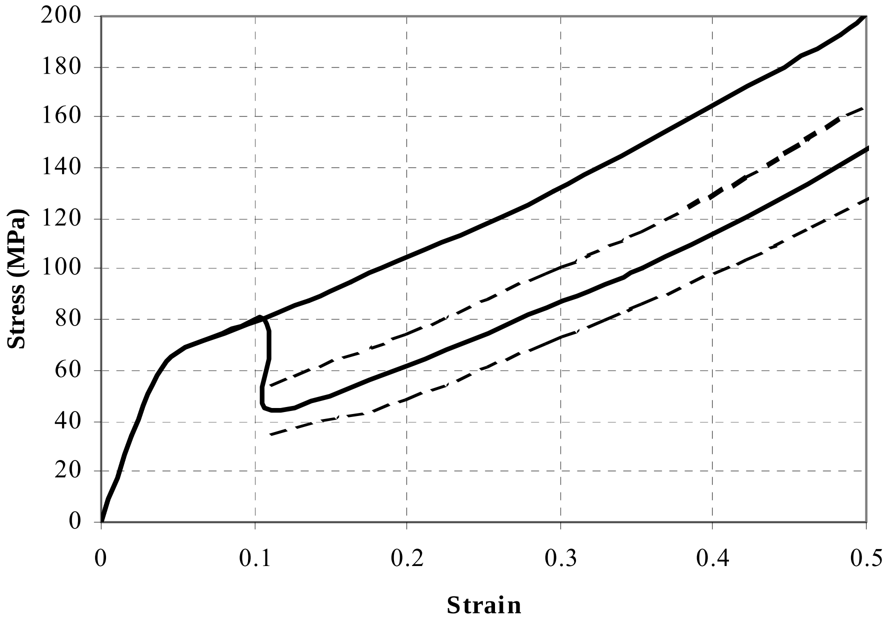
oscillatory stress superposition shown for a rate dependent material, illustrating overshoot

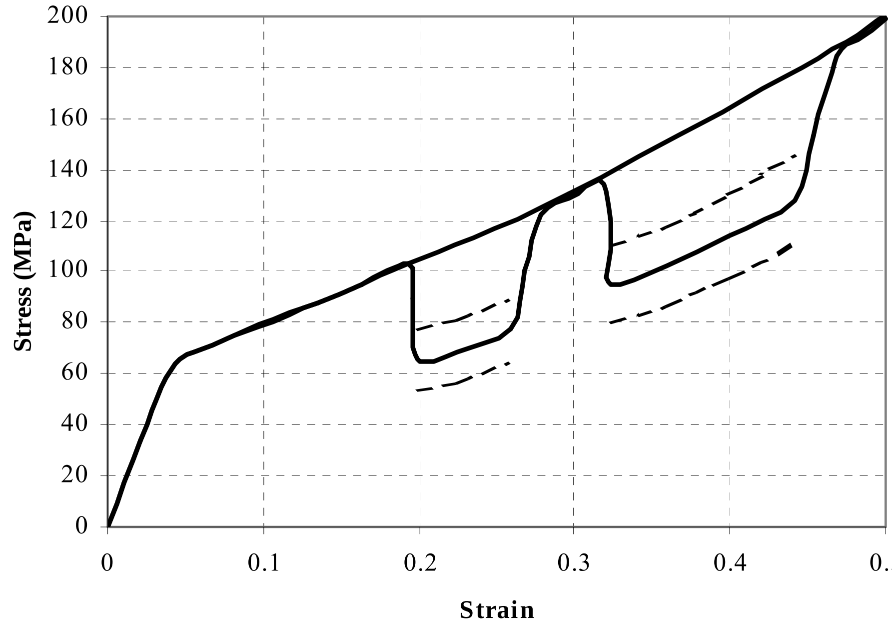
ultrasonic compression tests set-up



ultrasonic compression tests

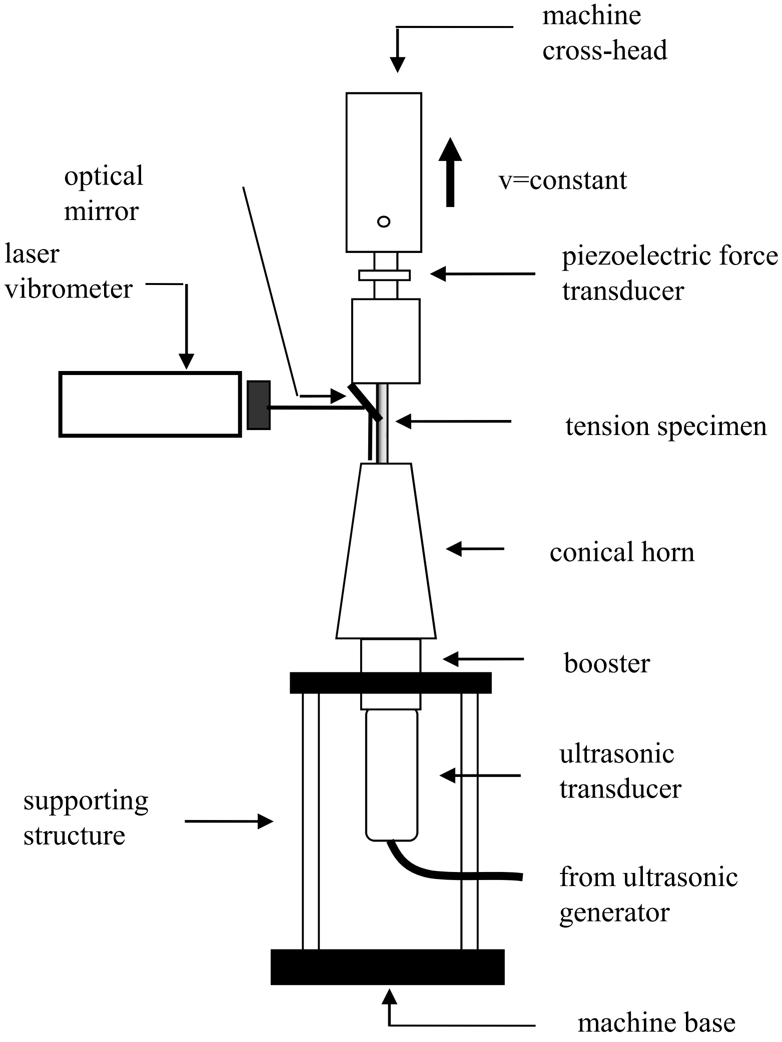
Aluminium 1050





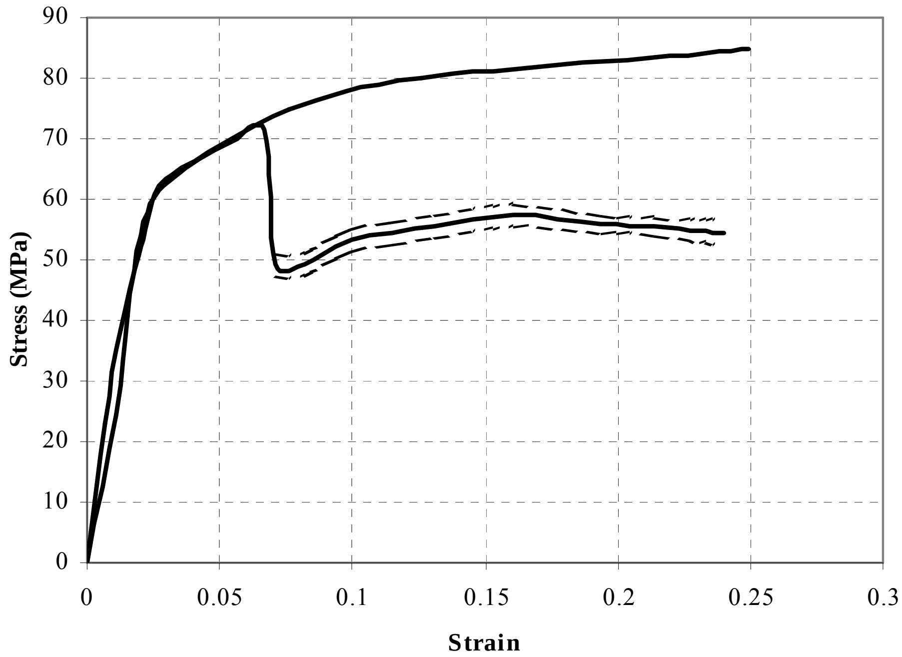
Measured static and ultrasonic compression test for dry surface, showing:
— static and mean stress, ----- paths of max. and min. oscillatory stress.

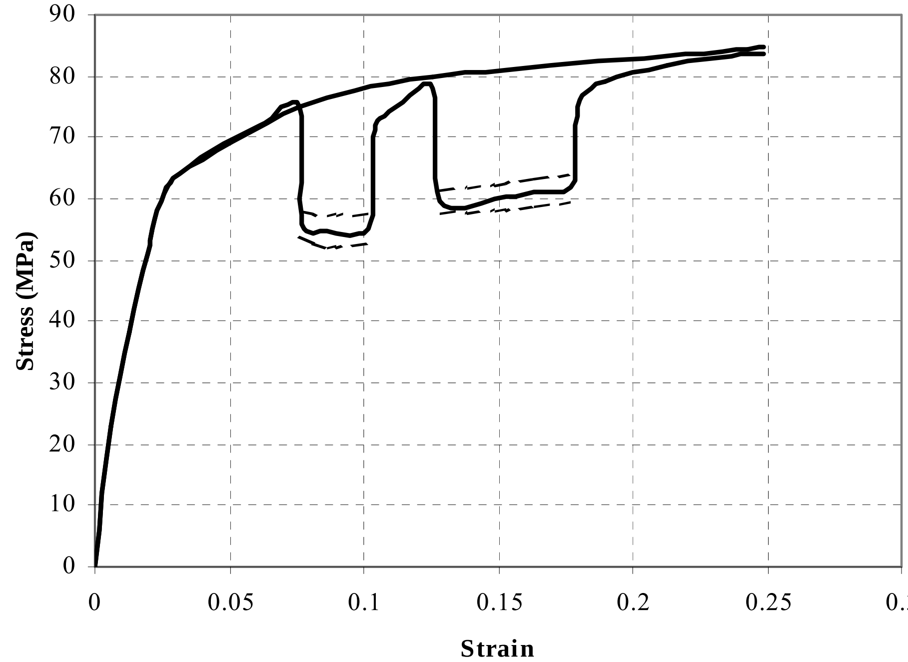
ultrasonic tension tests set-up



ultrasonic tension tests

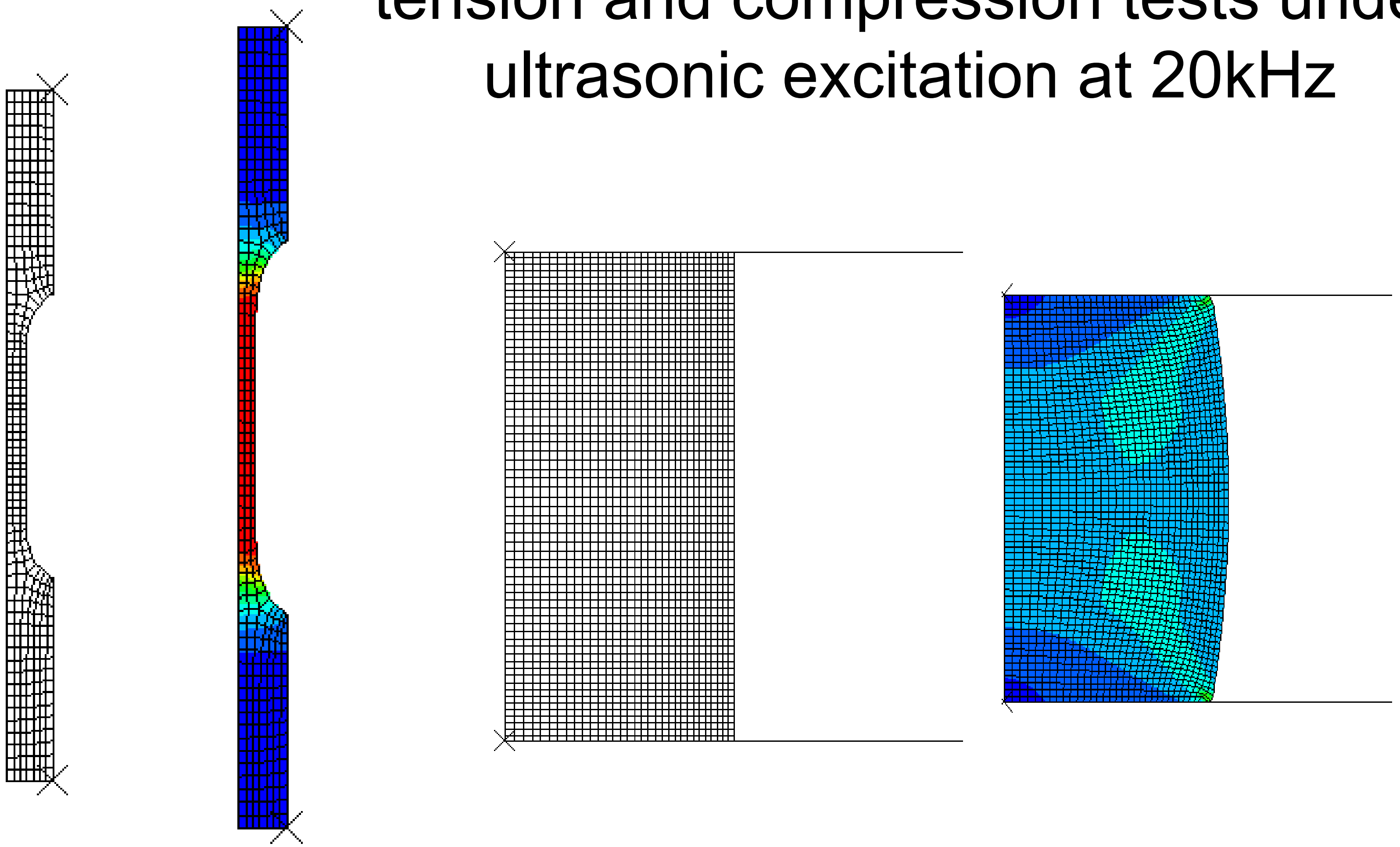
Aluminium 1050



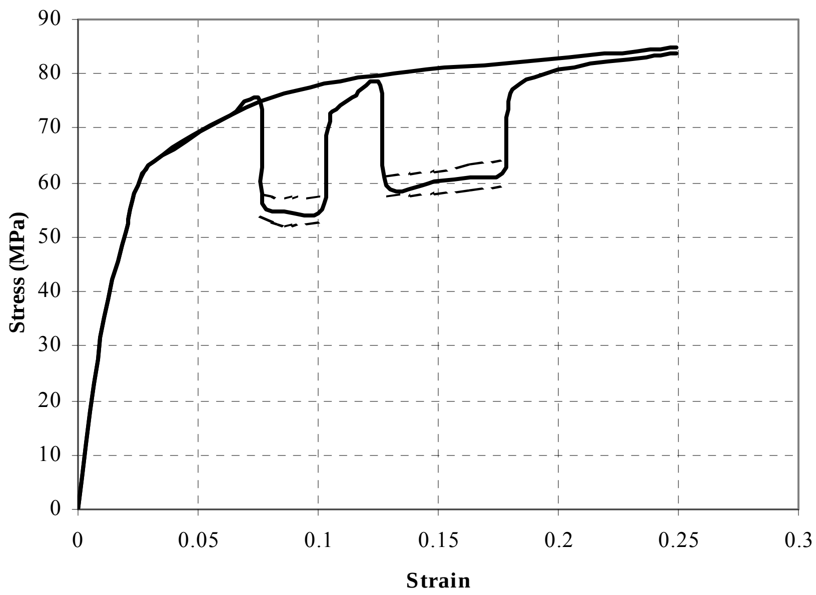


Measured static and ultrasonic tension tests, showing:
— static and mean stress, ----- paths of max. and min. oscillatory stress.

Finite element models of standard tension and compression tests under ultrasonic excitation at 20kHz



ultrasonic tension test data



<u>Tension test data:</u>

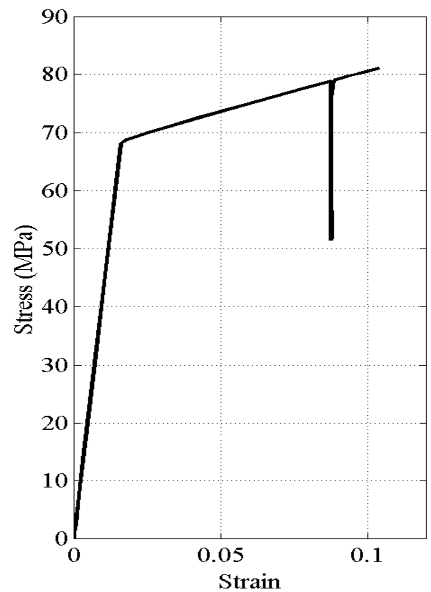
Reduction in mean stress is 23 MPa and pk-pk oscillatory stress amplitude is 5.5 MPa

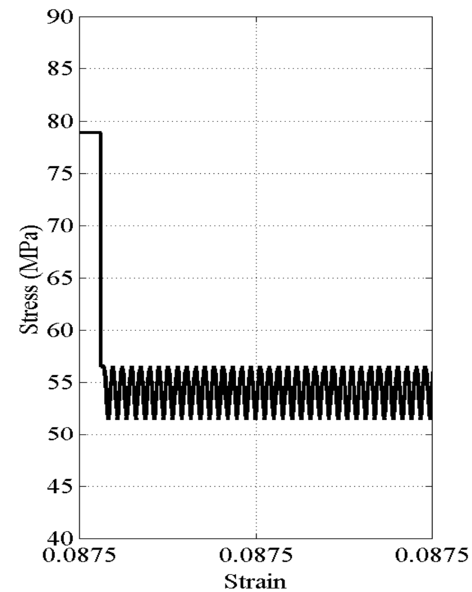
<u>FE model of tension test:</u>

A short interval of superimposed ultrasonic excitation; original material during static loading and softened material during static-ultrasonic loading.

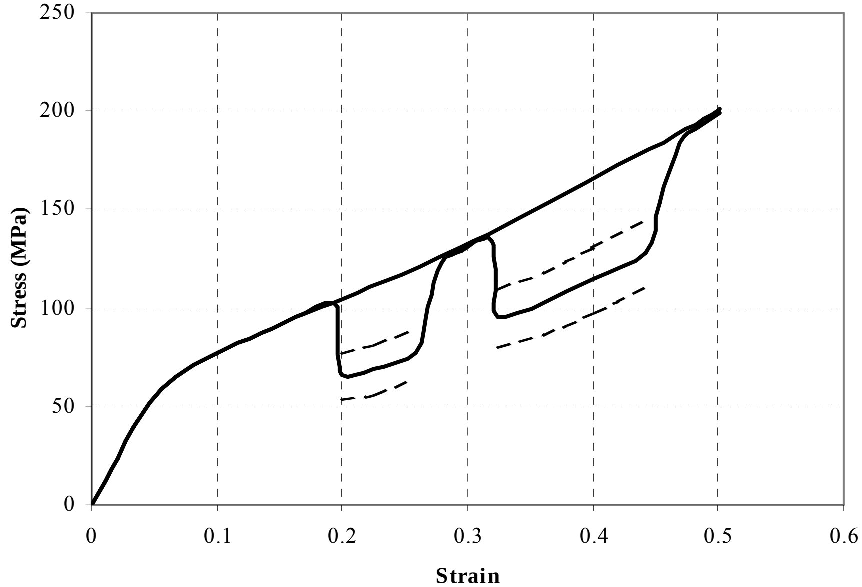
Close correlation is achieved with the experimental data:

Reduction in mean stress is 24 MPa and oscillatory stress amplitude is 5 MPa.





ultrasonic compression test data



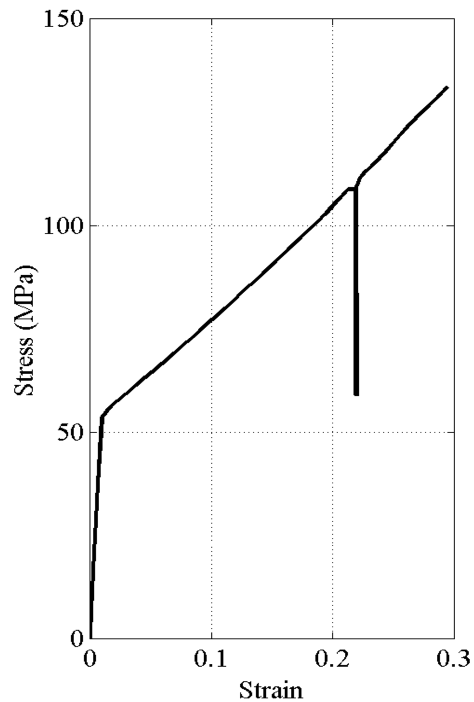
<u>Compression test data:</u>

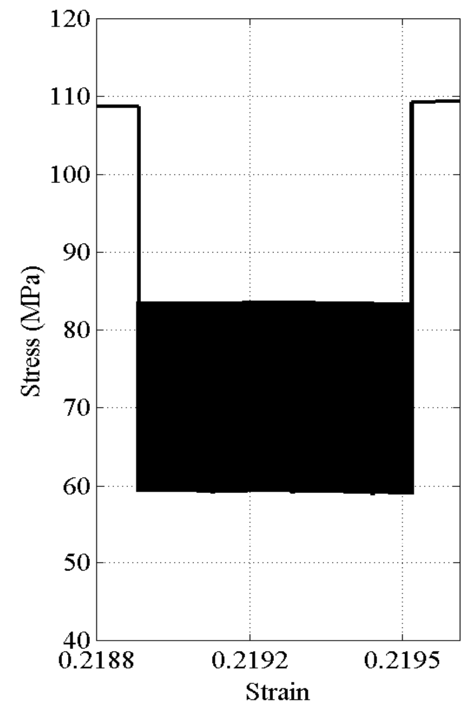
Reduction in mean stress is 40 MPa and pk-pk oscillatory stress amplitude is 24 MPa

<u>FE model of compression test:</u>

Combines a change to the softer material properties with a change in coefficient of friction from μ=0.25 to 0.15 during ultrasonic compression.

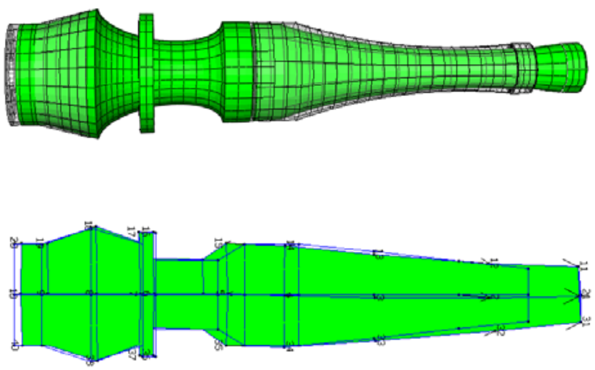
Reduction in mean stress is 38 MPa and oscillatory stress amplitude is 24 MPa





ultrasonic forming test

Ultrasonic transducer and die horn



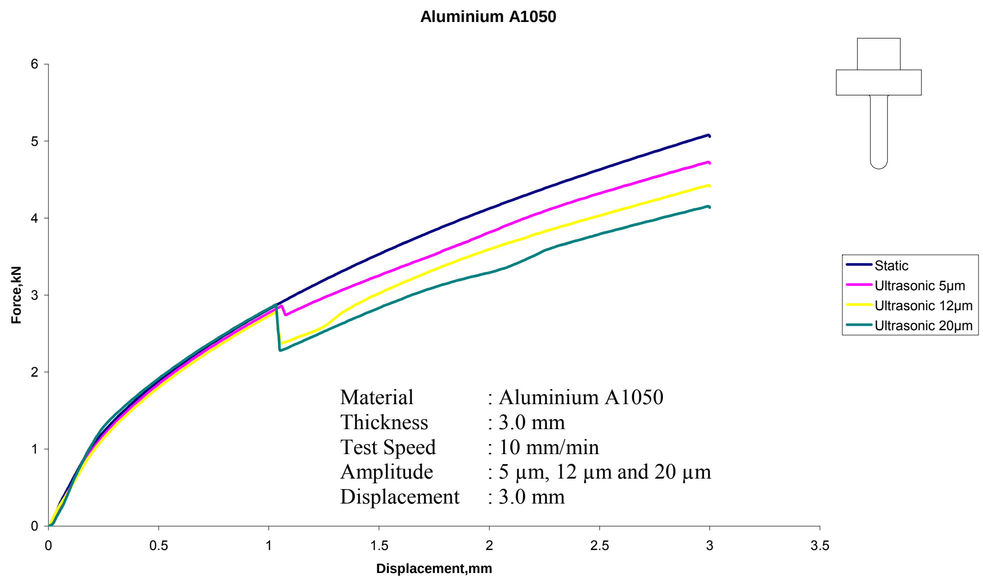
20.74 kHz

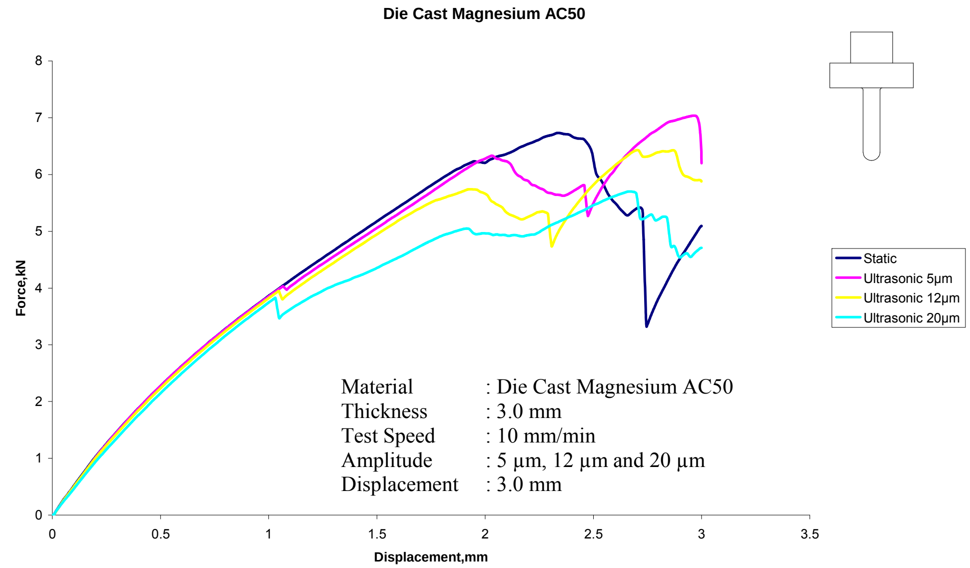
20.80 kHz

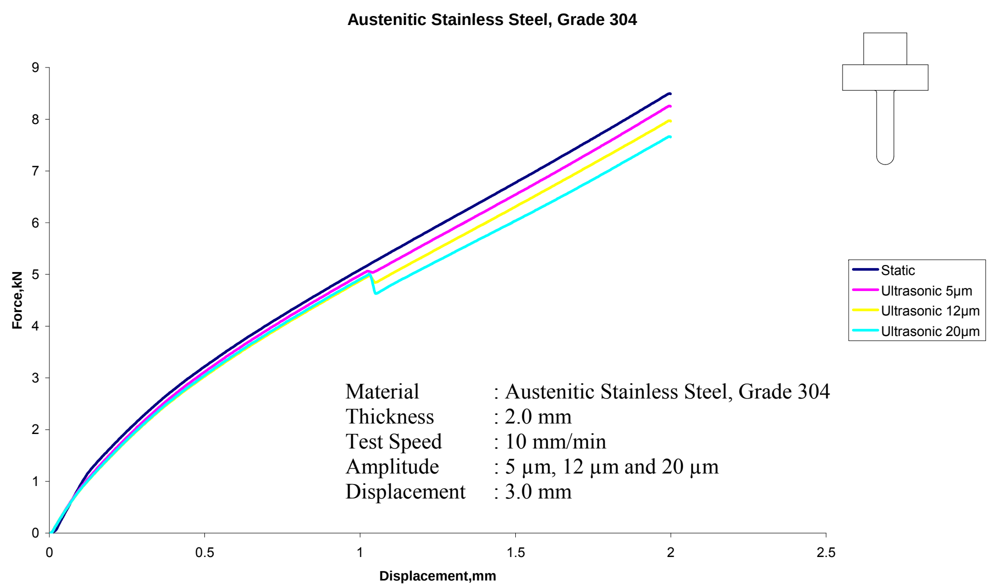
Comparison of FE predicted and EMA measured longitudinal mode and modal frequency.

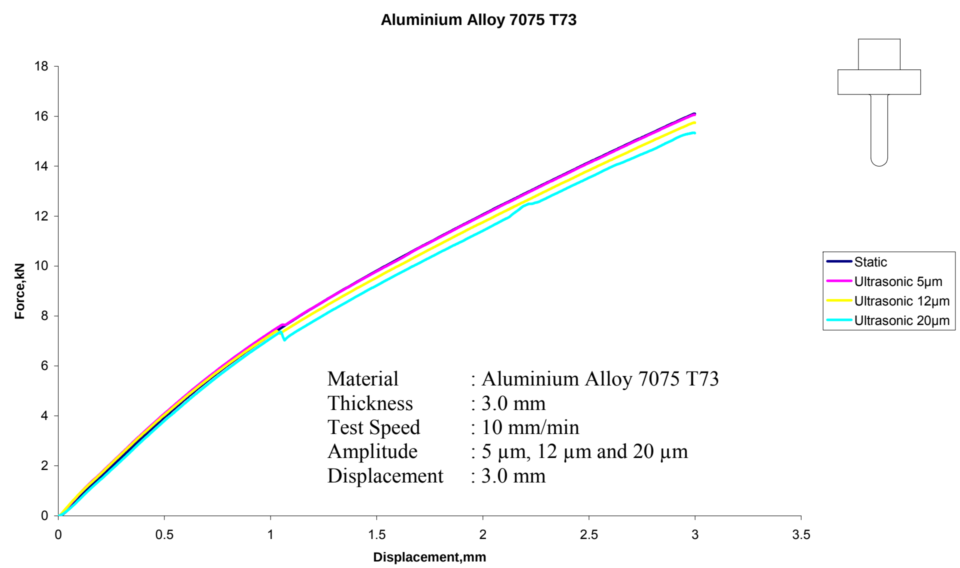
Material	Density, ρ	Modulus of Elasticity, E
Aluminium A1050	2705 kg/m^3	70 GPa
Die cast magnesium AC50	1740 kg/m^3	44 GPa
Austenitic stainless steel 304	8030 kg/m^3	193 GPa
Aluminium alloy 7075 T73	2810 kg/m^3	73 GPa

die forming test results

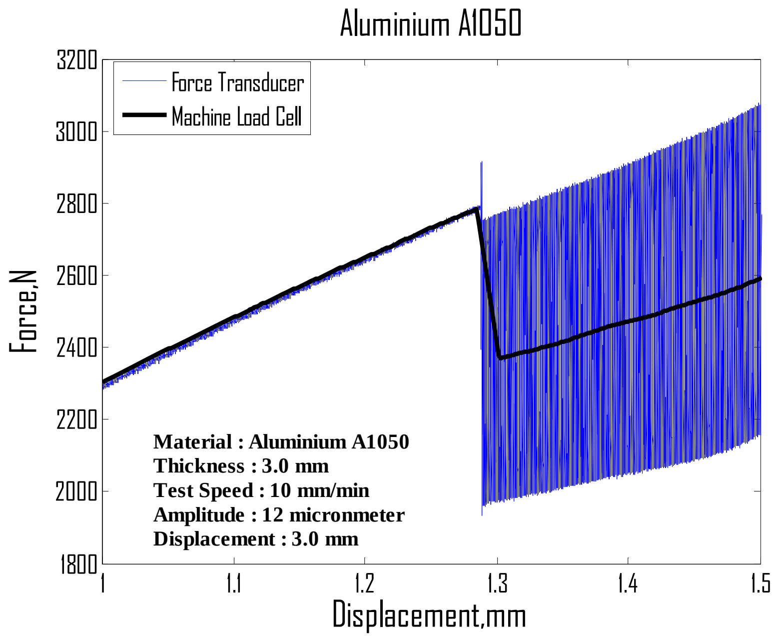


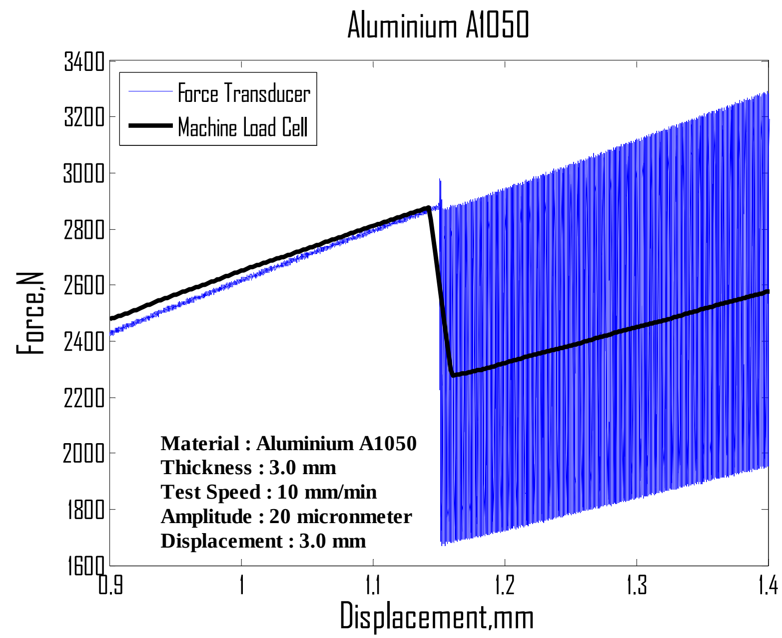


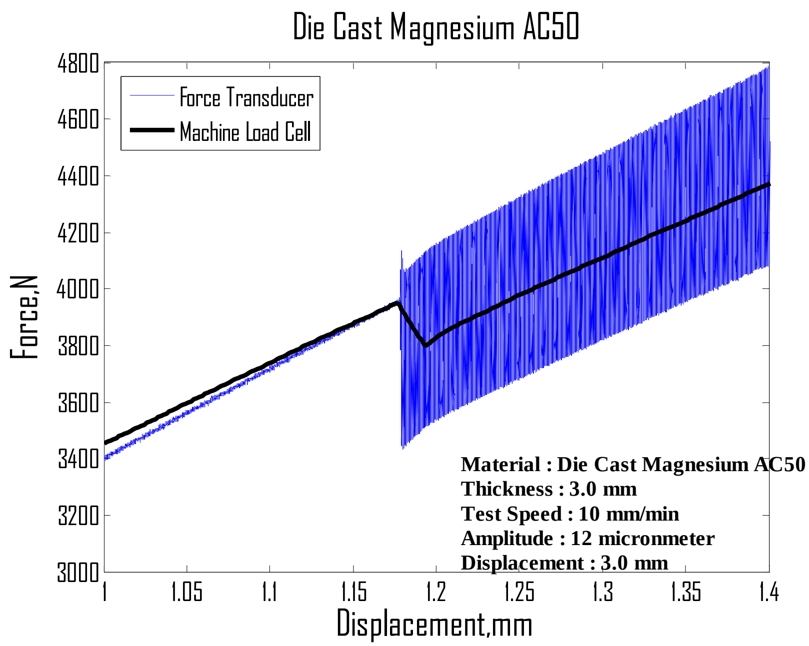


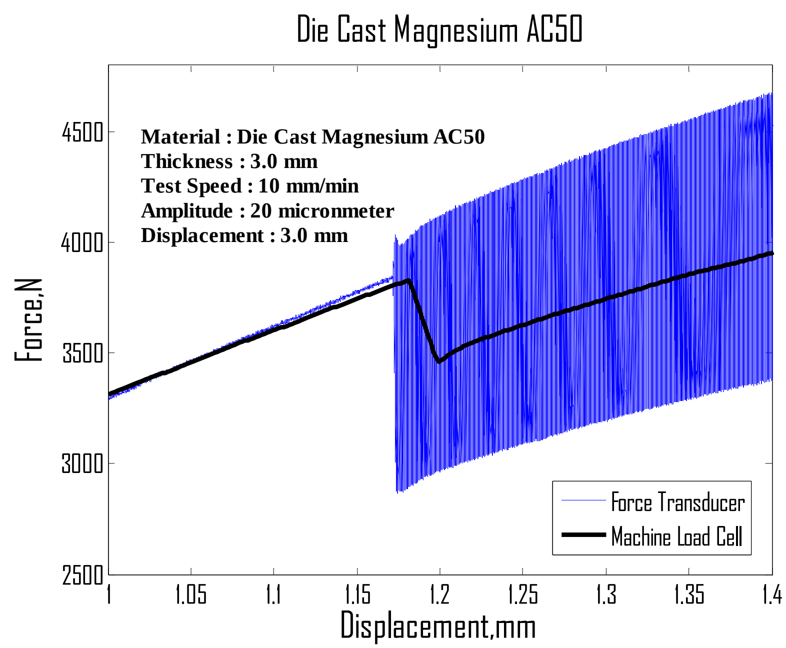


measured oscillatory force

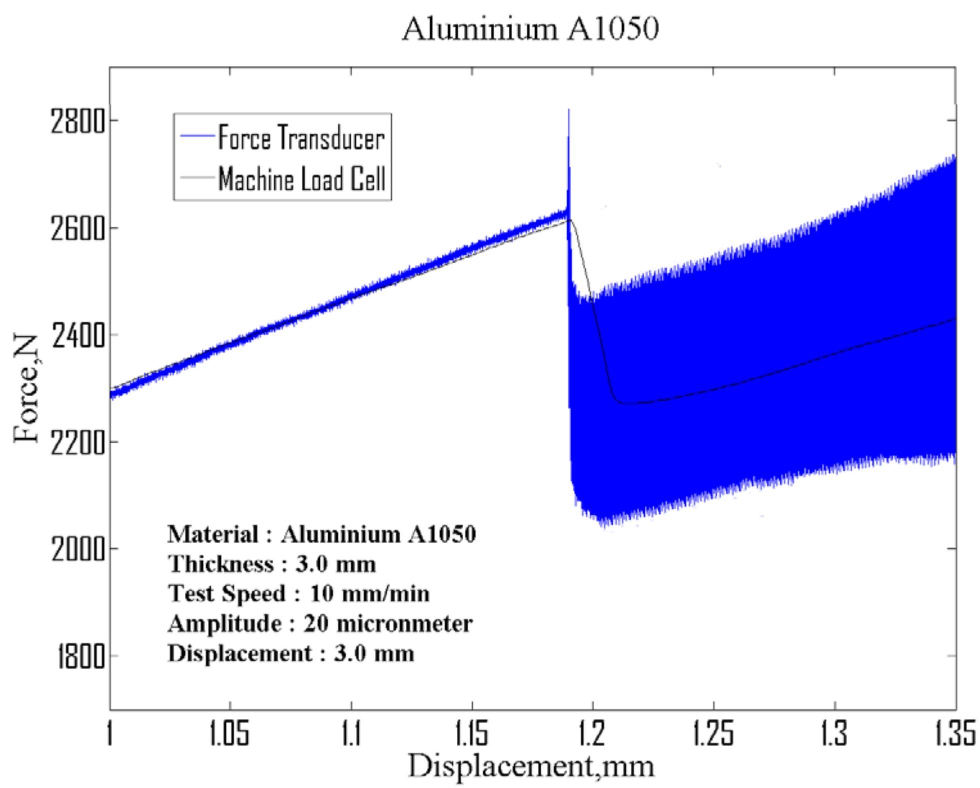








oscillatory force measurement, Al 1050



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conclusions

- Applying ultrasonic excitation in metal forming processes results in a reduction in the mean forming force.
- A reduction in the maximum oscillatory forming force during ultrasonic excitation of the die is an indication of an "effective acoustic softening".
- In ultrasonic compression tests an alteration to the contact condition also contributes to the measured force reduction.
- In a simple ultrasonically excited die forming test on a range of materials, a reduction in the mean forming force was always measured but there was not always a measurable indication of an acoustic softening effect.
- Results would indicate that interface friction changes are not wholly responsible for the measured benefits of applying power ultrasonics in metal forming operations.
- The effects of ultrasonic excitation can be measured even in difficult to form materials but the high forming loads present interesting challenges.

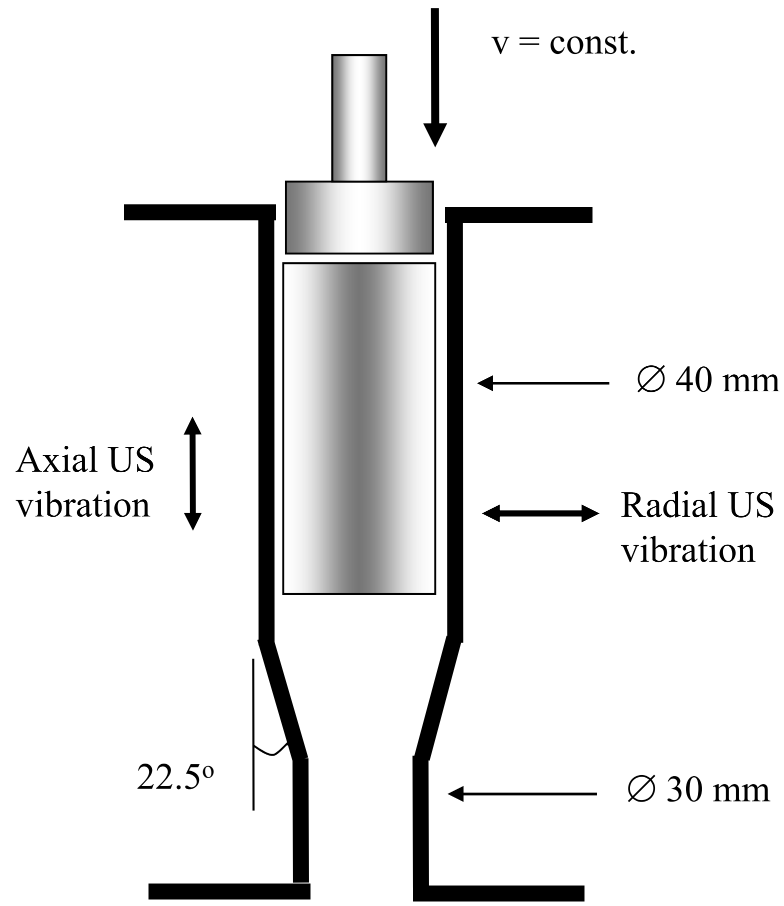
THANK-YOU

FE model of ultrasonic extrusion

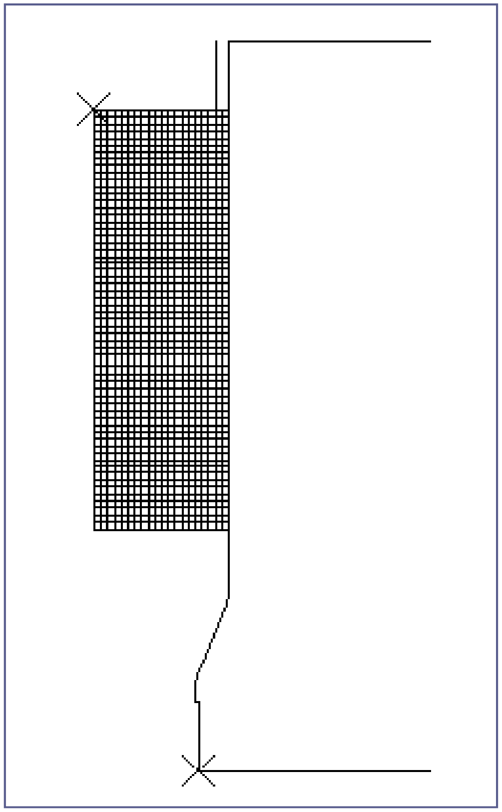
- To model a process which allows comparison with measurement data in the literature
- To confirm that the effects of radial and axial ultrasonic excitation are limited by a critical speed
- To investigate if reductions in the measured mean extrusion force and effective reductions in the coefficient of friction reported in the literature can be simulated in the FE model

finite element model of ultrasonic extrusion

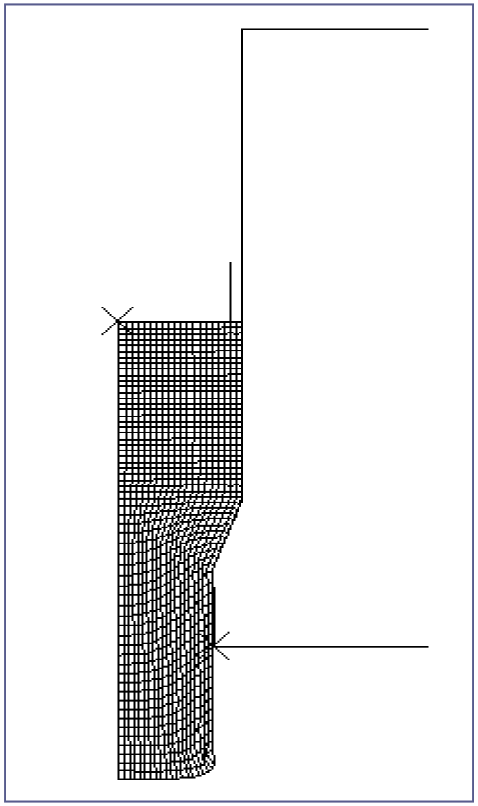
- The die and billet geometries used were based on previous well validated numerical studies of extrusion
- An initial billet diameter of 40mm, die diameter of 30mm, providing extrusion reduction of 43.8% and die half angle, $\alpha = 22.5^o$.



finite element model of the billet for extrusion



Undeformed mesh



Deformed mesh

Models presented are for 20 kHz radial or axial ultrasonic vibration of the die with peak amplitude of 3μm

radial US extrusion with constant μ = 0.05

(a) Extrusion speed = 380 mm/s
below critical speed
mean extrusion force: 122 kN
pk-pk oscillatory force: 2.3 kN

(b) Extrusion speed = 1000 mm/s
close to critical speed
mean extrusion force: 122.8 kN
pk-pk oscillatory force: 1.5 kN

(c) Extrusion speed = 3000 mm/s
higher than critical speed
mean extrusion force: 123 kN
pk-pk oscillatory force: 0.5 kN

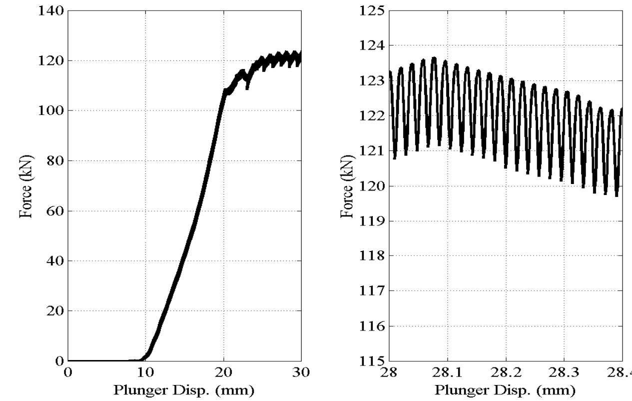
Critical speed, *Vc*:

$Vc = 2\pi af / \tan\alpha$ for radial ultrasonic excitation

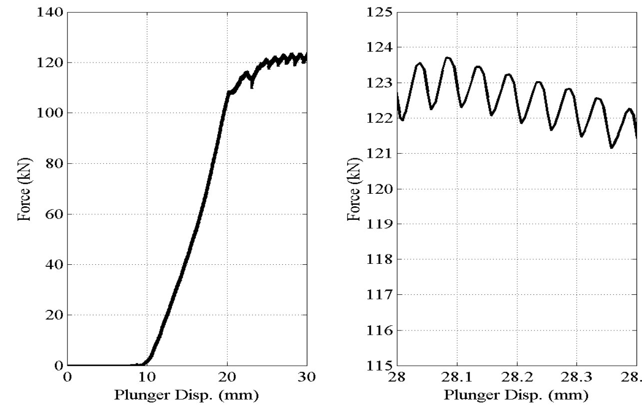
$Vc = 2\pi af$ for axial ultrasonic excitation

where a is the vibration amplitude, f is the ultrasonic frequency and α is the die half angle

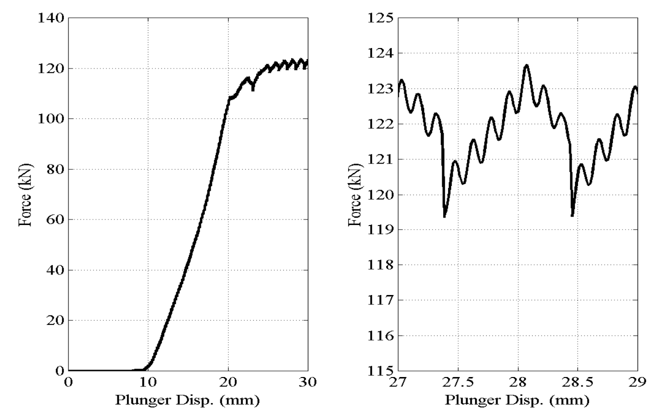
(a)



(b)



(c)

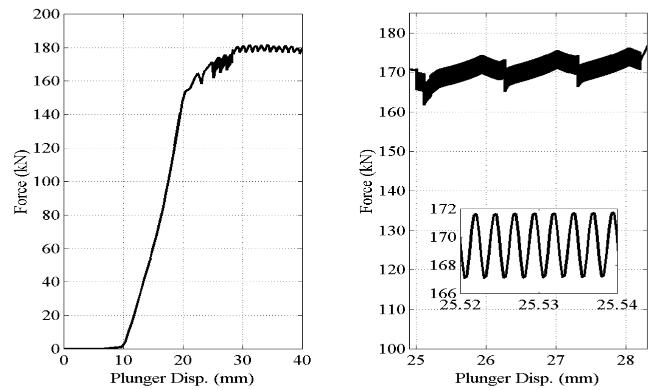


radial US excitation: 20kHz, 3μm, v=10mm/s

Radial ultrasonic excitation is superimposed for a short interval during plastic deformation, left inset figures show two expanded views of the oscillatory force

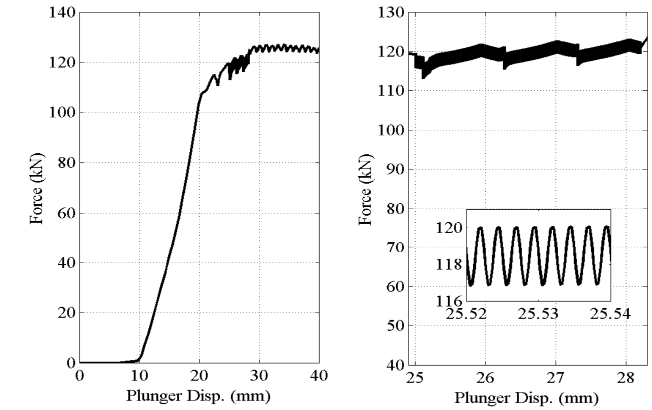
(a) Constant coefficient of friction, μ = 0.1, throughout

(a)



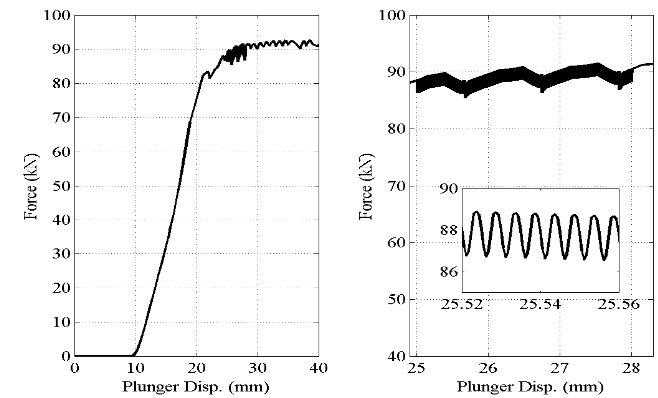
(b) Constant coefficient of friction, μ = 0.05, throughout

(b)



(c) Frictionless interface, μ = 0, throughout

(c)

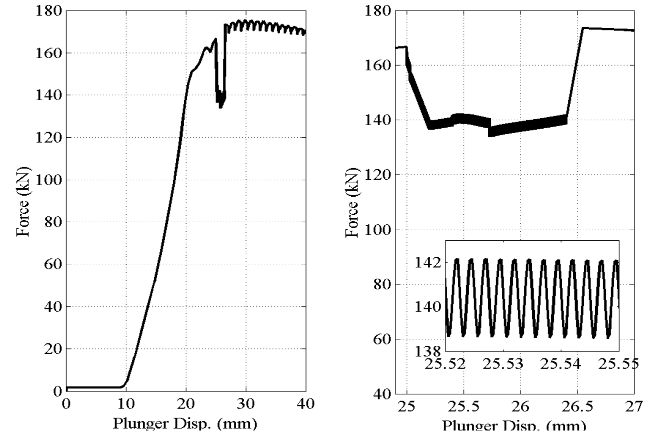


- Obeys principle of oscillatory force superposition
- pk-pk oscillatory force increases with increasing μ

radial US excitation: 20kHz, 3μm, 10mm/s

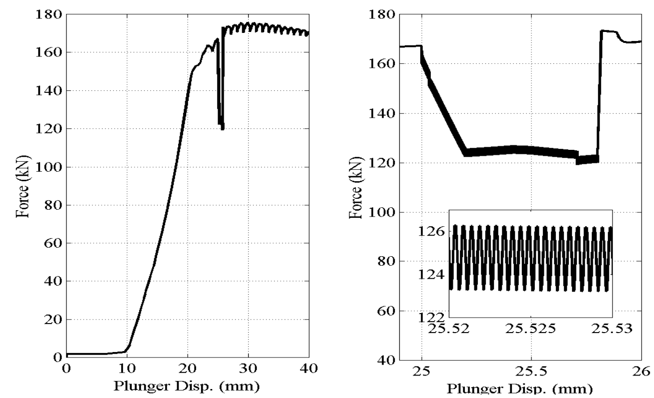
(a) $\mu = 0.1$ changed to $\mu = 0.07$ during ultrasonic excitation

(a)



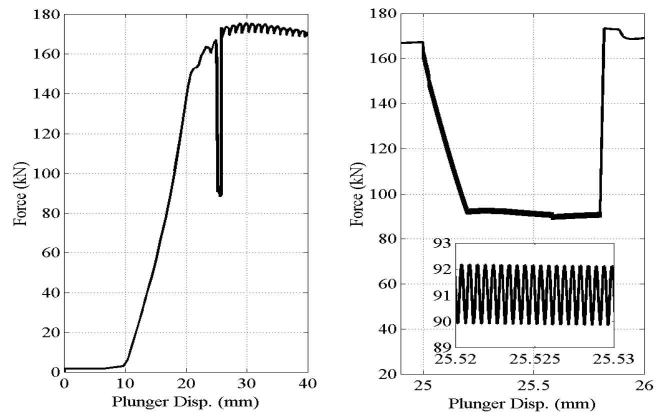
(b) $\mu = 0.1$ changed to $\mu = 0.05$ during ultrasonic excitation

(b)



(c) $\mu = 0.1$ changed to $\mu = 0$ during ultrasonic excitation

(c)



summary of finite element model predictions

Peak-peak oscillatory force for radial and axial ultrasonic extrusion

Coefficient of friction	Radial ultrasonic extrusion peak-peak force (kN)	Axial ultrasonic extrusion peak-peak force (kN)
$\mu = 0.1$	5.0	3.5
$\mu = 0.05$	3.0	2.5
$\mu = 0$	2.0	0.5

Mean force reduction due to the reduction of interface friction during ultrasonic extrusion

Reduction of μ from 0.1 to	Radial mode		Axial mode	
	Force reduction		Force reduction	
	(kN)	%	(kN)	%
$\mu = 0.07$ (30%)	27.5	16.7	27.5	16.4
$\mu = 0.05$ (50%)	43.0	25.6	43.5	25.9
$\mu = 0.0$ (100%)	77.0	45.8	76.5	45.5

summary of FE predictions compared to published measurement data

For ultrasonic forming processes:

- The maximum achievable effective reduction in the coefficient of friction as quoted in the literature is in the range 30 – 40%
- Typically quoted achievable reductions in the mean forming load are 35%
- By assuming that ultrasonic excitation significantly reduces the coefficient of friction, say by 50%, the FE model predicts the mean force is reduced by about 25% for radial and axial ultrasonic excitation of the die
- The results seem to support the earlier data from ultrasonic compression tests that a temporary reduction in the coefficient of friction cannot alone explain the measured reductions in mean forming force reported in the literature.

conclusions

- The benefits of applying ultrasonic excitation can only be achieved below a critical extrusion speed.
- A reduction in the mean extrusion force in the FE model is due to an effective reduction in the coefficient of friction during the intervals of ultrasonic excitation.
- The measured reductions in extrusion force reported in the literature are significantly higher than can be achieved by incorporating the commonly quoted friction coefficient reductions into the finite element model.
- This would indicate that interface friction changes are not wholly responsible for the measured benefits of applying power ultrasonics in metal forming operations.

THANK-YOU