Measurement of the acoustic softening effect in forming of metals

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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 “acoustoplastastic effect”) as a mechanism of forming force reduction due to ultrasonic excitation in these processes.
Measured compressive load due to superimposed ultrasonic vibration, (a) without ultrasonic vibration, (b) two intervals of superimposed ultrasonic vibration, (c) continuous ultrasonic vibration.

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

- Laser vibrometer
- Piezoelectric force transducer
- Specimen
- Double slotted block horn
- Booster
- Ultrasonic transducer
- From ultrasonic generator
- Machine base
- Machine cross-head
- $v = \text{constant}$
- $A \cos \omega t$
- Thermocouple
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

v = constant

machine cross-head

piezoelectric force transducer

tension specimen

conical horn

booster

ultrasonic transducer

from ultrasonic generator

machine base

supporting structure

laser vibrometer

optical mirror

supporting structure

machine base
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
FE model of tension test:

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.
Compression test data:
Reduction in mean stress is 40 MPa and pk-pk oscillatory stress amplitude is 24 MPa

FE model of compression test:
Combines a change to the softer material properties with a change in coefficient of friction from $\mu=0.25$ 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

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ( \rho ) [kg/m(^3)]</th>
<th>Modulus of Elasticity, ( E ) [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium A1050</td>
<td>2705 kg/m(^3)</td>
<td>70 GPa</td>
</tr>
<tr>
<td>Die cast magnesium AC50</td>
<td>1740 kg/m(^3)</td>
<td>44 GPa</td>
</tr>
<tr>
<td>Austenitic stainless steel 304</td>
<td>8030 kg/m(^3)</td>
<td>193 GPa</td>
</tr>
<tr>
<td>Aluminium alloy 7075 T73</td>
<td>2810 kg/m(^3)</td>
<td>73 GPa</td>
</tr>
</tbody>
</table>
Die forming test results

Aluminium A1050

Material: Aluminium A1050
Thickness: 3.0 mm
Test Speed: 10 mm/min
Amplitude: 5 µm, 12 µm and 20 µm
Displacement: 3.0 mm

Die Cast Magnesium AC50

Material: Die Cast Magnesium AC50
Thickness: 3.0 mm
Test Speed: 10 mm/min
Amplitude: 5 µm, 12 µm and 20 µm
Displacement: 3.0 mm

Austenitic Stainless Steel, Grade 304

Material: Austenitic Stainless Steel, Grade 304
Thickness: 2.0 mm
Test Speed: 10 mm/min
Amplitude: 5 µm, 12 µm and 20 µm
Displacement: 3.0 mm

Aluminium Alloy 7075 T73

Material: Aluminium Alloy 7075 T73
Thickness: 3.0 mm
Test Speed: 10 mm/min
Amplitude: 5 µm, 12 µm and 20 µm
Displacement: 3.0 mm
measured oscillatory force

Aluminium A1050

- Force Transducer
- Machine Load Cell

Material: Aluminium A1050
Thickness: 3.0 mm
Test Speed: 10 mm/min
Amplitude: 12 micrometer
Displacement: 3.0 mm

Die Cast Magnesium AC50

- Force Transducer
- Machine Load Cell

Material: Die Cast Magnesium AC50
Thickness: 3.0 mm
Test Speed: 10 mm/min
Amplitude: 20 micrometer
Displacement: 3.0 mm
oscillatory force measurement, Al 1050

Aluminium A1050

Material: Aluminium A1050
Thickness: 3.0 mm
Test Speed: 10 mm/min
Amplitude: 20 micronmeter
Displacement: 3.0 mm

Force, N

Displacement, mm
• 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
• 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
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, $\alpha = 22.5^\circ$. 
finite element model of the billet for extrusion

Models presented are for 20 kHz radial or axial ultrasonic vibration of the die with peak amplitude of 3μm
radial US extrusion with constant $\mu = 0.05$

(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, $V_c$:

$V_c = \frac{2\pi a f}{\tan \alpha}$ for radial ultrasonic excitation

$V_c = 2\pi a f$ for axial ultrasonic excitation

where $a$ is the vibration amplitude, $f$ is the ultrasonic frequency and $\alpha$ is the die half angle.
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, $\mu = 0.1$, throughout

(b) Constant coefficient of friction, $\mu = 0.05$, throughout

(c) Frictionless interface, $\mu = 0$, throughout

- Obeys principle of oscillatory force superposition
- $p_k$-$p_k$ oscillatory force increases with increasing $\mu$
(a) $\mu = 0.1$ changed to $\mu = 0.07$ during ultrasonic excitation

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

(c) $\mu = 0.1$ changed to $\mu = 0$ during ultrasonic excitation
Peak-peak oscillatory force for radial and axial ultrasonic extrusion

<table>
<thead>
<tr>
<th>Coefficient of friction</th>
<th>Radial ultrasonic extrusion peak-peak force (kN)</th>
<th>Axial ultrasonic extrusion peak-peak force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu = 0.1 )</td>
<td>5.0</td>
<td>3.5</td>
</tr>
<tr>
<td>( \mu = 0.05 )</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>( \mu = 0 )</td>
<td>2.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Reduction of ( \mu ) from 0.1 to</th>
<th>Radial mode</th>
<th>Axial mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force reduction</td>
<td>Force reduction</td>
</tr>
<tr>
<td></td>
<td>(kN)</td>
<td>%</td>
</tr>
<tr>
<td>( \mu = 0.07 ) (30%)</td>
<td>27.5</td>
<td>16.7</td>
</tr>
<tr>
<td>( \mu = 0.05 ) (50%)</td>
<td>43.0</td>
<td>25.6</td>
</tr>
<tr>
<td>( \mu = 0.0 ) (100%)</td>
<td>77.0</td>
<td>45.8</td>
</tr>
</tbody>
</table>
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.
• 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.
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