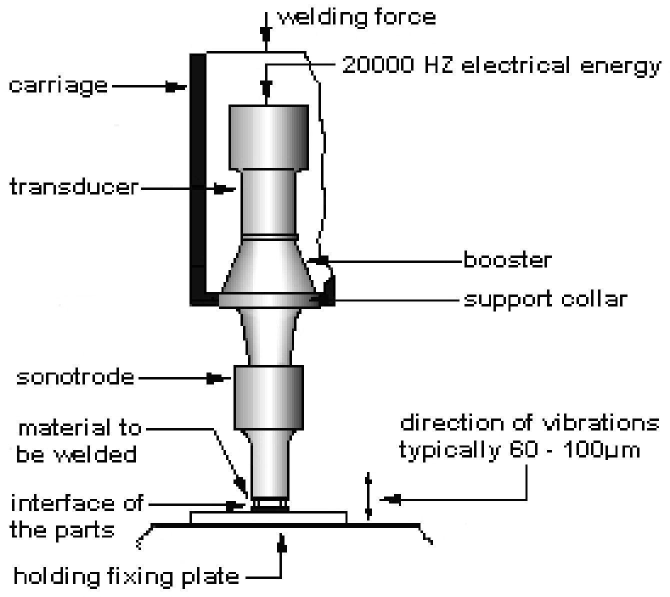
Ultra High Cycle Fatigue
5 November 2008
Turin, Italy

Department of Mechanical Engineering

Analysis of the Premature Failures of some Sonotrodes Made in Al Alloy for Ultrasonic Welding

M. Carboni, M. Annoni

Introduction – UW of plastics



An ultrasonic welding system for joining thermoplastics

- The vibrations are introduced vertically
- Frictional heat is produced so that material plasticizes locally, forging an insoluble connection between both parts within a very short period of time

Introduction - Sonotrodes

- No relevant studies on these tools: stresses are not yet known and understood! The design is made based only onto the experience of producers
- Largest amplitudes of the system: 50-100 μm
- Typical work frequency: 20 kHz
- Expected lifetime: 10 years

⇓

$\approx 10^{12}$ cycles!!!

Introduction

In the last period, the Customer had numerous unexpected failures after only two weeks of work (≈ $5.5x10^9$ cycles)

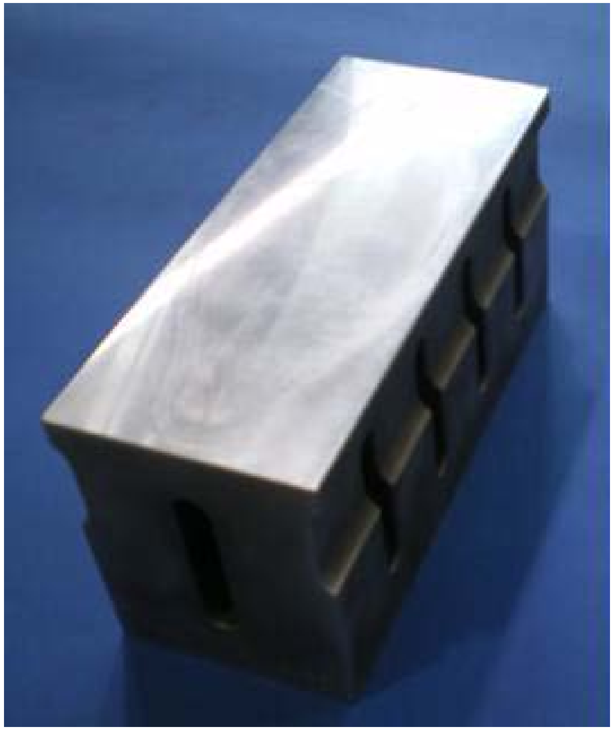
Such failures were discovered due to the changed dynamic behaviour of the welder (presence of cracks?)

No clear reason could be immediately understood as the cause of failures:

- material: ERGAL (Al7075 or DIN AlZnMgCu1.5) as for 90% of the sonotrodes all around the world
- geometry: different well-known and used geometries failed
- loads: the sonotrodes were used for typical production

Outline

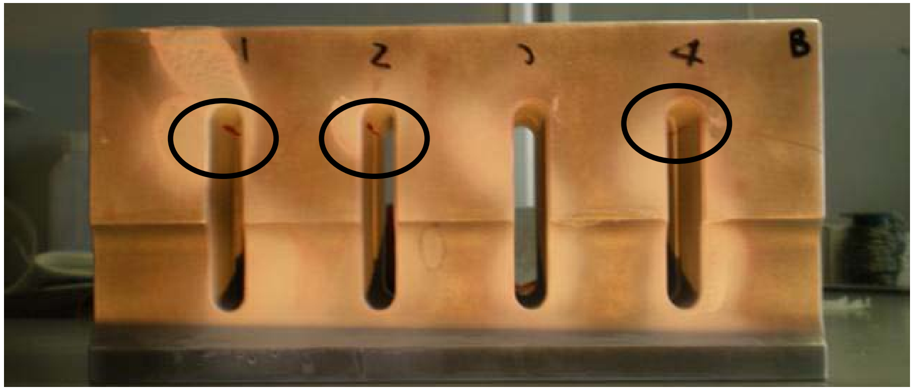
Between all the collected failed sonotrodes, two were investigated

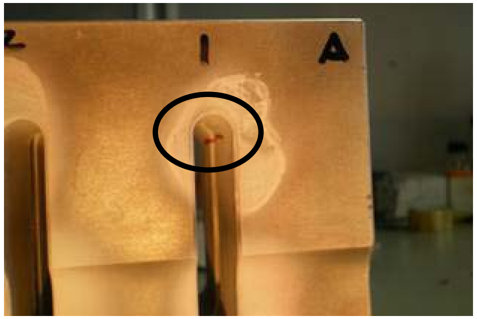


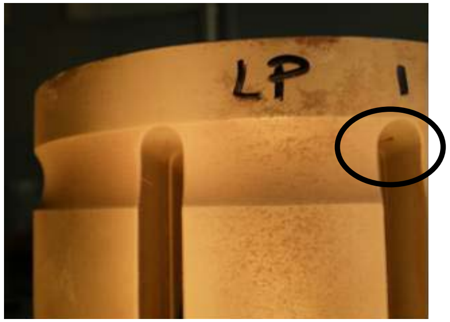
- NDT to individuate cracks
- qualitative and quantitative fracture surface analysis at the SEM
- influence of defects on fatigue strength

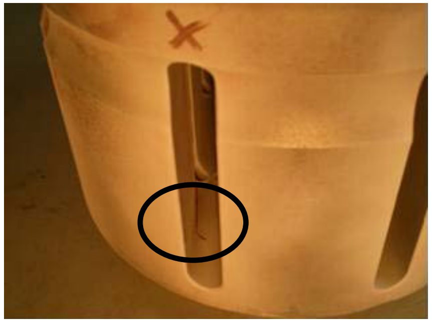
NDT onto sonotrodes

Liquid penetrants were applied





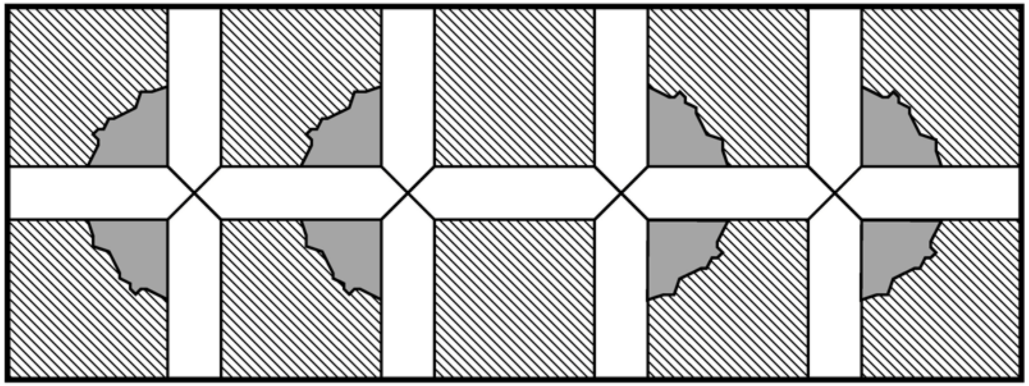




- Numerous cracks could be observed at stress concentrations even if typical geometries are involved
- Relevant dimensions of cracks ([cm]!)

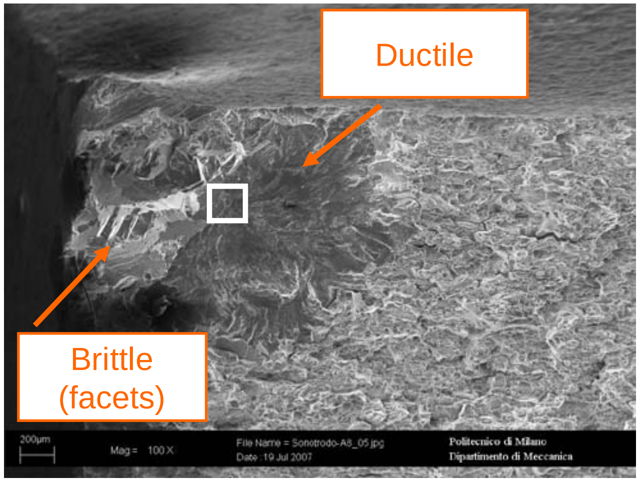
SEM analysis

Material Components Properties	Metric
Aluminum, Al	87.1 - 91.4 %
Chromium, Cr	0.180 - 0.280 %
Copper, Cu	1.20 - 2.00 %
Iron, Fe	<= 0.500 %
Magnesium, Mg	2.10 - 2.90 %
Manganese, Mn	<= 0.300 %
Other, each	<= 0.0500 %
Other, total	<= 0.150 %
Silicon, Si	<= 0.400 %
Titanium, Ti	<= 0.200 %
Zinc, Zn	5.10 - 6.10 %

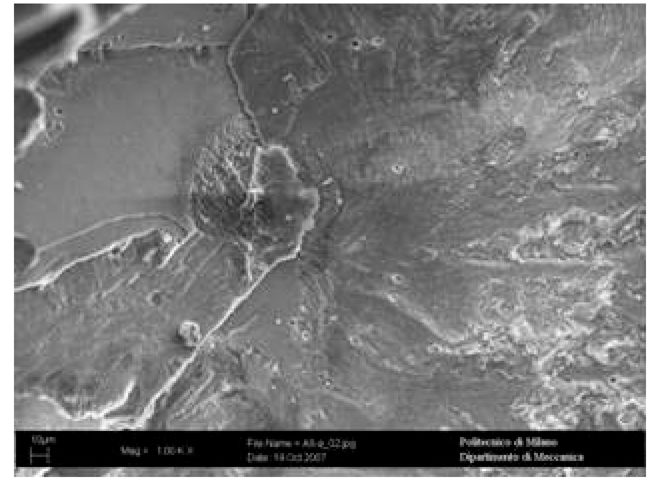


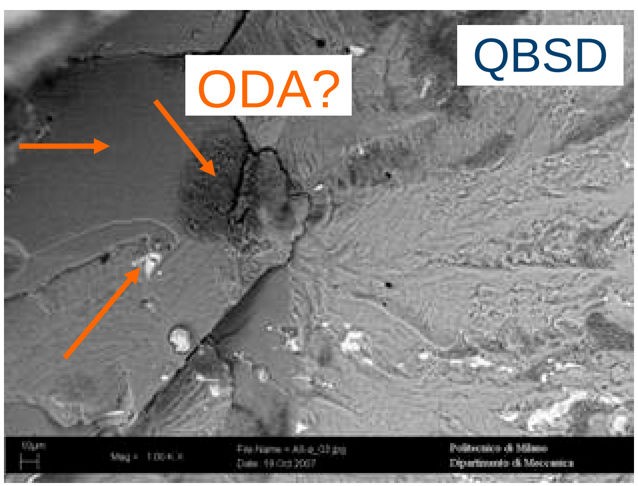
Fracture surfaces from the cylindrical sonotrode were completely ruined

SEM analysis



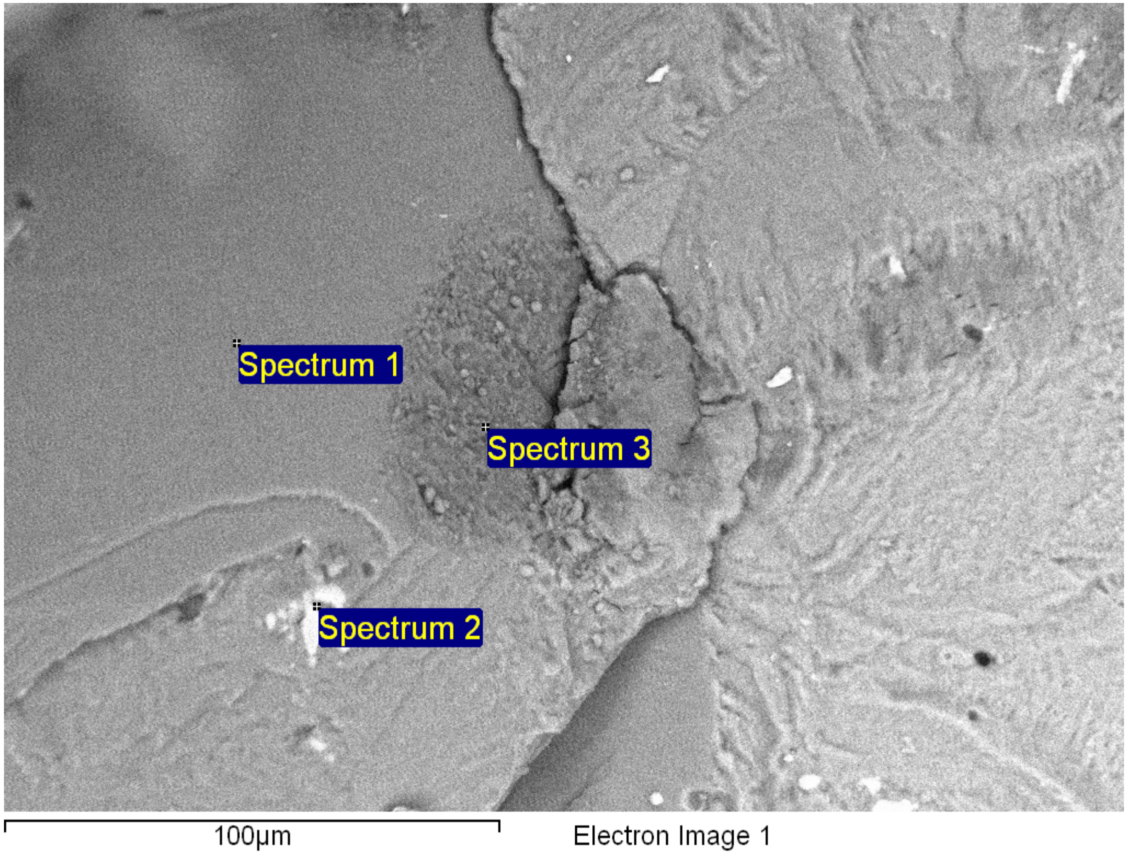
Brittle ←——— ———→ Ductile





- Nucleation in the interior, as typical for ultra high cycle fatigue
- at nucleation point a different chemical composition

SEM analysis

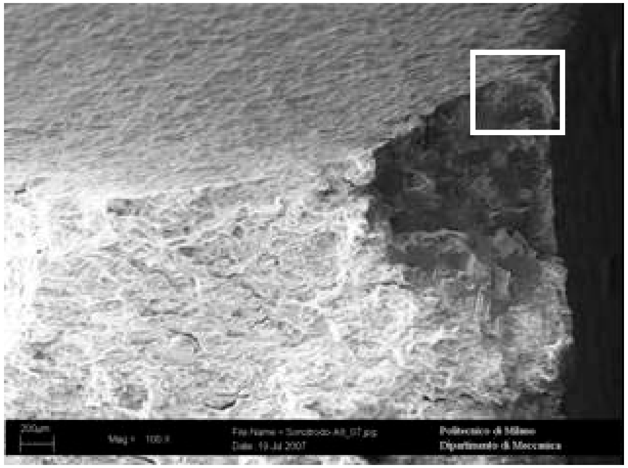


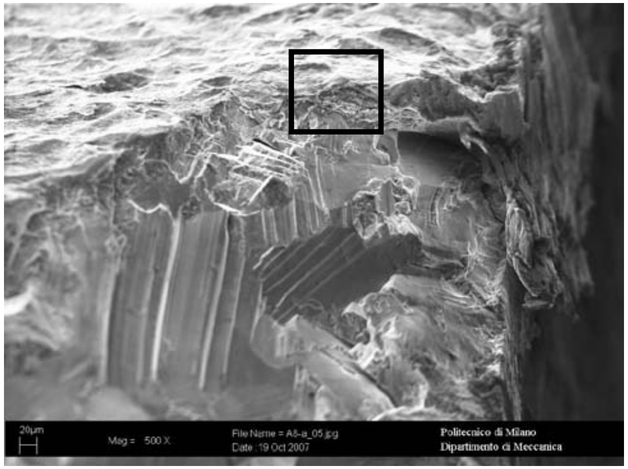
Spectrum	O	Mg	Al	Mn	Fe	Cu	Total
Spectrum 1		1.41	57.63			40.95	100.00
Spectrum 2		0.56	60.23	4.54	7.58	27.10	100.00
Spectrum 3	40.2	1.55	51.54			6.72	100.00

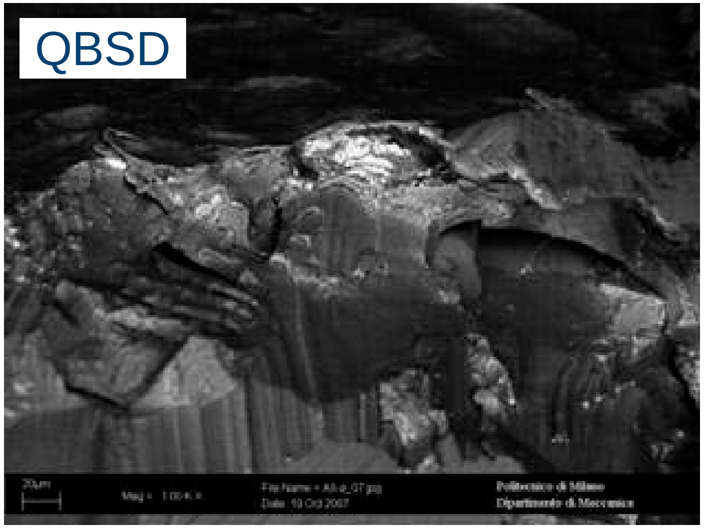
No Zn!

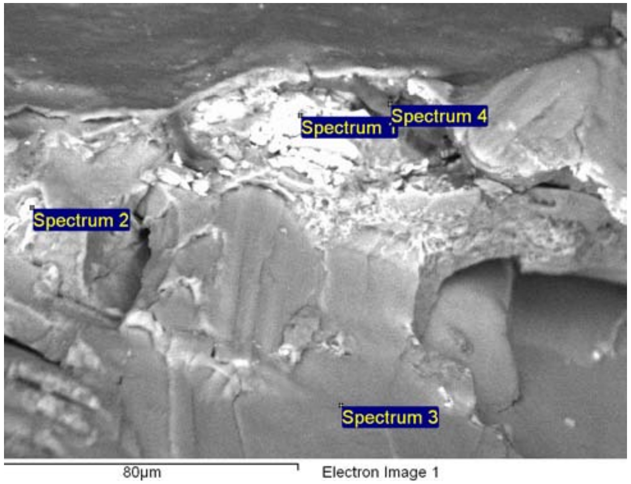
Very different chemical composition in respect to the nominal one

SEM analysis







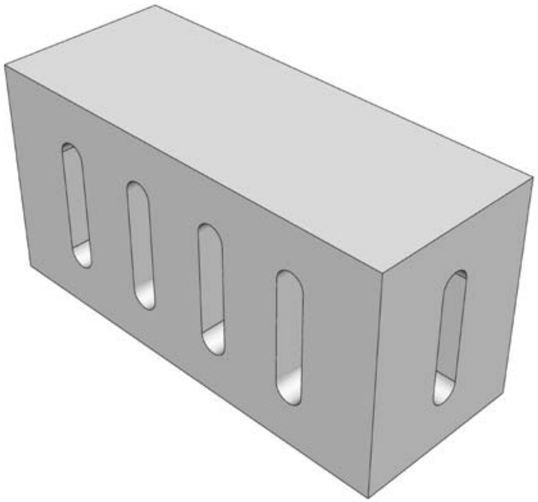


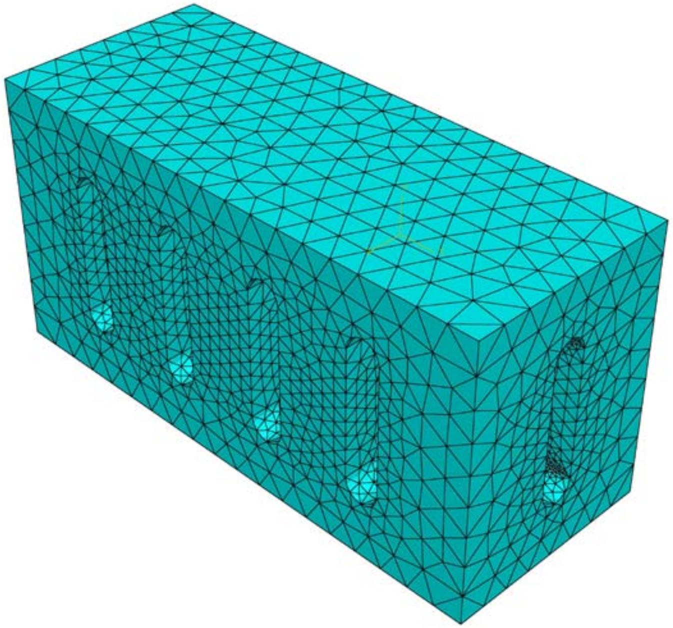
No Zn!

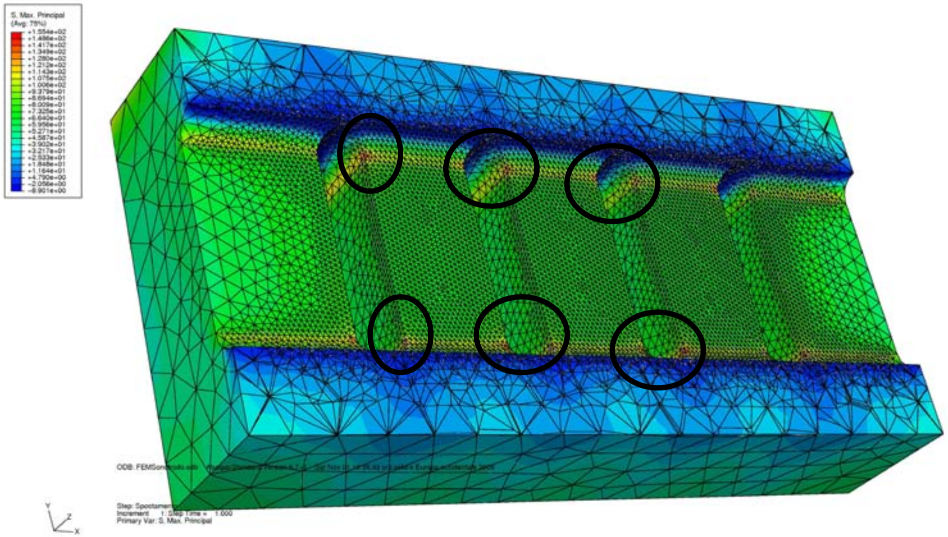
Spectrum	Mg	Al	Si	Mn	Fe	Cu	Total
Spectrum 1	0.72	48.43		1.68	4.36	44.81	100.00
Spectrum 2	1.77	87.51		0.85	1.88	7.99	100.00
Spectrum 3	1.24	85.73	1.10	0.89	2.07	8.96	100.00
Spectrum 4	1.24	85.95	0.82	0.54	1.75	9.69	100.00

FEM analysis

- Simplified geometry
- Dynamic analysis at 20 kHz
- Imposed displacement: 100 μm (R=-1)
- Rigid boundary conditions (conservative assumption)
- Quadratic elements





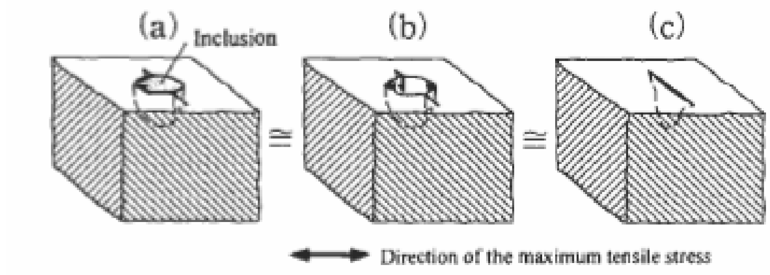


Maximum principal stress: 155 MPa

Influence of defects on fatigue strength

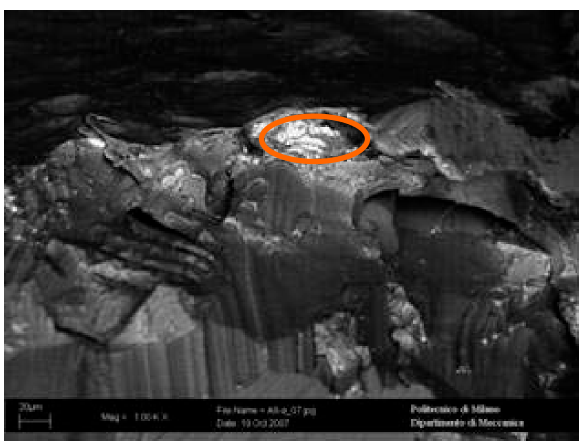
The endurance stress amplitude at R=-1 and 5x10^8 cycles is 160 MPa

The Vickers hardness is equal to 175 kgf/mm^2



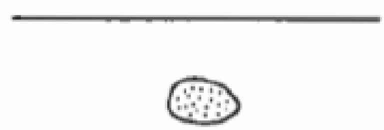
(b) Inclusion in touch with surface

$$\sigma_w = \frac{1.41\left(H_V + 120\right)}{\left(\sqrt{area}\right)^{\frac{1}{6}}}$$



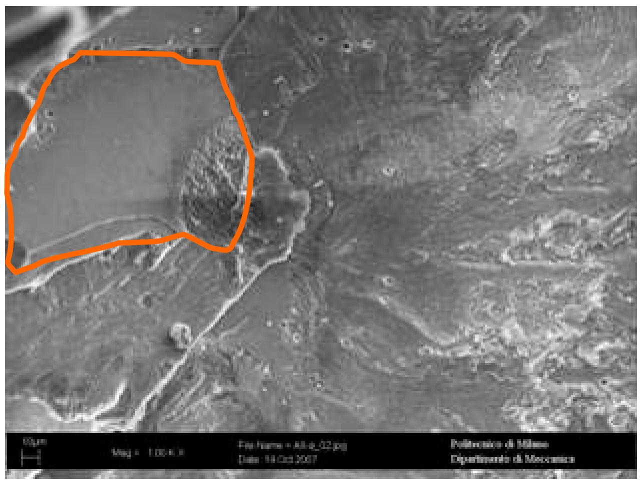
$$\sqrt{area} = 60\mu m \quad \Rightarrow \quad \sigma_w = 105 MPa$$

Influence of defects on fatigue strength



(c) Internal inclusion

$$\sigma_w = \frac{1.56\left(H_V + 120\right)}{\left(\sqrt{area}\right)^{\frac{1}{6}}}$$



$$\sqrt{area} = 150\mu m \quad \Rightarrow \quad \sigma_w = 100 MPa$$

Analysing all the nucleation points corresponding to each fracture surface, the lowest endurance stress for 5×10^9 cycles was:

95 MPa

Conclusions

Premature failures of some sonotrodes made in Al alloy for ultrasonic welding were analysed:

• the failures were due to unexpected nucleation of cracks in correspondence of stress concentration

• SEM analyses permitted to observe strange local chemical composition of the Al alloy

• FEM dynamic analyses were used to derive the stress at the critical points, where cracks could be observed

• the application of Murakami’s theory defined the relationship between defects and fatigue strength for the considered cases