Thermal fatigue testing of hot working tool steels

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Content of presentation

• Motivation 1-2
• Appearance of cracks on hot working tools (dies)
• Two new developed tests for thermal fatigue testing
• Shape of specimens and temperature fields on tested surface layers
• Thermal fatigue testing of surface layers:
  – Testing of roll steel for hot rolling
  – Testing of functionally graded materials (FGM)
  – Testing of heat treated and CrN coated layers, mechanical axial loading of test specimen
• Conclusions and future outlook
Motivation 1

• Origin of crack nucleation and their evolution (microstructure)

• By understanding the formation and spreading of cracks, materials with improved characteristics of materials can be produced

• How to determine the actual temperature field in practice, and how such field can be generated in the laboratory, the problem of the accuracy of the test: the constancy of temperature and loads, generation of prescribed temperature field, temp. gradients, etc.

• Thermal fatigue resistance is one of most important property of hot working tool steels. **Aim** — To optimize the entire processing chain of tool steel production, improvement of microstructure, characteristics related to carbides, increasing of heat conductivity, decreasing of coefficient of temperature expansion
Motivation 2

- Surface treatment of tools (nitriding, coatings, welding (FGM), etc.)
- Die casting tools for Al, Mg, brass, Zn, hot forging dies, rolls for hot rolling: optimization of heat treatment, nitriding and coating parameters, etc.
- HSS for e.g. rolls -> very important is to lower ability for nucleation and spreading of cracks, i.e. cracks propagation along eutectics, crushing of carbide networks in casted rolls (hot deformation)
- Comparative testing is desired: improved selectivity and time saving (test can take several days)
Appearance of cracks on hot working dies (die cast., hot forg., hot rolling, etc): different temperature and different $\Delta T$ prevail (Persson et al., JMPT 2004, Mellouli et al., Eng Fail Anal 2012)
Using of Gleeble 1500D simulator for thermal fatigue testing

- Displacement rate up to 2000mm/s (depending on load)
- Maximum load: in tension/compression 80 kN.
- Heating rate up to 10.000°C/sec (depending on sample size)
- Steady state equilibrium temperatures within +/-1°C
- Heating, cooling of specimen and anvile movement are computer guided
Testing of base materials for hot working tools: Test 1, variation in $T_{\text{max}}$ and $\Delta T$
Test for testing of surface layers

Test conditions: \( T = 500 \text{ – } 700^\circ\text{C} \),
\( N = 200, 500, 1000, 1500 \) thermal cycles

One temperature cycle with heating and quenching period (left), typical temperature cycles sequence during thermal fatigue testing (right).
Testing of base materials for hot working tools

Appearance of cracks

Sample preparation for microstructural analyses
Testing of roll steel: used for hot rolling

- The samples were freely spanned in the working jaws: $F = 0\ \text{N}$
- Aim: to obtain selective results of the influence of the testing parameters on the initiation and growth of the cracks

<table>
<thead>
<tr>
<th></th>
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<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
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<td>0.86</td>
<td>1.71</td>
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Testing of roll steel (hot rolling, 600°C, 1500 cycles)
Testing of roll steel (600°C, 1500 cycles)

Crack nucleation at carbides and graphite (a), at carbides (b), graphite (c) and crack growth (d).
Cracks growth in carbides and graphite and oxidation of cracks (a), distribution of oxygen in cracks internal and on crack tip (b).
Initiation of cracks at sharp shaped (flatened) graphite (a), spalling of small sized part of matrix at graphite, no crack growth (b),
Unification (linking) of cracks originate from different initial spots at surface (a), internal crack extending on carbides and graphite particles (b).
Testing of roll steel (hot rolling)

Relevant characteristics: average length of all cracks, cracks density and aver.length of longest cracks

Characteristics of cracks at test temperatures 500-700°C and 200 cycles (left), and at test temperature of 600°C for different number of cycles (right).
Average lengths of all cracks (a) and cracks density in dependence on number of thermal cycles and test temperature (b)
Average length of seven longest cracks at various test temperature and number of test cycles
Test for comparative testing of surface layers:
Test 2, variation in $T_{\text{max}}$ and $\Delta T$
(specimen with grooves for laser welding)
Test for testing of surface layers

- Cooling chamber (1),
- Nozzle (2),
- Inlet tube for water (3),
- Inlet tube for air (4),
- Outlet tubes (5),
- Water cooled anvils (6),
- Valve (7).

magnetic computer controlled valves
Test for testing of surface layers:
Test 2 (specimen with grooves for laser welding)
Test for testing of surface layers
Time course of temperature in different depths from test surface
Cooling time of specimen vs temperature difference on tested surface layer of specimen
Testing of functionally graded materials

Table 1
The chemical composition of the base and filler wire material, given in wt.%.

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(a) Test specimen
(b) Groove - FGM (laser welding)
Testing of functionally graded materials

Chem. analyses*:
(a) Si
(b) Cr
(c) Mo
(d) V

*JEOL SUPERPROBE 733 electron microanalyzer on JEOL 5610
Testing of functionally graded materials

Comparative testing of surface layers: laser welding in four layer in 1mm thickness, different content of Si in filler materials → different characteristics related to carbides

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Vickers hardness (HV) vs. distance from surface (mm)

- Base
- Filler 1
- Filler 2
- Filler 3

(a) & (b) images showing microstructures of different layers.
Testing of functionally graded materials

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2500 cycles

5000 cycles

7500 cycles
Testing of functionally graded materials

Average cracks length vs number of thermal cycles

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Average cracks length, µm

Numer of thermal cycles
Testing of functionally graded materials

- A gradual change in composition of Si was achieved
- The FGM with the best characteristics is 27 times more resistant than the base material.
- The study of carbides revealed a substantial increase of carbide size with the increase of thermal cycles
- Increased content of Cr eliminates the positive influence of decreased content of Si on thermal fatigue resistance.
- The thermal fatigue resistance is also closely related to the hardness profile of the surface layer.
Testing of surfaces layers (only heat treated):
axial loading → stress state

Appearance of surface of nitrided specimens after 1000 cycles, (left) Axially non-loaded specimen, (right) Axially loaded, ← direction of axial loading; quenching time 0.3 s.
Testing of heat treated (left, 1000 cycles) and CrN coated surface (right, 7500 cycles)

Appearance of surface of (left) non-nitrided specimens after 1000 cycles, axially non-loaded specimen, and (right) duplex treated surface layer (nitrided and CrN coated) at 7500 thermal cycles.
Conclusions and future outlook

• New thermal fatigue test rigs have been developed, heating and cooling is computer guided

• Comparative testing of different surfaces simultaneously, reducing of testing time and accuracy of obtained results is increased

• Optimization of surface treatment of tools (FGM, nitriding, coatings, etc.), comparative testing, surface engineering, and repairing of tools.

• Achieving of different temperature gradients at same (maximal) testing temperature is enabled

• In combination with additional mechanical loading various stress states can be simulated

• Origin of crack nucleation and their propagation can be studied

• Previous selection of optimal parameters in steel production process chain (solidification condition, soaking temperature, hot working, heat treatment, etc.) for achieving of appropriate microstructure of tool steels can be confirmed
Thank you for your attention!
Danke für Ihre Aufmerksamkeit!