Modelling and Simulation of the High Frequency Mechanical Impact (HFMI) Treatment of Welded Joints

Volker Hardenacke
Majid Farajian
Dieter Siegele
HFMI-Treatment of Welded Joints

Mechanical surface treatment

- The advantages of removing the potential threats of unwanted (tensile) residual stresses and exploiting the beneficial (compressive) residual stresses by mechanical surface treatments are already known in welding communities.

- In this context, high frequency mechanical impact treatment as a fatigue improvement technique is a statistically proven method to increase the fatigue life of welded joints.

- During this process, a hardened cylindrical metal pin with a spherical tip impacts the weld toe surface with high frequency and induces local plastic deformation.
HFMI-Treatment of Welded Joints
Mechanical surface treatment

- Main reasons for the increased fatigue strength
  - Notch stress concentration at the weld toe is reduced
  - Local hardness is increased (local work hardening of the material)
  - Compressive residual stresses are induced

- Despite the successful practical application, a fundamental description of the governing formation mechanisms of the surface material condition is still missing
  - Thus, it could be assumed that the full potential of this post-treatment technique is not utilized

- Therefore, the goal of the present study was to develop a computationally efficient approach for determination of the residual stresses induced by the HFMI process
  - Explicit simulations of the this post treatment process were performed utilizing the software package ABAQUS
HFMI-Treatment of Welded Joints
Simulation of mechanical surface treatment

- Sheet metal plate (specimen) with the dimensions $15mm \times 4mm \times 15mm$ and HFMI tool with a diameter of $D=4mm$ (at the tip)

- Specimen modelled as elastic-plastic (steel similar to S355, $\sigma_0=400\,MPa$)
- Hardened HFMI tool (indenter) modelled as rigid
- Hammering tool upgraded using a connector element (contains elastic spring and dashpot); enables the use of force controlled boundary conditions
HFMI-Treatment of Welded Joints
Simulation of mechanical surface treatment

- During the simulation, the indenter was moved $\Delta z=6\,mm$ in the $z$-direction using a stepped amplitude ($0.4\,mm$ infeed per step)

- Indenter oscillates in $y$-direction with constant frequency ($f=100\,Hz$) and amplitude $u=0.100\,mm$ (contact with friction coefficient $\mu=0.15$)

  process:
HFMI-Treatment of Welded Joints
Simulation of mechanical surface treatment

- Numerical studies
  - Resulting residual stress depth profiles ($\sigma_{xx}$) for different mesh refinements and contact conditions:

![Graphs showing residual stress depth profiles](image)

- Different mesh refinements:
  - Very fine (100x50x100 microns)
  - Fine (125x75x125 microns)
  - Medium (200x100x200 microns)
  - Coarse (250x150x200 microns)

- Different contact conditions:
  - Reference (fine mesh, indentation depth 0.1 mm)
  - Frictionless, $C_f=0.0$
  - Infeed per impact 0.2 mm (instead of 0.4 mm)
  - Kinematic contact algorithm (instead of penalty contact)
HFMI-Treatment of Welded Joints
Simulation of mechanical surface treatment

- Numerical studies

- Resulting residual stress depth profiles ($\sigma_{xx}$) for different boundary conditions and material models:

![Graphs showing residual stress depth profiles](image)
HFMI-Treatment of Welded Joints
Simulation of mechanical surface treatment

- Numerical studies

  - Resulting residual stress depth profiles ($\sigma_{xx}$) for different numerical features:
    - In general, the plastic deformation induces compressive residual stresses in the peened surface balanced by some tensile stress in the interior ($\sigma_{xx\text{-max}} = 600\text{MPa}$; in a depth of approximately $0.50\text{mm}$)
    - Fine mesh seems to be a good compromise between accuracy and numerical effort
    - Frictionless contact formulation considerably affects the stress depth profile
    - Displacement BC (given indentation $u$) in general yield a different solution compared to force BC (given accelerating force)
    - Material hardening law features an observable effect on stress depth profile; it mainly influences the peak value of the residual stress
HFMI-Treatment of Welded Joints
Consideration of residual stresses from welding

- **Welding simulation**
  - Plate with length 300 mm, width 240 mm and thickness 9.0 mm
  - Non-linear thermal analysis was performed
  - Weld modeled using the element birth technique (activation of weld-line elements sequentially during welding process)
  - After simulation of welding process, a specimen was cut out of the welded plate and HFMI-treated afterwards
General Information

- Hammering tool: 
  \( D=3\ldots4\ldots5\,mm \)
- Indentation (y-direction): 
  \( u=0.050\ldots0.10\ldots0.150\,mm \)
- Translation in z-direction 
  via given displacement: 
  \( \Delta z=20\,mm \) (\( \Delta x=0\,mm \))
  - 0.4\,mm/indentation
- Working angle:
  \( \alpha=0\ldots30^\circ \)
- Friction coefficient:
  \( \mu=0\ldots0.20 \)
HFMI-Treatment of Welded Joints
Simulation of HFMI-treatment of welded joints

Process:
HFMI-Treatment of Welded Joints
Simulation of HFMI-treatment of welded joints

Example 1

- Hammering tool: 
  \( D=4\, \text{mm} \)
- Indentation (y-direction): 
  \( u=0.075...0.10...0.125\, \text{mm} \)
- Translation in z-direction
  via given displacement: 
  \( \Delta z=20\, \text{mm} \) \( \Delta x=0\, \text{mm} \)
  - 0.4\, \text{mm/indentation}
- Working angle:
  \( \alpha=0^\circ \)
- Friction coefficient:
  \( \mu=0.15 \)

Half symmetrical model of the weld specimen
HFMI-Treatment of Welded Joints
Simulation of HFMI-treatment of welded joints

Example 1

- Hammering tool: $D=4\, mm$
- Indentation (y-direction): $u=0.075\ldots0.10\ldots0.125\, mm$
- Translation in z-direction via given displacement: $\Delta z=20\, mm$ ($\Delta x=0\, mm$)
  - 0.4$mm$/indentation
- Working angle: $\alpha=0^\circ$
- Friction coefficient: $\mu=0.15$

Half symmetrical model of the weld specimen
Example 1

- Resulting residual stress ($\sigma_{xx}$):

- **As welded**
- **After HFMI-treatment**
**HFMI-Treatment of Welded Joints**

**Simulation of HFMI-treatment of welded joints**

- **Example 1**

  - Resulting residual stress depth profiles ($\sigma_{xx}$) for different indentation depths $u$:

![Graph 1](image1.png)  
![Graph 2](image2.png)
Example 2 (stress peening)

- Hammering tool: 
  \( D=4\, \text{mm} \)
- Indentation (y-direction): 
  \( u=0.100\, \text{mm} \)
- Translation in z-direction via given displacement: 
  \( \Delta z=20\, \text{mm} \) (\( \Delta x=0\, \text{mm} \))
  - 0.4mm/indentation
- Working angle: 
  \( \alpha=0^\circ \)
- Friction coefficient: 
  \( \mu=0.15 \)

Half symmetrical model of the weld specimen – loaded with \( \sigma_{xx\text{-load}}=200\, \text{MPa} \)
HFMI-Treatment of Welded Joints
Simulation of HFMI-treatment of welded joints

- Example 2 (stress peening)
  - Resulting residual stress \( (\sigma_{xx}) \):

As welded + additional load

After HFMI-treatment (unloaded)
HFMI-Treatment of Welded Joints
Simulation of HFMI-treatment of welded joints

Example 2 (stress peening)

- Resulting residual stress depth profiles ($\sigma_{xx}$) before, during and after the enhanced HFMI-treatment; comparison to regular HFMI:
**HFMI-Treatment of Welded Joints**

**Simulation of HFMI-treatment of welded joints**

- **Example 3 (HFMI + load cycle)**
  - Hammering tool:
    \[ D=4\text{mm} \]
  - Indentation (y-direction):
    \[ u=0.100\text{mm} \]
  - Translation in z-direction via given displacement:
    \[ \Delta z=20\text{mm} \quad (\Delta x=0\text{mm}) \]
    - 0.4mm/indentation
  - Working angle:
    \[ \alpha=25^{\circ} \]
  - Friction coefficient:
    \[ \mu=0.15 \]

Half symmetrical model of the weld specimen – one load cycle after HFMI (\(\sigma_{xx-\text{load}}\leq\pm450\text{MPa}\))
Example 3 (HFMI + load cycle)

Resulting residual stress ($\sigma_{xx}$):

As welded

After load cycle ($\sigma_{xx\text{-load}}=350\,\text{MPa}$)
HFMI-Treatment of Welded Joints

Simulation of HFMI-treatment of welded joints

Example 3 (HFMI + one load cycle)

- Resulting residual stress depth profiles ($\sigma_{xx}$) before and after HFMI-treatment and during load cycle; comparison of different load levels:

![Graph showing residual stress depth profiles](image)

Tensile load
HFMI-Treatment of Welded Joints

Conclusions

- Explicit simulations of the high frequency hammer peening treatment were performed using the software package ABAQUS.

- Possible effects of different numerical modelling features (mesh refinement, mesh transition, contact formulation, loading boundary conditions and material model) could be identified.

- Implicit simulations of the welding process were performed using the software package ABAQUS.

- The established modelling technique was successfully applied for the calculation of the residual stress field of a weld specimen after HFMI treatment.

- Thus, the simulation technique established within the framework of this study provides the basis for a simulation loop:
  - Structural welding simulation
  - Simulation of the HFMI process
  - Estimation of the fatigue life of the structure.