Symposium Mechanical Surface Treatment 2019

8th Workshop Machine Hammer Peening

Karlsruhe
22 and 23 October 2019
Symposium Mechanical Surface Treatment 2019
8th Workshop Machine Hammer Peening

22 and 23 October 2019, Karlsruhe

DOI: 10.5445/IR/1000099108

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Preface

Dear colleagues,
ladies and gentlemen,
on behalf of the entire wbk Institute of Production Science, I would like to welcome you to this year's eight edition of the Machine Hammer Peening workshop in Karlsruhe. Launched in 2012 as the "Fachforum Festklopfen" in Darmstadt, the workshop, which alternates annually between the universities of Darmstadt, Vienna, Karlsruhe and Aachen, is enjoying increasing popularity.

At the same time this workshop is the 63rd meeting of the Working Group Mechanical Surface Treatments of the Deutsche Gesellschaft für Materialkunde (DGM). The group meets twice a year at German industrial and academic sites and discusses new aspects of all mechanical surface treatments starting with the technologies via the resulting surface states up to the improvements in the performance of the treated components in application.

Therefore the actual meeting is a kind of an experiment to bring together complementary but mutually interested groups from manufacturing technology and materials technology. This will enhance discussions which can be driven from both disciplines or viewpoints which have aims in common.

We are convinced that the technologies of mechanical surface treatments and especially the still new variants in the field of machine hammer peening have enormous potential in the field of finishing highly loaded machine components and tools and will continue to gain in importance in the future. The interaction of the DGM-group Mechanical Surface treatments running since a long time and the workshop Machine Hammer peening participants joins two really active groups and hopefully will glue.

With this in mind, I wish you an exciting and interesting workshop with many stimulating discussions.

Karlsruhe, 22 October 2019

Prof. Dr.-Ing. habil. Volker Schulze
Machine Hammer Peening (MHP)

Facing recent challenges
In the course of current and future technological and social trends, new fields of application are opening up for the MHP. In addition to shortening throughput in production, the MHP promises an improvement in the service life of dynamically highly stressed components and an increase in tool life. This results in an increase in productivity while simultaneously reducing costs. In addition, the MHP will gain in importance in the future in the field of finishing of additively manufactured components.

WMHP – An innovative exchange platform
The workshop focuses on the personal exchange and discussion between speakers, participants and scientists about research results, technology developments and successful applications. In addition, the workshop offers the opportunity to identify previously untapped potential of the MHP and to make it tangible for future research due to the bundling of competencies of different specialist areas.

To master machine hammer peening
By bringing together different technical expertise, the technologically complex interactions in machine hammer peening can be researched and discussed at the highest level. This enables sound scientific research under industrial boundary conditions.
Mechanical surface treatments as shot peening and deep rolling are important procedures to work hardening of surface areas and to induce compressive residual stresses. Mostly the aim is the improvement of fatigue properties, wear resistance or corrosion resistance of components of mechanical engineering, automotive and aviation. Alternative processes as ultrasonic, laser or cavitation peening including modifications using prestressing or thermal treatments are also included in the committees work. The committee meets every half year at an industrial member or at university institutes.

Aims of the DGM Technical Committee

- Covering industrial and scientific topics in the area of mechanical surface treatments with the focus on the improvement of component properties and the further development of the processes
- Working on a science-based knowledge of correlations of process parameters of mechanical surface treatments, component states and component properties
- Initiating of research and development projects: Joint projects of universities, research institutes and industry
- Exchange of experiences between teams working in the field of mechanical surface treatments, and networking
**Workshop History**

**Darmstadt, 11 October 2012**
- Foundation event “Fachforum Festklopfen” (FFF)
- 15 participants

**Vienna, 16 October 2013**
- Continuation as Workshop Machine Hammer Peening (WMHP)
- First draft of terminology for MHP
- Development of a Wikipedia entry for MHP
- 23 participants

**Aachen, 28 November 2014**
- 3rd Workshop Machine Hammer Peening
- Revised terminology
- 30 participants

**Karlsruhe, 24 November 2015**
- 4th Workshop Machine Hammer Peening
- VDI guideline for MHP for a uniform nomenclature
- 36 participants

**Darmstadt, 03 November 2016**
- 5th Workshop Machine Hammer Peening
- Wikipedia entry for MHP online available
- Joint CIRP paper
- 43 participants

**Vienna, 22 November 2017**
- 6th Workshop Machine Hammer Peening
- 43 participants

**Aachen, 12 and 13 November 2018**
- 7th Workshop Machine Hammer Peening
- 29 participants
# Lecture programme

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Reception

Prof. Dr.-Ing. habil. Volker Schulze

wbk Institute of Production Science

Karlsruhe Institute of Technology
LOCATIONS

Institute of Production Science

- Ehrenhof Karlsruhe Germany
  Manufacturing and materials technology
- Campus Nord Eggenstein-Leopoldshafen Germany
  Machines, equipment and process automation
- Suzhou China
  GAMi - Global Advanced Manufacturing Institute
- Shanghai China
  AMTC - Advanced Manufacturing Technology Center
- Fasanengarten Karlsruhe Germany
  Production systems
  Machines, equipment and process automation
- Material Research Center for Energy Systems Karlsruhe Germany
  Manufacturing and materials technology

RESEARCH PORTFOLIO

Institute of Production Science

- Manufacturing and Materials Technology
- Machines, Equipment and Process Automation
- Production Systems
- Micro Production
- Lightweight Manufacturing
- Electric Mobility
- Additive Manufacturing
- Industry 4.0

22 and 23 October 2019, Karlsruhe
PRODUCTION SYSTEMS

GLOBAL PRODUCTION STRATEGIES
- Strategic planning of production networks
- Site-specific production using Industry 4.0
- Information and quality management in supply chain networks
- Order-based production and logistics planning in networks

PRODUCTION SYSTEM PLANNING
- Adaptive production systems
- Industry 4.0 methods
- Digitalization strategies
- Machine learning and data mining
- Agile factory planning
- Robust, intelligent production control
- Cost evaluation and simulative validation
- Technology planning

QUALITY ASSURANCE
- In-line measurement technology for immature processes
- Soft sensors for intelligent data analysis
- Function-oriented measurements
- Autonomous measurement technology
- Measurement uncertainty evaluation
- Process control based on quality data

GAMI
Global Advanced Manufacturing Institute

The Global Advanced Manufacturing Institute (GAMI) tries to deepen the understanding of global production structures according to the three KIT pillars research, innovation and teaching and to develop new, robust and controlled production networks for industrial enterprises for the local framework conditions.

<table>
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<tr>
<th>FOUNDED</th>
<th>LOCATION</th>
<th>ENGINEERS</th>
<th>ADMINISTRATION</th>
<th>STUDENTS</th>
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<td>2008</td>
<td>Suzhou</td>
<td>20</td>
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<td>5</td>
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Global Advanced Manufacturing Institute

- Applied Research
- Industry Consulting for German Firms
- Continuing Education / Training / Coaching
Prozesssicherheit bei der mechanischen Oberflächenbearbeitung

Dr.-Ing. Oliver Maiß
Alfred Ostertag
Ecoroll AG Werkzeugtechnik
Prozesssicherheit bei der mechanischen Oberflächenbearbeitung

Systeme der Prozessüberwachung beim Walzen und Hämern

Dr.-Ing. Oliver Maiß, Alfred Ostertag
Karlsruhe, 22.10.2019

Lebensdauersteigerung durch Festwalzen

<table>
<thead>
<tr>
<th>Material</th>
<th>Geometry</th>
<th>Surface treatment</th>
</tr>
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<tbody>
<tr>
<td>p/d</td>
<td>s/d</td>
<td>Rm [N/mm²]</td>
</tr>
<tr>
<td>Process</td>
<td></td>
<td>0,2, 0,2, 0,2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,45, 0,45, 0,45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>turn., turn., turn.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900, 900, 900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,15, 0,2, 0,2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,45, 0,45, 0,6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>turn., turn., turn.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900, 900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,2, 0,2</td>
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<tr>
<td></td>
<td></td>
<td>0,45, 0,45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>turn. roll.</td>
</tr>
<tr>
<td>08.10.2019</td>
<td>DOM Fachauschuss, Karlsruhe - O. Maiß, A. Ostertag</td>
<td><a href="http://www.ecoroll.de">www.ecoroll.de</a></td>
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Effekte des Glatt- und Festwalzens

Mikrostruktur Textur Härte Eigenspannungen

Oberfläche Randzone

Eigenspannungen sind Spannungen im inneren eines Bauteils, die auch vorliegen, wenn keine äußeren Kräfte, Momente oder Temperaturgradienten anliegen.

Motivation

Prozess zur Festlegung von „richtigen“ Prozesseinstellgrößen:

Versuche → ESP-Messung → Lebensdauertests → Parameter Freeze

Lebensdauertest nicht ausreichend

Wie kann die Eigenspannung in der QS erfasst werden?
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Bestimmung der Walzkraft im Prozess

Prozessfehler bei mechanischen Walzwerkzeugen

- Zustellfehler beim Walzen
- Veränderung der Federkonstanten durch Kollision
- Geometrieabweichung bei Vorbehandlung
- Zerspanwerkzeug fehlerhaft eingeessen
Digitale Messuhr

Einfache Datenanalyse per eigener App
Kabellose Datenübertragung
KSS-beständiges Gehäuse
Direkte Kraftanzeige
Prozessüberwachung und -dokumentation

Agenda

Überwachung der Schlagenergie beim MHP

Prozessüberwachung beim Walzen mit hydrostatischen Walzwerkzeugen

Digitale Walzkraftmessung für mechanische Walzwerkzeuge
Verfahren - 3D-Walzen von Freiformflächen

Das Nachführsystem der HG-Werkzeuge ermöglicht das Glatt- und Festwalzen von Freiformflächen

Hydrostatisch gelagerte Werkzeuge
Prozessfehler beim Walzen mit hydrostatischen Werkzeugen

- Drossel verstopft
- Druckeinstellung durch Bediener fehlerhaft
- Aggregat ist defekt

Prozessüberwachung mit ToolScope

Alarm message
Self-learning of the maximum limit
Self-learning of tolerance limits
Detected signal
Process fault (fault signal is available)
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8th Workshop Machine Hammer Peening

Agenda

1. Digitale Walzkraftmessung für mechanische Walzwerkzeuge
2. Prozessüberwachung beim Walzen mit hydrostatischen Walzwerkzeugen
3. Überwachung der Schlagenergie beim MHP

Analyse des Schlagvorganges

Einzeleinschlag Nr. 1
R25 42CrMo4V
Einschlagenergie 2000 mJ

Einzeleinschlag Nr. 3
R16 42CrMoV
Einschlagenergie 2000 mJ

mm entspricht μm
Hämmernwerkzeuge ECOpeen (Konzept)

**Schlagsystem:**
Mechanisch-pneumatisch, Bekannt aus marktgängigen Bohrhammer Rückstoßfrei!

**Rückhub**

**Schlag**

---

**Schlagenergie - Schlagkraft**

Kinetische Energie (Schlagenergie)

\[ E_{kin} = \frac{1}{2} m v^2 \]

Umformenergie

\[ E_u = \frac{1}{2} F s \]

Schlagkraft

\[ F = \frac{2E_u}{s} \]

Schlussfolgerung:
- Schlagkraft ist abhängig von Schlagenergie und Verformungsweg.
- Ist als Leistungsangabe von Hämmernwerkzeugen ungeeignet.
Schlagenergie – Kennfeld ECOpeen A

Steuerung der Schlagenergie

Antriebsdrehzahl verändert Schlagenergie und Frequenz

Manuelle Taumelwinkelverstellung Verändert Schlagenergie bei konstanter Frequenz
Messung der Schlagenergie

Einbau des Schlagenergiesensors in den Arbeitsraum der Maschine.

Zyklisches Anfahren des Sensors für Kontrollmessungen.

Bei Abweichung Korrektur der Taumelwinkel-Einstellung oder Antriebsdrehzahl.
Vielen Dank für Ihre Aufmerksamkeit

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FE Simulation of the HFMI Treatment – Previous and Upcoming Results

Stefanos Gkatzogiannis

Steel & Lightweight Structures

Karlsruhe Institute of Technology
FE Simulation of the HFMI Treatment - Previous and Upcoming Results

Stefanos Gkatzogiannis, Peter Knoedel, Thomas Ummenhofer

Karlsruhe Institute for Technology
Steel & Lightweight Structures
Research Center for Steel, Timber & Masonry
Germany

Agenda

1. What is HFMI? – Application in Practice
2. Simulation of HFMI – Necessity and Main Aspects
3. Simulation of HFMI – Modelling of the Pin Motion
4. Simulation of HFMI – Calibration based on Drop Tests
5. Summary and Future Results
The HFMI Post Weld Treatment

The High Frequency Mechanical Impact or HFMI [Marquis, 2016] treatment is a post-weld mechanical treatment method applied for the increase of fatigue life of welded structures.

An appropriate device carrying a pin of hardened steel runs along the weld toe, deforms it by hammering and introduces compressive residual stresses at the surface layer, which counterbalance the welding tensile ones. Therewith, a significant increase of the weldment’s fatigue life is achieved.

There are two manufacturers of HFMI devices in Germany: HIFIT and PITEC.

HIFIT

PITEC

HIFIT treatment of a fillet weld

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The HFMI Post Weld Treatment

The High Frequency Mechanical Impact treatment is a post-weld mechanical surface treatment that increases the fatigue life of welded joints.

An appropriate device, called a hammer peening device, is used to hammer the weld toe, deforming it by hammering a peening ball against a fixed point at the surface layer, which creates compressive residual stresses. Furthermore, a significant increase in the fatigue life of the weld joint is achieved.

There are two manufacturers of the HFMI treatment device: HiFIT and PITEC.

HiFIT

The HFMI Post Weld Treatment – Experimental Validation

- The method has been thoroughly investigated experimentally and is proven to increase the fatigue resistance in the high cycle regime of welded joints by even more than 100%.

- A thorough review of experimental work up to 2013 is given in [Yıldırım, 2013].

- The KIT Steel and Lightweight Structures Institute has as well carried numerous experimental investigations on HFMI efficiency. Some of them are:
  - The REFRESH project [Ummenhofer, 2009]
  - The DASt Richtlinie project [Kuhlman, 2018]
  - The HFH-Korrosion project [Ummenhofer, 2018]

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22 and 23 October 2019, Karlsruhe
The HFMI Post Weld Treatment in Civil Engineering

- The method is applicable in both mechanical and structural civil engineering fields. Its application is regulated according to:
  - IIW recommendations [Marquis, 2016]
  - A new DAS guideline is now active for application as well in structural engineering [DAS, 2019]

- Possible Fields of application in Structural Engineering:
  - Steel and composite bridges
  - Welded Details of Towers and Jacket Structures like in Offshore Wind Energy Turbines
  - Cranes
  - and eventually every fatigue loaded structural welded detail.

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The HFMI Post Weld Treatment – Practical Aspects

- The two guidelines cover mostly practical aspects:
  - Application of the HFMI treatment including angle and working speed
  - Quality control based on groove geometry and surface quality
  - Fatigue design of HFMI treated weldments based on FAT classes and the approaches of nominal and hot-spot stress taking into consideration size effects etc.

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Simulation of HFMI

Simulation of the HFMI Treatment

- The validation of a simulation model that predicts the introduced residual stresses can enable a less conservative design and offer a better overview of the method through sensitivity analyses
- Coupling with fracture mechanics is possible, in order to predict with even better accuracy the fatigue life of a component
- Several simulation models have been proposed in the past neglecting though in most cases significant aspects of the problem
- Same physical problem with the indentation of a semi-infinite plate with a spherical indenter under significant initial velocity (non static case)

HFMI simulation is a multi-parameter analysis
Main aspects of the FE simulation of HFMI

1. Pin Movement
   - impact speed / intensity
   - frequency

2. Contact Definition
   - contact model
   - friction coefficients

3. Material Behaviour
   - strain rate dependent material behaviour in the HAZ
   - material model

4. Application Setup
   - application angle
   - travelling speed
HFMI Simulation – Material Behavior

Reversed plasticity
During spherical indentation, underneath the treatment surface, compressive stresses are introduced which are counterbalanced by outer tensile ones. During continuous treatment along a line, reversal of the plastic strains’ and residual stresses’ sign takes place.

Strain rate dependency
During HFMI strain rates of up to 400 s\(^{-1}\) are referred. Previous analyses have proven that yield stress is predominant for the introduced residual stresses. Its strain rate dependency under the present strain rate has to be considered.

Compression / Tension
Previous investigations [Cadoni, 2018] have shown that the strain rate sensitivity of structural steel significantly deviates in tension and compression.

HFMI simulation – Specimens of Parent Material

Specimens of parent material
- Specimens of parent material S355 simulated and measured in a previous study [Foehrenbach, 2016] were simulated as a first step for the validation of the method.

Highlights of the Simulation
- Simulation is carried out with LS Dyna [LS-Dyna, 2016]
- Coulomb-friction is applied: coefficients in previous studies and from textbook knowledge deviate from each other significantly. 0.30 to 0.15 is currently applied
- Bilinear material model, with kinematic, isotropic and mixed hardening is applied
- Strain-rate dependency is taken into consideration with the Cowper-Symonds model
- Rigid body properties (mass, inertia) attributed to the HFMI Pin

The Cowper Symonds material model
\[ \dot{\varepsilon}_{pl} = D \left( \frac{\sigma_y'}{\sigma_y} - 1 \right)^n \]

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Simultation of HFMI
Modelling the Pin Motion

HFMI Simulation – Modelling the Pin Motion

Two methods can be applied for modelling the pin vertical motion, a displacement- and a force-based

**Displacement-based**
- more straightforward to simulate
- measurement of the trace
- unrealistic strain rate evolution – erroneous coupling with strain rate dependent material

**Force-based**
- calibration of the model through trial and error is needed
- realistic strain rate evolution
- measurement of contact force or impact velocity

![Graphs showing displacement-based and force-based simulations.](Image)

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Drop Tests

Calibration of Material Behavior Through Drop Tests

- A series of drop tests was carried out in order to reproduce a single HFMI impact in the laboratory under known impact velocity and force (mass)

- Goal was the evaluation of the dynamic yield stress under the present deformation mode

- FE analyses would provide the strain rate for each impact

- Analytical calculations based on measurements of the trace or the rebound velocity would be applied for the calculation of the dynamic yield stress

- 1st step validation through comparison with high strain rate tensile tests [HFH-Simulation], literature – 2nd step validation through application of the calibrated material model in a HFMI Simulation and comparison with RS
Drop Tests

Test setup for the drop tests:

- A wooden bearing structure carries 4 rails – an impact assembly runs across the rails, the pin on its bottom hits the target.

Satisfactory accuracy:

- Impact velocities in the range of the measured for HIFT and PITEC achieved (2 m/s – 5 m/s).
- Maximum rotation of ± 1°.
- Adequate tolerance, no breaking down of the free fall.
- Rebound velocity measured with video camera 120 fps, accuracy of ± 0.001 m/s.

Drop Tests

Results:

- Determination of the strain rate with FE simulation of the experiment:
  - Strain rate independent elastic-plastic behavior
  - Strain rates too high especially at initiation of contact (singularities)
  - Split Hopkinson bar impact velocities of 9, 18 and 27 m/s lead to strain rates of 900 to 7000 s⁻¹ [Cadoni, 2018].

- Analytical calculation of the dynamic yield stress based on trace measurement analogous to cylindrical indentation [Limb, 1998]: not possible for present impact velocities and a spherical indenter.

- Analytical calculation of the dynamic yield stress based on rebound velocity [Tabor, 1948 - Johnson, 1985]:
  - Measurement of rebound velocity was successful
  - Satisfactory results for 5355 - unsatisfactory results for 5690, 5960.

- Factors of the method producing errors are:
  - The assumption of strain rate independent material behavior in the FE simulation of the experiment.
  - The formula for calculating yield strength based on rebound velocity too empirical.

Introduction of the plastic strain spherical zone underneath the impact surface - (a) Von Mises strain rate - (b) Maximum shear strain rate.
Drop Tests

Dynamic yield stress of S355

- Determination:
  - strain rate
  - strain rate
  - split Hopkinson bar
  - 900 to 700
- Analytical calculation
  - analogous to cylindrical velocities and assumptions
- Analytical calculation
  - Johnson
  - measurement
  - satisfaction
- Factors of the model:
  - the assumption of the experiments
  - empirical

Results

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22 and 23 October 2019, Karlsruhe
HFMI Simulation - Results

Results with the displacement-based (DB) method

- Two models were simulated, a strain rate independent (RI) and a dependent (RD)
- Simulated RS results follow qualitatively the pattern of the measured transverse RS – nevertheless, the peak lies significantly deeper in the simulation
- In the case of the longitudinal RS, the model does not predict the RS profile not even qualitatively, especially near the surface

- The introduction of the strain rate dependency seems to improve the agreement between measurements and simulation, nevertheless its use with a displacement base approach is questionable and has no potential for further improvement (measurement restrictions)

HFMI Simulation - Results

Results with the force-based (FB) method

- Four different models were simulated
- Simulated RS results follow qualitatively and quantitatively the pattern of the measured RS, both for the transverse and the longitudinal case
- In the case of the transverse RS, all models provide similar agreement with the measured stresses

- Against initial expectations the compressive strain rate dependent model is less accurate – input data is to be accounted for [Glatzoggiannis, 2019 a]
- In the case of the longitudinal RS, the strain rate independent models seem to underestimate the RS near the surface
- The overall evaluation of the results strain rate dependency is predominant for 355
HFMI Simulation – Summary of Previous Results and Open Questions

Two main aspects of the HFMI Simulation were investigated by modelling specimens of parent material:

- Modelling the movement of the HFMI Pin:
  - Two different approaches for simulating the predominant vertical motion of the pin were applied: a displacement- and a force-based
  - Introduction of strain rate dependency into the simulation improves significantly the agreement between simulated and measured RS, however introduction to the displacement-based simulation is questionable
  - Force-based approach provides better agreement with the measured profiles and allows for the consideration of a strain rate dependent behaviour

- Calibration of Material behaviour based on the Drop Tests:
  - Cowper Symonds strain rate dependent material model was calibrated based on the results of the drop tests
  - Compressive results by [Cadori, 2018] were taken into consideration as well to increase the sample
  - Simulation of HFMI using the calibrated, strain rate dependent material model, presents much better agreement with the measured RS than the strain rate independent plasticity models

Open Questions

- Real scale welded components – numerical capacity problems arise [Gkatzogiannis, 2019 b]
- Influence of WRS – coupling with welding simulation [Gkatzogiannis, 2019 b]
- Coupling with fracture mechanics investigations
HFMI Simulation – Upcoming Results

- Dissertation [Gkatzogiannis, 2019 b]
- Ongoing research project ends in December, 2019: Schubnell J., Gkatzogiannis S., Farajian M., Knoedel P., Ummenhofer T: IGF-Vorhaben Nr. 19227 N – Rechnergestütztes Bewertungstool zum Nachweis der Lebensdauerverlängerung von mit dem Hochfrequenz-Hämmerverfahren (HFMI) behandelten Schweißverbindungen aus hochfesten Stählen

Research partners:

Industrial partners:

Funded by:

Fraunhofer KIT

Material characterisation

Welding simulation

HFMI simulation of real scale components

Fatigue tests

22 and 23 October 2019, Karlsruhe
Thank you very much for your attention!

References


Stefanos Glatsogiannis, 8th Workshop Machine Hammer Peening – 22 and 23 October, Karlsruhe Institute of Technology, Germany

22 and 23 October 2019, Karlsruhe

34
Influence of mechanical surface treatments on propagation and opening behavior of physically short cracks in Inconel 718

Alexander Klumpp

IAM-WK – Institute for Applied Materials

Karlsruhe Institute of Technology
Influence of mechanical surface treatments on propagation and opening behavior of physically short cracks in Inconel 718

Einfluss mechanischer Oberflächenbehandlungen auf das Ausbreitungs- und Öffnungsverhalten physikalisch kurzer Risse in Inconel 718

Symposium Mechanische Oberflächenbehandlung, 22.10.2019
Alexander Klumpp

**Motivation: Turbine disc material Inconel 718**

- Fir tree base („Tannenbaumfuß“) for vibration damping
  - Complex highly-stressed
  - Shot peening: SAE / AMS;
    *Intensity: 0.18 ~ 0.25 mmA* [1]

- Low cycle fatigue design

- Scope: Characterization of near-surface short crack growth
  - Focus: Physically short cracks
    *(0.2 mm < a < 1 mm); K-concept* [2]

---

[1] Polanetzki, H.; MTU AG; DGM workshop material
Motivation: Recent developments in machine hammer peening (MHP)

- Studies regarding residual stress evolution in Inconel 718:
  - Mechanical MHP system type „EcoPeen“
  - Several millimeters of residual stress penetration depth are feasible
  - Investigation of crack behavior after shot peening and other mechanical surface treatments

Outline

- Basics of fracture mechanics
- Material and mechanical surface treatments
- Experimental setup for characterization of short crack propagation and opening
- Results and discussion
- Conclusion
K-concept and „intrinsic“ approach

- Stress intensity $K_I / K / K_{nom}$ for characterization of mechanical crack load in mode I
  $$K_{nom} = \sigma \sqrt{\pi a Y} \quad \text{(static load)}$$
  $$\Delta K_{nom} = \Delta \sigma \sqrt{\pi a Y} = K_{max} - K_{min}$$
  $$R_{nom} = \frac{K_{min}}{K_{max}} \quad \text{(cyclic fatigue load)}$$

- Cyclic fatigue crack growth governed by the material’s „intrinsic“ resistance (Ritchie, 1988)
  ➔ Against formation of new surfaces

---

Closure-based („extrinsic“) concept

- Paris diagram (1961) for long crack propagation
  $$\frac{da}{dN} = C \cdot \Delta K_{nom}^m$$

- Instable crack propagation
  $$\Delta K_{th, nom} = K_{max} - \max(K_{min}, K_{op})$$

- Crack closure effect (Elber, 1971)
  ➔ Effective threshold $\Delta K_{th, eff}$
  ➔ Dependent on work hardening

- Further effects of residual stresses?
Effects of residual stresses

- Residual stress intensity $K_{rs}$
  - Weight function / numerical determination (FE)
- No closure, bath with res. stress
  - Local load ratio ($R_{eff}$) affected, but not $\Delta K_{eff}$
    $\Delta K_{eff} = \Delta K_{nom}$
    $R_{eff} = \frac{K_{min,rs}}{K_{max,rs}} \neq R_{nom}$
- Closure effect with res. stress
  - Both $\Delta K_{eff}$ and $R_{eff}$ are affected
    $\Delta K_{eff} = K_{max} - K_{op}$
    $R_{eff} = \frac{K_{op,rs}}{K_{max,rs}} \neq R_{nom}$

$\rightarrow$ Numerical and experimental methods are required!

Material: Alloy „Inconel“ 718

<table>
<thead>
<tr>
<th>Chemical composition (mass %)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Fe</td>
</tr>
<tr>
<td>Basis</td>
<td>18.80</td>
</tr>
</tbody>
</table>

- Heat treatment: ASTM B637
  - $\gamma''$-precipitation hardening with two step tempering:
    - $955 \, ^\circ C$ (1h)
    - $720 \, ^\circ C$ (8h)
    - $620 \, ^\circ C$ (8h)
- Mean $\gamma$-grain size: approx. 19 $\mu$m

- Micro hardness: app. 460 HV 0,1
- Tests at $20 \, ^\circ C$ and $550 \, ^\circ C$
- Mechanical properties [1]

Mechanical surface treatments (Support by OSK Kiefer, Malsch)

- Goal: Variation of profiles of residual stresses and work hardening (Measure: Micro hardness)

- Application of:
  - Shot peening: Cut wire G3 Ø 0.8 / S170; 0.21 ~ 0.76 mmA intensity; 100 ~ 300 % coverage
  - Deep rolling: hard metal Ø 6.35; 200 ~ 250 bar pressure; 0.03 ~ 0.04 mm stepover distance
  - Piezo peening: Hard metal Ø 5; 36 µm stroke; 500 impacts/s; 0.25 mm stepover distance

(Print version: All results of surface treatments)

- Shot peening

- Deep rolling / piezo peening

22 and 23 October 2019, Karlsruhe
Experimental procedure

- Linear electro motor based test bench (Instron)
  - Fine vacuum to avoid oxidation

- Specimen geometry for 3P-bending
  - Crack growth and opening tests
    - Load ratios: \( R_{\text{load}} = 0.01 / 0.5 / 0.7 \)
    - Test temperatures: 20 °C; 550 °C
    - Captured crack length: 0.25 mm ~ 1.60 mm
  - Necessary: Measurements with very high resolution

Determination of crack opening loads:
Classic procedure: Specimen compliance

- Principle: Increasing stiffness due to crack closure

- Actual record for a long crack (1.56 mm)

Resolution is not sufficient for measurements on short cracks after mechanical surface treatments!

---

Determination of crack opening loads: Classic procedure: *Potential drop method*

- Plateau formation of electrical voltage due to crack opening
- Suitable for long cracks; no proper resolution for short cracks

**Other methods:** DIC, Eddy, Ultrasonic, ISDG (Laser), Barkhausen

→ Get the maximum out of the potential drop method


---

The „elevated current potential drop method“

**Principle:**

- Extremely high currents (>300 A) → reduction of disturbance and noise
- Setting of test temperature directly by Ohmic losses
- Potential probes as near as possible to the crack → maximum sensitivity

→ Necessary: Extensive preliminary studies
Reproducibility of test temperature

- Statistical deviations
- Warming during tests

- Reproducible and nearly constant test temperatures
- Numerical error analyses regarding temperature, work hardening influence and probe positions: **Compromises are necessary**
- Measurement of crack opening loads becomes feasible

Determination of crack opening loads

- Untreated state
- Deep rolled state

- Bilinear fit, equal to [1]
- Trilinear fit

**Significant effect of surface treatment:** „complete“ / „incomplete“ crack closure may occur

Correlation opening - growth

Correlation between $a$, $\Delta K_{\text{nom}}$, $\Delta K_{\text{eff}}$ (by means of FEM)

Qualitative correlation exists:
$F_{\text{op}} \uparrow \rightarrow \Delta K_{\text{eff}} \downarrow \rightarrow da/dN \downarrow$

Discussion: Uncertainties during determination of crack driving forces

- Contribution of roughness-induced crack closure
- Localization of deformation (shear bands)
- Main challenge: Surface cracks after surface treatments

Further measures are necessary for clearer results

22 and 23 October 2019, Karlsruhe
Validation approach: FEM load analysis

- Quarter model; evaluation of $K$ using „contour integral“ method
- Relaxed (cyclic-thermical) residual stresses as initial condition

$\rightarrow$ Determination of crack opening loads by using residual stress profiles approximately prevailing at crack initiation

Validation and discussion:
Prediction of crack opening in the crack center

- Coincidence for very short cracks
- Increasing deviation with crack depth

$\rightarrow$ Explanation: multicausal crack closure; no prediction possible by means of simple elastic FE analysis!
Absence of crack closure for $R_{\text{nom}} > 0.5$

- Untreated state
- Deep rolled state

\[ \text{No closure regardless of surface treatment and crack size} \]

Absence of crack closure for $R_{\text{nom}} > 0.5$

- Untreated
- Shot peening P1
- Shot peening P4
- Deep rolling

\[ \text{No closure regardless of surface treatment and crack size} \]
\[ \text{But: Marked effect of mechanical surface treatments on crack growth} \]
Effective driving forces and crack growth rates

- Partial correlation for various $R_{\text{nom}}$
- Resulting lifetimes

Inconel 718
$|F_{\text{max}}| = 5.3$ kN
$823$ K

Conclusion

- Crack propagation and opening behavior in untreated, shot peened and deep rolled Inconel 718 was investigated.
- An experimental method for the measurement of crack opening loads was developed
  - Good means of characterization despite inherent uncertainties
- Closure-based crack growth description approach was presented
  - Strong effect of mechanical surface treatments even in the case of non-closure
  - Description of crack propagation in residual stress field requires at least two driving variables
Thank you.
Controlled Pneumatic Needle Peening – New Peening Technology for Aerospace Applications

Holger Polanetzki

MTU Aero Engines GmbH
Contents

- Objectives
- Technology Description
- Experimental Procedure
- Results
  - Surface Roughness
  - Residual Stress Distribution
  - Fatigue Testing
- Application
- Conclusion
- Acknowledgement
Objective

- Develop new technique that could fulfill requirements:
  - Comparable or **better** results than conventional shot peening
    - Surface Finish
    - Residual Stress Distribution
    - Fatigue Life
  - Acceptable on Rotating Parts
    - Small head for better accessibility
    - No risk of Foreign Object Damage (FOD)
  - Very reproducible process
    - No operator influence

SPIKER® Features

- Different Heads and End Caps for different Geometries
- Standoff distance maintained at all times
- Portable unit for easy transportation
- Each needle monitored in real time
- Interface guides operator, record process parameters and makes intensity calculations
- Comparable or better results than flapper or conventional peening
- Save Data to USB key for quick reporting

22 and 23 October 2019, Karlsruhe
SPIKER® 4 Needle Linear Head with 3 End Caps

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needles</td>
<td>S230 tip (0.60mm), Tungsten Carbide, 4 needles</td>
</tr>
<tr>
<td>End Caps</td>
<td>3 included end caps: Flat surface, Corner radius down to 0.09” (2.3mm) and edge radius</td>
</tr>
<tr>
<td>Sensors</td>
<td>Individual tracking for each needle</td>
</tr>
<tr>
<td>Input</td>
<td>Proprietary air and electrical input</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Replaceable needles and end caps</td>
</tr>
<tr>
<td>Intensity range</td>
<td>0.004A - 0.016A – Inch (0.10A - 0.40 mmA)</td>
</tr>
<tr>
<td>Pressure range</td>
<td>5 - 60 PSI (0.34 – 4.08 bar)</td>
</tr>
</tbody>
</table>

SPIKER® - Radius 0.09 requirements interchangeable caps
**SPIKER® 1 needle Corner Head**

- Used on corner, pocket, radius
- Tool in contact with surface enables accurate intensity and repeatability
- Can meet radius of 0.09 inch
- Reach intensity between 4A to 16A

---

**SPIKER® Performance Testing**

- Test program was performed at Technology University Clausthal in Germany under Prof. Dr. L. Wagner’s supervision
- Testing was done under the leadership of MTU Aero Engines AG
- Testing looked at surface roughness, residual stress distribution and fatigue life
Experimental Procedure

- Peening Equipment

  CNC Conventional Peening
  Controlled Rotary Flapper Peening using the FlapSpeed® Controller
  Controlled Needle Peening using the Spiker® tool

Experimental Procedure

- Controlled Rotary Flapper Peening

  Flap
  Mandrel
  Magnetic Block

Almen Intensity vs. RPM Curve

\[ y = 0.210x^2 + 17.362x + 0.9895 \]

RPM (rev./min) vs. Intensity (mmA)
Experimental Procedure

Almen strip holder for Controlled Pneumatic Needle Peening and Forming (all dimensions are in millimeter)

Almen Intensity vs. Pressure Curve

Experimental Procedure

- Material

Ti-6Al-2Sn-4Zr-6Mo
- Near-β-Alloy
- Lamellar Microstructure

DA718
- Nickelbase-Superalloy
Experimental Procedure

- **Coupon Design**

  Flat Specimen for:
  - Roughness measurement
  - Residual stress measurement
  - Metallographic Examination

  ![Flat Specimen](image1)

  Flat-Bar Bending Test
  Specimen for Cyclic Bending Test

  ![Flat-Bar Bending Test Specimen](image2)

Experimental Procedure

- **Specimen Holder**

  ![Specimen Holder](image3)

  - Flexible fastener for assemble / disassemble of the specimen

  Surface area of strengthening

  ![Specimen Holder with Surface Area](image4)
Results

• **Surface Finish:** A strip, 0.006-0.008A Intensity

![Surface Finish Images](image1)

10x  
20x  
50x

Results

• **Surface Roughness Ti-6246**

![Surface Roughness Graph](image2)

- Roughness rises with Intensity.
- Roughness achieved by the Flapper Peening is an order of magnitude lower than Shot Peening.
- Pneumatic needle peening tool gives roughness in the same scale as Flapper Peening.
**Results**

- **Surface Roughness DA718**

![Surface Roughness DA718 Graph](image)

- **Residual Stress Distribution Ti6246, Intensity = 0.004A**

![Residual Stress Distribution Graph](image)

*Graph shows no significant difference between the different techniques.*
Results

- Residual Stress Distribution Ti6246, Intensity = 10A

- Conventional Peening produced the greatest depth of compressive layer.
- The Spiker® produced the most negative stress level on the surface.

Results

- Residual Stress Distribution DA718, Intensity = 0.004A
Results

- Residual Stress Distribution DA718, Intensity = 0.008A

![Graph showing residual stress distribution](image1)

- Fatigue Results Ti6246, Intensity = 0.004A

![Graph showing fatigue results](image2)

- Conventional Peening and Flapper Peening produced similar results
- The Spiker® provided the most significant fatigue life improvement
Results

- Fatigue Results Ti6246, Intensity = 0.010A

Higher intensity peening confirms the trend shown in the previous slides.

- Fatigue Results DA718, Intensity = 0.004A
Results

- Fatigue Results DA718, Intensity = 0.008A

Spiker® Applications
Spiker® Applications

V2500 Turbine Exhaust Case
Save of 40 man hours

CF6-80 HPT Blades
Tip-Repair

Bulhead Pockets and
difficult to reach geometries

Specification

AMS 2545  Controlled Pneumatic Needle Peening,
Straightening and Forming

Issued 2017 – 11

Nadcap Checklist AC7117/6 for Needle Peening

Ballot for Approval 2019 - 07
Conclusion

- In this study, the new Spiker® Needle Peening Tool has shown:
  - A Surface Finish that is equivalent to flapper peening and usually better than conventional peening
  - Residual Stress Distribution that can be deeper on the surface that conventional or flapper peening
  - Fatigue Life that are equivalent and often much better than conventional or flapper peening
  - Easy application on aero-engine components with significant cost saving potential

Acknowledgement

- Prof. Dr. L. Wagner and his employees at the institute of material technology at the University of Technology Clausthal for their support and realization of the scientific investigations.
- Mr. Norbert Huber and Götz Lebküchner for their support and helpful consultation during the development of the head for the Spiker™ tool
Experimental analysis of the surface integrity of stainless steel modified by robot based machine hammer peening

Lars Uhlmann

Laboratory for Machine Tools and Production Engineering WZL

RWTH Aachen University
Experimental analysis of the surface integrity of stainless steel modified by robot based machine hammer peening

Thomas Bergs, Lars Uhlmann*, Robby Mannens, Daniel Trauth

Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen

Symposium Mechanical Surface Treatment 2019, Karlsruhe, 22.10.2019

Motivation
Usage of stainless steel X5CrNi18-10 (1.4301)

Desalination plant

X5CrNi18-10 is used in chemically active environments, e.g. for shafts of seawater pumps.
- The surface layer is exposed to
  - high tribological loads and
  - dynamic loads leading to the formation of microcracks.
- This results in the following surface requirements:
  - hard and wear-resistant surface layer and
  - soft and ductile inner material.
**Introduction**

**Machine hammer peening (MHP)**

- Work hardening and compressive residual stresses are induced into the surface layer.
- Surface of the specimen may be structured or smoothed.

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact angle</td>
<td>( \beta )</td>
</tr>
<tr>
<td>Stepover distance</td>
<td>( s )</td>
</tr>
<tr>
<td>(Hammer) head diameter</td>
<td>( d )</td>
</tr>
<tr>
<td>Hammering frequency</td>
<td>( f )</td>
</tr>
<tr>
<td>Stroke</td>
<td>( h )</td>
</tr>
<tr>
<td>Projected area of indentation</td>
<td>( A_1 )</td>
</tr>
<tr>
<td>Distance of indentations</td>
<td>( a )</td>
</tr>
</tbody>
</table>

(acc. to VDI 3416)

---

**Agenda**

1. **Introduction**
2. **Experimental set-up**
3. **Surface integrity of peened surfaces**
4. **Description model for the Vickers hardness**
5. **Summary and outlook**
**Experimental set-up**

**Processing of X5CrNi18-10 with a robot based MHP system**

<table>
<thead>
<tr>
<th>Experimental design</th>
<th>MHP system adapted to an industrial robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full factorial experimental design with variation of the factors:</td>
<td>Industrial robot IRB6660-250/1.9 (ABB)</td>
</tr>
<tr>
<td>Head diameter $d$ [mm]</td>
<td>Hammer head type 2002 (ACCURAPULS)</td>
</tr>
<tr>
<td>6</td>
<td>Plunger</td>
</tr>
<tr>
<td>12</td>
<td>Specimen (95 x 40 x 30)</td>
</tr>
<tr>
<td>Stroke $h$ [mm]</td>
<td>Force measuring platform 9257B (Kistler)</td>
</tr>
<tr>
<td>0.3</td>
<td>Hammer bench</td>
</tr>
<tr>
<td>Distance of indentation $a$ [mm]</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Impact angle $\beta_i$ [°]</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

In addition:

- Experiment with multiple processing ($n = 5$):
  - $d = 6$ mm; $h = 1.2$ mm; $a = 0.05$ mm; $\beta_i = 0°$

- Center point experiment:
  - $d = 8$ mm; $h = 0.75$ mm; $a = 0.225$ mm; $\beta_i = 15°$

$n$: number of processing

---

**Experimental set-up**

**Robot based machine hammer peening**

- The velocity profile consists of three characteristic areas.
- The highest set speed was reached sufficiently fast.

**Path accuracy**

- The maximum path deviation was $\Delta y = 21 \mu m$.
- Overshoot in opposite direction after maximum deviation was observed.

Consideration of the robot acceleration is necessary. The high path accuracy is reached due to a high robot stiffness.
**Experimental set-up**

**Peening force**

- The specimen was fixed by clamping.
- MHP at the center of the specimen to ensure a direct force application.
- Specimen (42CrMo4) was treated by MHP in advance to the tests.

![Graph showing the relationship between stroke and maximum peening force.](image)

Up to a frequency of 60 Hz the maximum force rises with frequency. Between 60 Hz and 200 Hz the maximum force does not vary much. Results qualitatively in accordance with TRAUTH [TRAU16].

**Experimental set-up**

**Limitation of the adjustable stroke by the frequency (Video)**

- Free stroke decreases with increasing frequency.
- The stroke may not be greater than the free stroke.
- Restriction of the combination of the stroke and the frequency exists.
- For frequencies smaller or equal $f = 100$ Hz the stroke may be $h < 1.955$ mm. For $f = 200$ Hz the stroke may only be $h < 0.416$ mm.
Agenda

1. Introduction
2. Experimental set-up
3. Surface integrity of peened surfaces
4. Description model for the Vickers hardness
5. Summary and outlook

Surface integrity of peened surfaces
Evaluation of the residual stresses

- Removing material results in a new stress equilibrium achieved by deformation.
- Deformation is measured by using optical interferometry.
- Removed stress is calculated from measured displacement.

- Raising the stroke results in inducing compressive residual stresses into a deeper surface layer depth.
- Decreasing the distance of indentation $a$ results in higher compressive residual stresses until a depth of $z \approx 0.11$ mm.

Source: www.stresstech.com

© WZL/Fraunhofer IPT
Surface integrity of peened surfaces

**EBSD analysis**

<table>
<thead>
<tr>
<th>0 – 100 µm (initial state)</th>
<th>0 – 100 µm (peened)</th>
<th>200 – 300 µm (peened)</th>
<th>400 – 500 µm (peened)</th>
<th>900 – 1000 µm (peened)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IPF maps</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>KAM maps</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

KAM: Kernel average misorientation, IPF: Inverse pole figure

Subgrain refinement in the surface layer until a depth of z = 900 µm observed. Misorientation maps suggest an increase in dislocation density.

---

**Surface integrity of peened surfaces**

**Evaluation of the surface roughness**

\[ a = 0.4 \text{ mm} \]

The surface is *smoothened* by adjusting the parameter settings as followed:

- **Head diameter** \( d \):
  - \( h = 0.3 \text{ mm}; a = 0.05 \text{ mm} \)
  - \( h = 0.3 \text{ mm}; a = 0.40 \text{ mm} \)
  - \( h = 1.2 \text{ mm}; a = 0.05 \text{ mm} \)
  - \( h = 1.2 \text{ mm}; a = 0.40 \text{ mm} \)

- **Stroke** \( h \):
  - \( d = 6 \text{ mm}; a = 0.05 \text{ mm} \)
  - \( d = 6 \text{ mm}; a = 0.40 \text{ mm} \)
  - \( d = 12 \text{ mm}; a = 0.05 \text{ mm} \)
  - \( d = 12 \text{ mm}; a = 0.40 \text{ mm} \)

- **Distance of indentation** \( a \):
  - \( d = 6 \text{ mm}; h = 0.3 \text{ mm} \)
  - \( d = 6 \text{ mm}; h = 1.2 \text{ mm} \)
  - \( d = 12 \text{ mm}; h = 0.3 \text{ mm} \)
  - \( d = 12 \text{ mm}; h = 1.2 \text{ mm} \)
Surface integrity of peened surfaces
Evaluation of the surface hardness

Work hardening is influenced by the investigated process parameters as followed:

- Head diameter $d$
- $h = 0.3 \text{ mm}; a = 0.05 \text{ mm}$
- $h = 0.3 \text{ mm}; a = 0.40 \text{ mm}$
- $h = 1.2 \text{ mm}; a = 0.05 \text{ mm}$
- $h = 1.2 \text{ mm}; a = 0.40 \text{ mm}$

- Stroke $h$
- $d = 6 \text{ mm}; a = 0.05 \text{ mm}$
- $d = 6 \text{ mm}; a = 0.40 \text{ mm}$
- $d = 12 \text{ mm}; a = 0.05 \text{ mm}$
- $d = 12 \text{ mm}; a = 0.40 \text{ mm}$

- Distance of indentation $a$
- $d = 6 \text{ mm}; h = 0.3 \text{ mm}$
- $d = 6 \text{ mm}; h = 1.2 \text{ mm}$
- $d = 12 \text{ mm}; h = 0.3 \text{ mm}$
- $d = 12 \text{ mm}; h = 1.2 \text{ mm}$

Agenda

1. Introduction
2. Experimental set-up
3. Surface integrity of peened surfaces
4. Description model for the Vickers hardness
5. Summary and outlook
### Description model for the Vickers hardness

#### Developing the description model

**Equation of a description model acc. to KLOCKE**

\[
\hat{V}(x, t, u, \ldots) = c_0 \cdot x^{c_1} \cdot t^{c_2} \cdot u^{c_3} \cdot (\ldots)^{c_3}
\]

- \(\hat{V}\): Vickers hardness as quality feature
- \(x, t, u\): Input variables
- \(c_0, c_1, c_2, c_3\): Coefficients of the regression model

The regression model was developed from the friction model of PILZEK and LUDWIG.

KLOCKE extend the existing model to be suitable for general use. Therefore the model is suitable to be used to describe the behavior of the Vickers hardness after MHP.

The experimental parameters and results served as data to determine the coefficients of the regression model \(c_0, c_1, c_2\) and \(c_3\).

The parameters and results of the center point experiment was not used to determine the coefficients of the regression model. Instead they were used for the validation.

---

### Description model for the Vickers hardness

#### Accuracy of the description model

\[
\hat{V}(d, h, a, \beta) = 2.19 \cdot d^{0.393} \cdot h^{0.227} \cdot a^{0.285} \cdot \beta^{1.057}
\]

- \(\hat{V}\): Vickers hardness as quality feature
- \(d\): Hammer diameter
- \(h\): Stroke
- \(a\): Distance of Indentation
- \(\beta\): Impact angle

The Vickers hardness of the center point experimental measurement and the model prediction deviates by 9.6%. The highest deviation of the model and the measured value is 10.3%.
Summary and outlook
Conclusions from the investigations

**Summary**

- The positioning accuracy of the industrial robot is high during MHP.

- Grain refinement due to MHP was observed up to a depth of \( z \approx 900 \mu m \).

- Compressive residual stresses of maximal \( \sigma = -820 \) Mpa were induced.

- The linear description model has a high prediction accuracy with a maximum deviation of 7.6 % within the considered process room.

**Outlook**

- Investigation of the cause-effect relations between process parameters, grain refinement and dislocation density.

- Developing an accurate description model for the roughness by extending the linear description model to a quadratic model.

- Improving a finite element model to support the experimental results by predicting the dislocation density and grain size.
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Bibliography


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Analyses of technical and true overlap in hammer peening operations

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Karlsruhe Institute of Technology
ANALYSES OF TECHNICAL AND TRUE OVERLAP IN HAMMER PEENING OPERATIONS

E. Segebade, A. Hillgardt, V. Schulze

**MOTIVATION**

What is overlap?

- Overlap of indentations in hammer peening operations defines the resulting percentage overlap of surface.
- It is the main factor to control in order to reach defined treatment intensities or surface textures.

As per the definition in VDI 3416:

- Percentage overlap of surface $\alpha = \sum A_i / A_{total}$
- In the following, "Technical Overlap"
- "...it has to be mentioned, that $\alpha$ can reach values of $\geq 100\%$, even if not all of the surface was hit at least once."

- Technical Overlap is not accurate for complex indentation shapes.
- Is it accurate for simple indentation shapes?
### Technical Overlap vs. Kinematic Overlap vs. True Overlap

#### Technical Overlap
Simple calculation of area of indentation:
- Calculate secant:
  \( s = \sqrt{l_{\text{depth}} \times (d - l_{\text{depth}})} \)
- Calculate area of indentation
  \( A_i = \left(\frac{s}{2}\right)^2 \times \pi \)
- Calculate \( \phi_s = \pi \times A_i / A_{\text{total}} \)

#### Kinematic Overlap
Numerical calculation in Matlab:
- Load STL geometry
- Create master-indentation (dxf)
- Create translation matrix
- Calculate new surface with \( w \) and without \( w/o \) consideration of former indentations

#### True Overlap
Full thermo-mechanical FEM:
- Material model
  - Voce-Kocks-Vöhinger (AISI 4140)
- Body boundary conditions
  - 5 x 5 x 5 mm elastic body
  - 0.5 x 0.5 x 0.1 mm elastic-plastic body
- Rigid tool, constant Temperature: RT
- Surface element edge length
  - 0.005 mm, no remeshing
- Tool movement
  - Position & velocity based

- Kinematic overlap w/o consideration of former indentations and technical overlap should be the same.
- Elasto-plastic FE-simulation result should be closest to the truth and higher than kinematic overlap (w).

### Example Calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball diameter ( d )</td>
<td>2 mm</td>
</tr>
<tr>
<td>( A_{\text{total}} )</td>
<td>( 0.5 \times 0.5 \times 0.25 ) mm²</td>
</tr>
<tr>
<td>( n )</td>
<td>25 (5 x 5 indentations)</td>
</tr>
<tr>
<td>( a = s )</td>
<td>0.05 mm</td>
</tr>
</tbody>
</table>

\[ d = 2 \text{ mm} \]
\[ l_{\text{depth}} = 0.01 \text{ mm} \]

\[ A_i = 0.029 \text{ mm}^2, \phi_s = 5 \times 5 \times A_i / A_{\text{total}} = 6.252 \]

- Technical overlap in our example totals 625.2% as per VDI 3416.
Symposium Mechanical Surface Treatment 2019
8th Workshop Machine Hammer Peening

KINEMATIC OVERLAP
Exemplary calculation

Kinematic overlap
Numerical calculation in Matlab:
• Load .stl geometry
• Create master-indentation (dextel)
• Create translation matrix
• Calculate overlap with and without consideration of former indentations

Main sources of errors
• .stl element edge length (eel)
• x-y surface resolution (res)

stl element edge length convergency
resolution convergency
**Symposium Mechanical Surface Treatment 2019**

**8th Workshop Machine Hammer Peening**

---

**KINEMATIC OVERLAP**

**Exemplary calculation**

- Kinematic overlap
  - Numerical calculation in Matlab:
    - Load, sl geometry
    - Create master-indentation (dixel)
    - Create translation matrix
    - Calculate overlap with and without consideration of former indentations
      - $e_{il} = 5 \mu m$
      - $res = 1.25 \mu m$

- Kinematic overlap w/o consideration of former indentations ~ technical overlap (622.3% vs. 625.2%)
- Kinematic overlap considering former indentations is significantly lower: 252.7%
- Maximum number of tool contacts is also very different (23 w/o vs. 8 w)

---

**TRUE OVERLAP**

**Exemplary calculation**

- True overlap
  - Full thermo-mechanical FEM:
    - **Material model**
      - Voce-Kocks-Vöhringer (AISI 4140)
    - **Body boundary conditions**
      - $5 \times 5 \times 5$ mm elastic body
      - $0.5 \times 0.5 \times 0.1$ mm elastic-plastic body
    - **Rigid tool, constant Temperature: RT**
    - **Surface element edge length**
      - $0.005$ mm, no remeshing
    - **Tool movement**
      - Position & velocity based

- Model setup:
  - Workpiece comprised of "glued" elastic and elastic-plastic bodies

---

**Elasto-plastic body**
- Persistent hexmesh comprised of 26k elements with 10.5k nodes on relevant surface

---

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**TRUE OVERLAP**

**Exemplary calculation**

**True overlap**
- Full thermo-mechanical FEM:
  - Material model
    - Voce-Kocks-Vöhringer (AISI 4140)
  - Body boundary conditions
    - 5 x 5 x 5 mm elastic body
    - 0.5 x 0.5 x 0.1 mm elastic-plastic body
  - Rigid tool, constant Temperature: RT
  - Surface element edge length
    - 5 µm, no remeshing
  - Tool movement
    - Position & velocity based
- Full thermo-mechanical FEM enables calculation of true overlap considering material displacement
- True overlap is significantly lower than technical overlap (378.5% vs. 625.2%)
- True overlap is significantly higher than kinetic overlap considering former indentations (378.5% vs. 252.7%)

**COMPARISON**

Is technical overlap accurate enough for simple indentation shapes?

**Technical overlap**
- Simple calculation of area of indentation:
  - 625.5%

**Kinematic overlap**
- 622.3% w/o consideration of former indentations
- 252.7% w/ consideration of former indentations

**True overlap**
- 378.5% full thermo-mechanical FE-simulation

- Technical overlap severely overestimates the contact area!
- True overlap is closer to kinematic overlap (w) than technical overlap.
  - Kinematic overlap (w) features the best time invested vs. accuracy ratio.
Is kinematic overlap accurate enough for complex indentation shapes?

Technical overlap
- Supposing an area comprised of two half-ovals

Kinematic overlap
- w/o consideration of former indentations
- w consideration of former indentations

True overlap
- Thermo-mechanical FE-Simulation

5 x 5 indentations

\[ r_s = 0.4 \text{ mm} \]
\[ r_b = 0.04 \text{ mm} \]
\[ \beta = 90^\circ \]
\[ \gamma = -7^\circ \]
\[ \alpha = 7^\circ \]
\[ l_{\text{depth}} = 0.01 \text{ mm} \]

Exemplary calculation

Technical overlap
Simple calculation of area of indentation:
- Calculate half-ovals area:
  \[ A_i = \left( a_1 + b_1 + a_2 + b_2 \right) \times \pi / 2 \]
- Calculate Overlap
  \[ \phi = \pi \times A_i / A_{\text{total}} \]
- Technical Overlap = 144.5%

Kinematic overlap
Numerical calculation in Matlab:
- Load .stl geometry
- Create master-indentation (dext)
- Create translation matrix
- Calculate new surface with and without consideration of former indentations

True overlap
Full thermo-mechanical FEM:
- Material model
  - Voce-Kocks-Vöhringer (AISI 4140)
- Body boundary conditions
  - 5 x 5 x 5 mm elastic body
  - 0.5 x 0.5 x 0.1 mm elastic-plastic body
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- Surface element edge length
  - 0.005 mm, no remeshing
- Tool movement
  - Position & velocity based

- Kinematic overlap (w/o) and technical overlap should be the same.
- Elasto-plastic FE-simulation result should be closest to the truth and higher than kinematic overlap (w).
**COMPARISON**

Is kinematic overlap accurate enough for complex indentation shapes?

**Technical overlap**
Simple calculation of area of indentation:
- 144.5%

**Kinematic overlap**
- 139.5% w/o consideration of former indentations
- 72.8% w consideration of former indentations

**True overlap**
- 117.5% full thermo-mechanical FE-simulation

- Technical overlap is harder to calculate for complex indentation shapes.
- Analogous to simple indentation shapes, kinematic overlap (w/o) is closest to technical overlap.
  → Kinematic overlap (w) is less accurate for the indentation shape we analyzed!

---

**VDI 3416 EXTENSION?**
Considering deterministic surface topographies produced by hammer peening

**Deterministic, recurring surface topographies**
- Depend on all process parameters (distance of indentation, stepover distance, indenter shape etc.)
- Result in calculable technical and kinematic percentage overlap of surface

**Representative percentage of overlap \( \alpha \)**
- Calculated as per VDI within \( A \)
- Allows comparison of processes or process parameters without defining arbitrary areas or including peripheral phenomenon in the calculation
OUTLOOK

We did
- Calculate overlap of indentations in different ways considering arbitrary indentation shapes.

We found
- Technical overlap is neither accurate, nor comparable regardless of indentation shape.
- All overlap values calculated so far require knowledge of the surface area considered.

We propose
- Extension of VDI 3416 considering deterministic surfaces: representative percentage of overlap.

What comes next
- Compare calculated overlap and surface topography with experimental results using different indentation shapes.
- Refine tool movement in FE-simulation and in kinematic calculations (e.g. acceleration & energy based).

Thank you for your kind attention!
Influence of the process parameters on the penetration behaviour of ceramic particles in Composite Peening

Michael Seitz

IAM-WK – Institute for Applied Materials

Karlsruhe Institute of Technology
Influence of the process parameters on the penetration behaviour of ceramic particles in Composite Peening

Symposium Mechanische Oberflächenbehandlung 2019, Karlsruhe
Michael Seitz
Hybrid and Lightweight Materials

Institute for Applied Materials (IAM-WK)

Motivation
Composite Peening

Metal Matrix Composites (MMC)
- Improvement of specific properties, for instance by particle reinforcement
- Strengthening of the surface layer
- Functionally graded materials (FGM)

Micro Shot Peening
- Surface strengthening process
- Increase in fatigue strength
- Lower roughness compared to shot peening
- Ceramic blasting particles < 100 μm
- Embedment of blasting particles [2]

Composite Peening
- Manufacturing of a metal matrix composite by peening process
- Introduction of particles without liquid phase

[2] Amir et al., 2005

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Motivation

Penetration behaviour

- Observation from current research [3-5]
  - After composite peening a hill-valley profile is formed
  - The ceramic particles are mainly located in the valleys
  - Penetration depth is up to 30 μm
  - Particles are significantly smaller than their initial size

What happens to the blasting particles during the composite peening process?

Agenda

- Manufacturing
- Penetration behaviour
  - Deep Impact in Metals
  - Solid Particle Erosion
  - Composite Peening
- Conclusion

![Diagram showing process and structure of composite peening](image)
Manufacturing

Experimental setup

- Work chamber
- AccuFlo MicroBlasting System
- Heating device
- CNC-Machine
- Temperature controller
- Control unit
- PC
Manufacturing

**Temperature profile**

Cooling during machining

---

### Manufacturing

**Process parameters for Composite Peening**

<table>
<thead>
<tr>
<th>AW 1050</th>
<th>AW 6082</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="image" /></td>
<td><img src="image2.png" alt="image" /></td>
</tr>
</tbody>
</table>

**Materials:**
- Al₂O₃
- SiC
- WC

**Symbols:**
- Feed rate \( v \)
- Pressure \( p \)
- Number of operation \( z \)
- Working distance \( a \)
- Path distance \( b \)

**Parameters Table**

<table>
<thead>
<tr>
<th>Pressure ( ) (bar)</th>
<th>Number of operation</th>
<th>Temperature ( T ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4, 7</td>
<td>2, 4, (10)</td>
<td>0,8; 0,9; 0,95</td>
</tr>
</tbody>
</table>

**Dimensions:
- Feed rate \( v \) 1,28 – 1,81 mm/s
- Pressure \( p \) 28 – 81 %
- Mass flow rate 8,2 – 14,8 g/min

**Additional Information: 100,000,000 Particles/mm²**
Deep Impact in Metals

Formulation of the penetration depth

- Deep penetration of a non-deformable projectile with different geometrical characteristics [11]
  - Single particle impact
  - Penetration depth depends on momentum conservation, geometry of the projectile and dynamic-cavity expansion.

\[ X = \frac{2M}{\pi d^2 B \rho N_2} \ln \left( 1 + \frac{B \rho N_2 V_0^2}{AYN_1} \right) \]

Particle properties
- \( M \): Mass of the projectile
- \( d \): Diameter of the projectile
- \( N_1, N_2 \): Projectile Shape

Target properties
- \( A, B \): Material constants
- \( \rho \): Density
- \( Y \): Yield strength

Process properties
- \( V_0 \): Velocity of the projectile
- \( X \): Penetration depth

Deep Impact in Metals

**Particle properties**

**Shape and Size**
- Fracturing of the particles during processing?
- Average Diameter and size distribution
  - Before Peening: 12.8 +/- 0.2 µm
  - After Peening: 12.2 +/- 0.1 µm

\[ X = \frac{2M}{\pi d^2 B \rho N_2} \ln \left( 1 + \frac{B \rho N_2 V_0^2}{A Y N_1} \right) \]

No significant reduction in grain size

**Velocity of the particles**
- \( V_{\text{bar}} = 195 \text{ m/s} \)

\[ \text{Al}_2\text{O}_3 \]

20 µm

[Image of particles and equations]

---

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Deep Impact in Metals

Target properties

- Certain material properties depend on the process temperature during composite peening
  - Yield Strength
  - Young’s modulus

High temperature tensile test

- $B = 1.041$ for Aluminium [13]
- $\rho_{Al} = 2.7 \text{ g/cm}^3$

\[ X = \frac{2M}{\pi d^2B\rho N_2} \ln \left(1 + \frac{B\rho N_1 V_0^2}{AY N_1}\right) \]

Deep Impact in Metals

Penetration depth

Influence of the target material

Influence of the projectile size

[14] TA Instruments, Inc.

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Deep Impact in Metals
Penetration depth

- Penetration depth along a blasting path
- Cooling from 0.95 $T/T_S$ to 0.75 $T_S$

$0.95 T/T_S$

$0.75 T/T_S$

Temperature $0.95 T/T_S$
Pressure 7 bar
Feed rate 2 mm/s
Number of operation 1
Solid Particle Erosion (SPE)

**Composite Peening**

- Difference: Single particle impact – Composite Peening
- During compound blasting, ~100 million particles / mm² hit the surface.

**Multiple Particle Impact**

- Similar to Solid Particle Erosion
Solid Particle Erosion

Overview

- Field of research since WW II [16]
  - Power plant vessel
  - Pneumatic transportation systems
  - Helicopter rotor blades
- Occurs when granular particles hit a material surface
- Impact angle is an important factor in SPE
  - Maximum erosion of brittle materials at 90°
  - Maximum erosion of ductile materials at 15° - 45°
- Kinetic energy is mainly converted into elastic-plastic deformation and fracture energy
- Luminescence can also be observed [17]

Composite Peening, Al₂O₃ & AW 1050

Solid Particle Erosion

Aluminium

- With aluminium, no erosion rate can be observed at an impact angle of 90° because blasting particles are embedded [16]
- SPE at AW 1100 showed a hill-valley profile and embedded particles [20]
Solid Particle Erosion
Particle Fracturing

- Several authors have proven that particles fracture on impact (according to Bousser [21])
  - Wada presents the thesis that particles fragment upon impact when the hardness of the particles ≤ hardness target material [23]
  - Particle toughness is also important

- After Composite Peening, nanoscale aluminium oxide particles can be found in the surface layer

Multiple impacts cause the particles to fracture

Sand particle on tungsten carbide surface [22]

Composite Peening
Composite Peening

Determination of penetration depth

$ L = 10 \text{ mm} $

$ 10 \% \text{ Al}_2\text{O}_3 $

The penetration depth of Composite Peening is slightly above the penetration depth of the single particle impact.

The model of Chen [11] can be used to estimate the influence of the process parameters during Composite Peening.

Penetration depth of up to 30 $\mu\text{m}$ is achieved.

The penetration depth can be increased by multiple processing.

\[ X = \frac{2M}{\pi d^2 B \rho N_2} \ln \left( 1 + \frac{B \rho N_2 V_0^2}{4 A Y N_1} \right) \]
**Conclusion & Outlook**

- Estimation of penetration depth during compound peening based on a ballistic model
- Influence of individual process parameters on the penetration depth
- Correlation between Composite Peening and Solid Particle Erosion
- Adaptation of the model to other material combinations
  - WC and SiC as blasting particles

---

**Thank you for your attention!**

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The authors would like to thank the German Research Foundation (DFG) for the financial support.

DFG
WE4273/15-1
References

Residual stress relaxation in HFMI-treated fillet welds after single overload peaks

Jan Schubnell

Institute for Mechanics of Materials IWM

Fraunhofer
RESIDUAL STRESS RELAXATION IN HFMI-TREATED FILLET WELDS AFTER SINGLE OVERLOAD PEAKS

Symposium Mechanische Oberflächenbehandlung
KIT Karlsruhe, 22.-23.10.2019

Jan Schubnell, Eva Carl, Majid Farajian (IWM)
Stefanos Gkatzogiannis, Peter Knödel, Thomas Ummenhofer (KIT)
Robert Wimpory (HZB)
Hamdollah Eslami (IFS)

AGENDA
Residual stress relaxation at HFMI-treated fillet welds after single overload peaks
I IW – Document XIII-2829-19

- Motivation
- Experimental set-up
  - Material and weld detail
- Residual stress analysis
  - Experimental study
  - Numerical study
- Conclusion

X-ray-diff.r. Neutron-diff.r. FEA
Motivation

- Significant fatigue life improvement of HFMI-treated welded joints is statistically proved (Marquis and Barsoum 2016) based on numerous studies under constant amplitude (CA) loading.
- Studies have shown that the fatigue life benefit decreases at variable amplitude (VA) loading (Marquis 2010, Leitner et al. 2018).
- It is assumed that this decrease is strongly related to the compressive residual stress relaxation under high peak stresses.

\[
\begin{align*}
S_{max}/S_{min} &= +/ -0.45f_y & \text{Marquis et al. (2013)*} \quad (R < -0.125) \\
S_{max}/S_{min} &= +/ -0.6f_y & \text{Mikkola et al. (2017)} \quad (R = -1) \\
S_{max}/S_{min} &= +/ -0.8f_y & \text{Haagensen and Maddox (2013)**} \\
S_{min} &= -0.8f_y / S_{max} = f_y & \text{Kuhlmann et al. (2018)***}
\end{align*}
\]

Aim: Quantify the compressive residual stress relaxation

\[
S_{max} = \text{Maximum nominal stress}, \quad f_y = \text{nominal yield of the base material} \\
R = \text{Stress ratio}
\]

*Current IWW-Recommendation (HFMI) / ** Hammer & Needle Penning / *** German DAST guideline (not resolved yet)
Material and specimen details

- Steel: S355J2+N / S960QL
- Weld detail: Transverse stiffener
- Weld type: Single layer fillet weld*
- Weld process: GMAW (135)*
- HFMI: Pneumatic Impact treatment (PIT)


<table>
<thead>
<tr>
<th>Materials</th>
<th>Yield strength [MPa]</th>
<th>Ultimate Strength [MPa]</th>
<th>Elongation [%]</th>
<th>Hardness [HV10]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2+N</td>
<td>420</td>
<td>536</td>
<td>25*</td>
<td>189</td>
</tr>
<tr>
<td>S960QL</td>
<td>1011</td>
<td>1060</td>
<td>14*</td>
<td>318</td>
</tr>
</tbody>
</table>

*data sheet

Experimental test set-up / residual stress analysis

„Stress peaks“ from VA loading were approximated by single static loads (majority of residual stress relaxation occurs at N=1 (Farajian et al. 2010, Leitner et al. 2018)

Load set-up (IFS)
PLM 630N

Tension

Compression

Exp.  Num.
Experimental test set-up / residual stress analysis

“Stress peaks” from VA loading were approximated by single static loads (majority of residual stress relaxation occurs at N=1 (Farajian et al. 2010, Leitner et al. 2018))

Load set-up (IFS)

PILm 630N

500 N

Tension

Compression

Experimental value

Numerical value

Material modelling: Heat affected zone*

S355J2+N

Measurement

Gleeble

S960QL

Measurement

Gleeble


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Numerical simulation: Constitutive model

 Implemented as VUMAT-Subroutine by Maciolek 2017*

Uniaxial load cycle:

\[ \sigma = \Omega_1 + \Omega_2 + k \varepsilon_p (\text{MPa}) \]

\[ \varepsilon_p = \varepsilon_{pl} \]

\[ k = \text{hardening exponent} \]

\[ n = \text{hardening coefficient} \]

---

Numerical simulation: Residual stress analysis

Finite-Element simulation according to Hardenacke et al. (2015), Föhrenbach et al. (2016), Schubnell et al. (2017) and Ernoult et al. (2019)

**S960**

\[ S_{max} = 0.9f_y \]

\[ S_{max} = -0.9f_y \]

**S355**

\[ S_{max} = 0.9f_y \]

\[ S_{max} = -0.9f_y \]
**Numerical / Experimental residual stress analysis S355**

![Graph showing residual stress analysis S355 with tensile and compressive load plots.](image)

**Numerical / Experimental residual stress analysis S960**

![Graph showing residual stress analysis S960 with tensile and compressive load plots.](image)
Residual stress analysis: $S_{\text{max}} \sim \Delta\sigma_{\text{RES}}$

**Transverse residual stress maximum $\sigma_{\text{RES, max}}$**

$S_{\text{max}} / f_{\text{y, real}} [-]$

- S960 Sim.
- S960 Exp.
- S355 Sim.
- S355 Exp.

Related to measurement volume 2x2x5 mm³

$S_{\text{nom}}$: Maximum nominal stress, $f_{\text{y}}$: yield strength of the base material

**Residual stress analysis: $S_{\text{max}} \sim \Delta\sigma_{\text{RES}}$**

$S_{\text{max}} / S_{\text{min}} = +/- 0.45 f_{\text{y}}$

$S_{\text{max}} / S_{\text{min}} = +/- 0.6 f_{\text{y}}$

$S_{\text{min}} = -0.8 f_{\text{y}}$

$S_{\text{max}} = f_{\text{y}}$

**Transverse residual stress at surface $\sigma_{\text{RES, surf}}$**

$S_{\text{surf}} / f_{\text{y, real}} [-]$

- S960 Sim.
- S960 Exp.
- S355 Sim.
- S355 Exp.

Related to diameter on surface of Ø 1 mm
### Conclusion

- Compressive overloads close to the base materials yield strength (-0.9f_y) lead to nearly full residual stress relaxation for S960 and around half residual stress relaxation for S355.
- For tensile overloads close to the base materials (0.9f_y) yield strength only minor residual stress (-10% to -35%) relaxation was observed for both steel grades.
- Significantly less residual stress relaxation was determined for S355 than for S960 at the same normalized nominal stress $S_{\text{max}} / f_y$.
- IIW-recommendation of $S_{\text{max}} / f_y$ shows a clear over-conservatism.

### Literature

**Marquis et al. (2013)**

**Haagensen & Maddox (2013)**

**Mikkola et al. (2013)**

**Kuhlmann et al. (2018)**
Interne Verfestigungsdomänen durch mechanische Oberflächenbehandlung während der additiven Fertigung

Dr.-Ing. Daniel Meyer
IWT Manufacturing Technologies
University of Bremen
Interne Verfestigungsdomainen durch mechanische Oberflächenbehandlung während der additiven Fertigung

Symposium Mechanische Oberflächenbehandlung am 22. und 23. Oktober 2019

Dr.-Ing. D. Meyer
M.Sc. N. Weiβki

**Scope of this presentation**

*Additive Manufacturing*  
*Parts with limited surface quality and complex microstructures*

*Post-Processing influencing the Surface Integrity*
Potential of milling and deep rolling
in post-processing of AM parts

Printing parameters
- Layer thickness l: 50 µm
- Laser power P_l: 235 W
- Scan velocity v_s: 700 mm/s
- Hatch distance h_h: 150 µm, 120 µm

Milling parameters
- Cutting speed v_c: 80 mm/min
- Feed speed v_f: 100 mm/min
- Depth of cut a_e: 0.3 mm

Deep rolling parameters
- Ball diameter d_b: 6 mm
- Deep rolling pressure p_r: 100, 200, 400 bar
- Rolling speed v_r: 100 mm/min
- Stepover s_r: 0.1 mm

Hardness depth profiles
after milling and deep rolling of AM parts

Influence of hatch distance

<table>
<thead>
<tr>
<th>Distance from the surface z</th>
<th>Hardness H V 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>400</td>
<td>300</td>
</tr>
</tbody>
</table>

Top face
Lateral face
Milled
Milled
Deep rolled

Deep rolled
Top face
**Hardness depth profiles**
after milling and deep rolling of AM parts

**Influence of hatch distance**
- Increasing hardness with increasing deep rolling pressure for both hatch distances
- Hatch distance influences the density/prosity and thus the hardness depth profiles

---

**Influence of post-processing**

![Graph showing hardness depth profiles for different post-processing conditions](image)

- $h_y = 120 \, \mu m$
- $p = 400 \, \text{bar}$ (milled)
- $p = 200 \, \text{bar}$

---

**Deep rolled**
- Top face

---

**Milled**
- Top face
**Hardness depth profiles**

**after milling and deep rolling of AM parts**

Influence of hatch distance
- Increasing hardness with increasing deep rolling pressure for both hatch distances
- Hatch distance influences the density/prosity and thus the hardness depth profiles

Influence of post-processing
- Hardness values are comparable for both post-processing strategies

---

**Hatching depth profiles**

**after milling and deep rolling of AM parts**

Influence of hatch distance
- Increasing hardness with increasing deep rolling pressure for both hatch distances
- Hatch distance influences the density/prosity and thus the hardness depth profiles

Influence of post-processing
- Hardness values are comparable for both post-processing strategies

Influence of layer orientation

<table>
<thead>
<tr>
<th>Distance from the surface μm</th>
<th>H = 120 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>p = 100 bar</td>
</tr>
<tr>
<td>200</td>
<td>p = 200 bar</td>
</tr>
<tr>
<td>400</td>
<td>p = 400 bar</td>
</tr>
</tbody>
</table>

---

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**Hardness depth profiles**

after milling and deep rolling of AM parts

- **Influence of hatch distance**
  - Increasing hardness with increasing deep rolling pressure for both hatch distances
  - Hatch distance influences the density/prosity and thus the hardness depth profiles

- **Influence of post-processing**
  - Hardness values are comparable for both post-processing strategies

- **Influence of layer orientation**
  - Increasing hardness with increasing deep rolling pressure for both faces of the cube
  - The courses differ more from each other at the lateral face

---

**Surface topography**

after deep rolling of AM parts

- **Top face**
  - Sa = 6423.0 nm
  - As printed

- **Top face**
  - Sa = 162.7 nm
  - As printed + 400 bar

- **Lateral face**
  - Sa = 10010.0 nm
  - As printed

- **Lateral face**
  - Sa = 390.2 nm
  - As printed + 400 bar
Surface topography
after deep rolling of AM parts

Deep rolled only

Sa = 3053.6 nm
As printed + 100 bar

Sa = 162.7 nm
As printed + 400 bar

Milled + deep rolled

Sa = 60.6 nm
Milled + 100 bar

Sa = 54.9 nm
Milled + 400 bar
Scope of this presentation

Additive Manufacturing → Parts with limited surface quality and complex microstructures

Post-Processing influencing the Surface Integrity → Influence the bulk material or inaccessible areas locally

The concept of internal reinforced domains

- Make use of temporary accessibility of all areas during the build phase in AM
- Perform mechanical surface treatment with high depth effect locally
- Apply additional layers by Additive Manufacturing
- Generate three-dimensional internal reinforced domains with adapted Material Integrity

Internal reinforced Domains
The vision behind the concept

Schematic microstructure

Approach

Surface Integrity
- Surface roughness
- Hardness and residual stress alterations
- Porosity

Material Integrity within internal reinforced domains
- Attachment of additional layers
- Remaining hardness alterations
- Resulting microstructures
Surface Integrity after deep rolling of AM-parts

Surface Topography

\[ Sa = 4.61 \mu m \]

\[ Sa = 0.10 \mu m \]

\[ F_r = 956 N, \text{ top face} \]

As printed, top face

Material Ratio [%]

Material: AISI 316L
Part dimensions: 50 x 50 x 50 mm
Laser power: 235 W
Layer thickness: 50 µm
Hatch distance: 120 µm, 150 µm
Scanning velocity: 700 m/s

Deep rolling
Bail diameter: 6 mm
Rolling pressure: 100 bar, 200 bar, 400 bar
Rolling force: 205 N, 441 N, 956 N
Feed: 0.1 mm
Rolling velocity: 100 mm/min

Attachment of additional SLM-layers

Selective Laser Melting
Deep Rolling in CNC Machine
Sel. Laser Melting

Material: AISI 316L
Part dimensions: 50 x 50 x 50 mm
Laser power: 235 W
Layer thickness: 50 µm
Hatch distance: 120 µm
Scanning velocity: 700 m/s

Deep rolling
Bail diameter: 6 mm
Rolling pressure: 400 bar
Rolling force: 956 N
Feed: 0.1 mm
Rolling velocity: 100 mm/min
**Surface Integrity after deep rolling of AM-parts**

*Hardness depth profiles*

- **Top face**
  - $p_1 = 100$ bar
  - $p_2 = 200$ bar
  - $p_3 = 400$ bar

- **Lateral face**

**Selective Laser Melting**

- Material: AISI 316L
- Part dimensions: $50 \times 50 \times 50$ mm
- Laser power $P_L$: 235 W
- Layer thickness $t$: 50 μm
- Hatch distance $h$: 120 μm
- Scanning velocity $v_s$: 700 m/s

**Deep rolling**

- Ball diameter $d_b$: 6 mm
- Rolling pressure $p_r$: 100 bar; 200 bar; 400 bar
- Rolling force $F_r$: 205 N; 441 N; 956 N
- Feed $f$: 0.1 mm
- Rolling velocity $v_r$: 100 mm/min

**Remaining strain hardening after continued SLM**

- **Surface after initial deep rolling**
- **Annealing effects**
- **Remainder hardness alterations**

**Selective Laser Melting**

- Material: AISI 316L
- Part dimensions: $50 \times 50 \times 50$ mm
- Laser power $P_L$: 235 W
- Layer thickness $t$: 50 μm
- Hatch distance $h$: 120 μm
- Scanning velocity $v_s$: 700 m/s

**Deep rolling**

- Ball diameter $d_b$: 6 mm
- Rolling pressure $p_r$: 400 bar
- Rolling force $F_r$: 956 N
- Feed $f$: 0.1 mm
- Rolling velocity $v_r$: 100 mm/min
Remaining microstructural effects after continued SLM

Dislocation slip and twinning effects

Conclusions and Outlook

- Smooth surfaces do not cause issues regarding attachment of additional layers
- Parts of the strain hardening effects after deep rolling are preserved after continuation of SLM
- Recrystallization effects occur due to re-heating effects
- Internal reinforced domains with enhanced Material Integrity can be generated using conventional machines and printers
- Reduce the depth effect of re-heating by adaptation of SLM parameters
- Generate specific hardness profiles in an alternating operation mode
- Consider effects of varying temperature in the building chamber
- Integrate the deep rolling process into the 3D-printer
Thank you for your kind attention!

Interne Verfestigungsdomainen durch mechanische Oberflächenbehandlung während der additiven Fertigung

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Influence of MHP on the material structure of CrNi steels

Markus Prießnitz

Institute of Production Engineering and Photonic Technologies

TU Wien
Influence of MHP on the material structure of CrNi steels

Workshop Machine Hammer Peening
October 23rd, 2019

Markus Prießnitz
Institute of Production Engineering and Photonic Technologies

Agenda

<table>
<thead>
<tr>
<th>1</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Metastable austenitic stainless steels</td>
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<td>1.2</td>
<td>Martensitic transformation in stainless steels</td>
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<tr>
<td>2</td>
<td>Experimental investigation</td>
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<td>2.1</td>
<td>Material selection</td>
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<td>Sensor</td>
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<td>2.3</td>
<td>Setup</td>
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<tr>
<td>2.4</td>
<td>Outcomes</td>
</tr>
<tr>
<td>3</td>
<td>Application examples and outlook</td>
</tr>
</tbody>
</table>
Background of the research

- Previous work
  - Magnetic properties of stainless steel can be affected by MHP

- Interest
  - Materials science behind the process
  - Systematization and application
  - Code material and detect code

- Dissemination
  - Bachelor thesis
  - Patent protection

Types of magnetism

**Diamagnetism**
- Graphite plate
- Permanent magnet

**Paramagnetism**
- Molecular magnet
- Magnetic field line

**Ferromagnetism**
- Grain boundary
- Domain wall
- Magnetic spin

22 and 23 October 2019, Karlsruhe
Magnetic properties of stainless steels

**Ferritic stainless steels**
- Crystalline structure bcc
- Magnetically soft behaviour
  - Induction
  - Shielding of magnetic fields
- Regulation of magnetic properties through alloying and heat treatment

**Martensitic stainless steels**
- Crystalline structure bcc
- Magnetically hard behaviour
- Regulation of magnetic properties through alloying and heat treatment

**Austenitic stainless steels**
- Crystalline structure fcc
- Diamagnetic behaviour
  - Neutral exposed to magnetic fields
- Paramagnetic properties due to plastic deformation and residual ferrite

Source: [3]

Metastable austenitic stainless steels

**Stabilisation of austenite**
- Mechanically
  - Increase in volume during austenite to martensite transformation
- Chemically
  - Nickel, carbon and cobalt widen austenitic phase field

Relative permeability after cold working

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>μrel</th>
<th>μrel</th>
<th>μrel</th>
<th>μrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>X8CrNiSi18-9 (1.4305)</td>
<td>1.003</td>
<td>1.059</td>
<td>1.620</td>
<td>3.420</td>
</tr>
<tr>
<td>X8CrNiSi18-9 (1.4301)</td>
<td>1.012</td>
<td>1.046</td>
<td>1.626</td>
<td>3.050</td>
</tr>
<tr>
<td>X2CrNiMo18-11-3 (1.4435)</td>
<td>1.007</td>
<td>1.008</td>
<td>1.024</td>
<td>1.130</td>
</tr>
<tr>
<td>X3CrNiCu18-9-4 (1.4587)</td>
<td>1.005</td>
<td>1.005</td>
<td>1.012</td>
<td>1.082</td>
</tr>
</tbody>
</table>

Source: [4]
Martensite transformation - Initiation

- Thermal initiation
  - Driving force due to supercooling
- Mechanical initiation
  - Deformation induced
  - Strain induced
- Initiating the transformation by introducing the necessary enthalpy difference
- If MS<RT no thermal initiation at RT
- Additional mechanical enthalpy enables transformation at RT
- Martensite quantity dependent on stacking error energy

- Effect in sheet metal working known and undesired
- Targeted control of the introduced enthalpy possible through MHP
- Targeted exploitation of the regionally changed magnetic properties

![Diagram showing martensite transformation](source.png)

Agenda

| 1  | Background                  |
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| 1.2 | Martensitic transformation in stainless steels |
| 2  | Experimental investigation |
| 2.1 | Material selection         |
| 2.2 | Sensor                     |
| 2.3 | Setup                      |
| 2.4 | Outcomes                   |
| 3  | Application examples and outlook |
Material selection

- X5CrNi18-10 (1.4301)
- 125x60x2mm
- E-MHP accurapuls
- Haas VF3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of hammerhead d</td>
<td>6mm</td>
</tr>
<tr>
<td>Hammering frequency f</td>
<td>200Hz</td>
</tr>
<tr>
<td>Stroke h</td>
<td>1mm</td>
</tr>
<tr>
<td>Feed rate v</td>
<td>1200mm/min</td>
</tr>
<tr>
<td>Stepover s</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Distance between impressions a</td>
<td>0.1mm</td>
</tr>
</tbody>
</table>

Detection of magnetic permeability

- Magnetic induction
  - Coil on core
- Magnetic flux density
  - Hall-Effect
  - Magnetoresistance
- Ferromagnetism
  - Magnetic scale
Symposium **Mechanical Surface Treatment 2019**
8th Workshop Machine Hammer Peening

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**Sensor design**

- **Sensor 1**
  - Field coil
  - Exploring coil
- **Sensor 2**
  - Field coil
  - Exploring coil

<table>
<thead>
<tr>
<th>Parameter (Sensor 2)</th>
<th>Value and Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windings of field coil</td>
<td>2x 10 windings</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Windings of exploring coil</td>
<td>10 windings</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Resistance of field coil</td>
<td>0.302Ω</td>
</tr>
<tr>
<td>Inductance of field coil</td>
<td>27.3μH</td>
</tr>
<tr>
<td>Resistance of exploring coil</td>
<td>0.437Ω</td>
</tr>
<tr>
<td>Inductance of exploring coil</td>
<td>106.92μH</td>
</tr>
</tbody>
</table>

---

**Experimental setup**

- Sensor
- HSK-63 adapter
- Spindle nose
- Specimen
- Jig
- Excitation wire
- Measuring wire
- Machine table
- View
- Frequency generator
  - 1 kHz
  - Vp-p = 5V
**Outcomes – Sensor 2**

**Schematic trend**

![Graph showing trend analysis for Sensor 2.](image)

**Single field probing without jig**

![Graph showing single field probing results for different settings.](image)
Outcomes – Sensor 2

Double field probing (1x – 2x)

<table>
<thead>
<tr>
<th>Distance in mm</th>
<th>Sheet</th>
<th>Shot off yj</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
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<tr>
<td>30</td>
<td>80</td>
<td>80</td>
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<td>40</td>
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<td>50</td>
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<tr>
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<tr>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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   2.4 Outcomes
3 Application examples and outlook
Application examples

- Treatment with MHP system on conventional NC systems
- Removal of machining marks by surface removal or coating possible
- Codification, marking
- Position measuring systems
- Locking systems
- Protection against operating errors
- OEM parts monitoring

Intellectual property protection

- Patent application 2018111316194000DE
- “Verfahren zur Bearbeitung eines einen Informationsbereich aufweisenden Bauteils, Bauteil mit einem Informationsbereich und Messsystem”
- Area-wise applied information area on metallic surface with varied intensity
- Application using elastic/plastic forming
- Strain-induced microstructure transformation
- Use of information area
  - Codification, marking
  - Metrology
  - Locking systems
  - ...
- Reading head for decoding the workpiece
Outlook

- Miniaturisation and testing of spatial resolution
  - Sensor
  - MHP-Process
- Combined sensors
  - Static measurements
  - Edge detection
- Contactless detection
- Detection on smooth surfaces
- Alternative approaches for detection
  - Hall-Effect sensor

Discussion

Thank you for your attention!
Questions?

Influence of MHP process on the material structure of CrNi steels
Markus Prießnitz
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We thank the Machine Tool Technologies Research Foundation (MTTRF) for the loaned equipment, on which part of the presented work has been carried out.
Symposium Mechanical Surface Treatment 2019
8th Workshop Machine Hammer Peening

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Image sources

[1]: Diamagnetic graphite levitation, Author: Splarka, CC0 1.0.
[2]: Paramagnetic probe with varying magnetic fields, Author: Jens Böning, CC0 1.0.
[8]: Helmut Fischer Gmbh, “Broschüre Feritscope FMP30”

Influence of the hammer head geometry when machining higher strength materials by MHP

Peter Sticht

Institute for Production Engineering and Forming Machines

Technische Universität Darmstadt
Machine hammer peening (MHP) is a dynamic process to smoothen tool surfaces, increase hardness and introduce residual compressive stresses into the surface layer. Additionally, MHP can be used to apply surface textures that act as lubricant pockets onto tools with specifically shaped hammer heads. MHP-treated surfaces have proven to minimize friction and decrease wear and tear of sheet metal forming tools. As of now, the applicability on higher strength materials in the context of bulk metal forming processes has not yet been investigated sufficiently.

The presentation focuses on the application of MHP in the field of cold forging tools. High strength materials as hardened tool steel, powder metallurgical steel and cemented carbide are treated by MHP and the surface characteristics by means of roughness are investigated. It is shown that MHP allows for a mechanical treatment of higher strength material and that adapted hammerhead geometries can lead to enhanced surface characteristics.

Forming processes and their reliability are heavily affected by the surface integrity of the tools used. Therefore, high effort is put into the finishing of tool surfaces. [1] MHP is commonly used for smoothing technical surfaces [2] and introducing residual compressive stresses [3] as well as causing strain hardening in the surface layer of the components treated [4]. By using specially shaped hammer heads, surface textures, which serve as lubricant pockets, can be applied onto the surface in the same process step [5]. The aforementioned effects are caused by an oscillating hammerhead that is deterministically guided over the surface by an industrial robot or a machining center [6].

Within the modern industrial environment, mainly electro-magnetic [7] or pneumatic [8] systems are used, whereas piezo-electric [9] actuators are used in current research applications. Primarily, MHP is used in the tool and mold making industry to ensure the surface integrity of the tools that will be involved in production processes such as deep drawing. It has been shown that micro textures can lower the friction coefficients by about 30 % compared to manually polished surfaces [5]. Also, wear phenomena and locations change, as particles that would be able to move in process direction are being caught by the micro textures and prevented from causing further abrasive wear on the tool [10]. Not only sheet metal forming processes, but also cold forging processes can benefit from hammer peened surfaces. The tribological loads in these processes are considerably higher and therefore, higher strength materials are selected to meet the criteria regarding durability.

So far, the effect of different hammerhead diameters on the smoothening behavior on tool steel and nodular cast iron has been investigated extensively whereas always spherical hammerheads have been used.

Different tool materials are measured in a variety of conditions. These values define the benchmark for the ongoing surface treatment by machine hammer peening.

In the next step, higher strength materials commonly used in the cold forging industry are treated by machine hammer peening with different parameter settings and an increasing number of repetitions, where necessary. It is shown that, for the most materials, it is possible to reach the desired characteristic surface values.

Following the study an approach to improve the MHP-treatment of higher strength material is presented, taking different hammer head geometries into consideration. The latest
developments regarding the MHP treatment of higher strength materials as well as an outlook on further investigations conclude the presentation.

The authors would like to thank all participating industrial partners as well as the funding organizations for their contribution to the MHP technology.

References
Optimization of the stream finishing process for mechanical surface treatment by numerical and experimental process analysis

Patrick Neuenfeldt

wbk Institute of Production Science

Karlsruhe Institute of Technology
OPTIMIZATION OF THE STREAM FINISHING PROCESS FOR MECHANICAL SURFACE TREATMENT BY NUMERICAL AND EXPERIMENTAL PROCESS ANALYSIS

P. Neuenfeldt, A. Kacaras, F. Zanger, V. Schulze

AGENDA

1. Explanation of the Stream Finishing process
2. Discrete element modeling
3. Scientific gaps
4. Experimental setup and discrete element modeling
5. Results
6. Conclusion and outlook
EXPLANATION OF THE STREAM FINISHING PROCESS

Process properties
- Rotating bowl filled with granular material (media)
- Types of media
  - Bonded: abrasive particles fixed in a matrix
  - Unbonded media
- Defined positioning of workpiece
  → relative velocity between media and workpiece’s surface

Different types of bonded media

Stream Finishing of a turbine blade

AGENDA

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DISCRETE ELEMENT MODELING

Simulation method
- Numerical method to determine the movement of solids
- No meshing of the computation area needed like e.g. in CFD
- Mesohing of solids only
- Different kinds of geometries and properties of solids possible
- DEM-Software Rocky DEM

Simulation procedure in general
- Definition of boundary conditions
- Definition of machine and workpiece kinematics
- Filling of the calculation area by stochastic distribution of solids
- Time-discrete calculation while executing machine and workpiece kinematics
  → transient simulation

Filling of the calculation area
Executing machine and workpiece kinematics
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INTRODUCTION

Present scientific gaps for mass finishing

Proportional relationship between material removal and the power equivalent is still unproven for mass finishing (Brocker)

Knowledge of local contact forces and velocities is not available

No approach for a realistic description of spatial flow formation is available

No consideration of surface states besides surface topography and correlation with process parameters

Scientific goal

- Cause-effect relationships between process parameters, contact conditions and surface integrity
- Experiment:
  - Normal force $F_n$
  - Material removal $\Delta m$
  - Roughness $S_a$
  - Residual stress $\sigma_{02}$
- Simulation:
  - Normal force $F_n$
  - Tangential velocity $v_t$
  - $P = F_n \cdot v_t$
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EXPERIMENTAL SETUP AND DISCRETE ELEMENT MODELING

Equipment and target values

Experimental equipment:
- Stream finishing machine SF1 68
- Alumina media KXMA 16 wetted with water and compound SC15 (grain size 1.7 to 2.4 mm)
- Disc shaped quenched and tempered AlSi 4140 specimen
- Piezo resistive normal force sensors

Stream Finishing of a specimen using KXMA 16
EXPERIMENTAL SETUP AND DISCRETE ELEMENT MODELING

**Processing parameters**

**Constant parameters**
- Radius of immersion \( r = 270 \text{ mm} \)
- Media height of \( 220 \text{ mm} \)

**Varied parameters**
- To evaluate the influence of process parameters a broad parameter range was used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height above the bowl bottom ( z )</td>
<td>75 to 150 mm</td>
</tr>
<tr>
<td>Rotational speed ( n )</td>
<td>30 to 90 U/min</td>
</tr>
<tr>
<td>Angle of immersion ( \phi )</td>
<td>0° to 45°</td>
</tr>
<tr>
<td>Workpiece orientation ( \gamma )</td>
<td>-50° to 50°</td>
</tr>
</tbody>
</table>

**Visualisation of varied parameters**

---

**EXPERIMENTAL SETUP AND DISCRETE ELEMENT MODELING**

**Simulative approach**

- Abstracting trough a linear analogy channel
- Velocity distribution trough discrete path velocities on the ground
- Particle distribution trough gravitational acceleration equivalent normal to the outer wall
- Media modelled by spheres (\( \Phi 2 \text{ mm} \))

- Physical media properties according to dry \( \text{Al}_2\text{O}_3 [7, 8, 9] \)
- 1.25 Mio. particles
- Particles Young’s modulus reduced by factor \( 1 \times 10^3 [10, 11] \)
  
  \[ \text{Downscaling provides comparable particle velocity vectors and flow formation [11]} \]

**Exemplary representation of the simulation model**
AGENDA

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RESULTS

Correlation of simulation and experiments

- Vertically oriented groove direction before stream finishing (after surface grinding)
- Range of $h_{eff}$ is largely in accordance to the experimental determined texture directions
- Good correlation of local texture directions (pos. a, 2, b) between experiment and simulation
RESULTS
Normal Force

Variation of process angles
- Variation of \( \gamma \) or \( \varphi \) to higher/lower values than 0 should always lead to reduced normal force \( F_n \) due to
  - Vector distribution of forces
  - Reduced impoundment effects due to a reduced projected area

Translational velocity in m/s

<table>
<thead>
<tr>
<th>( \gamma )</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.7</td>
</tr>
<tr>
<td>20°</td>
<td>1.275</td>
</tr>
<tr>
<td>45°</td>
<td>1.05</td>
</tr>
<tr>
<td>60°</td>
<td>0.85</td>
</tr>
<tr>
<td>90°</td>
<td>0.425</td>
</tr>
</tbody>
</table>

Shift of stagnation point derived from simulation

Inverse relation between normal force and tangential velocity is expected

Experimentally determined local normal forces depending on \( \gamma \)

RESULTS
Simulation results

Simulative determined normal forces and tangential velocities

- Normal force \( F_n \) and tangential velocity \( v_t \) are inversely influenced by process parameters
  - Increase of \( v_t \) leads to a decrease of \( F_n \)
  - Decrease of \( v_t \) leads to an increase of \( F_n \)

Power equivalent derived from simulation

Introduction of the power equivalent \( P \) is necessary for a holistic process description
RESULTS

Material removal

- 20 min of stream finishing for each parameter
- Stationary roughness state despite of highly varying material removal
- $P/\Delta m$ ratio shows standard deviation of 68%
- Prestons law is therefore not applicable
- Results by Brocker can be confirmed

→ No proportional correlation!

Increase of power equivalent $P$ leads to an increase of material removal $\Delta m$ (qualitatively)

RESULTS

Surface integrity

- Comparison of residual stress $\sigma_{R}^a$ and $P$
- Residual stress measured at position 2
- Evaluation of depth profiles up to 5 µm is reasonable
- Qualitative correlation of $P$ and $\sigma_{R}^a$
- Assumption of Kacarşas et al. can clearly be confirmed

Increase of power equivalent $P$ leads to an increase of compressive residual stress
AGENDA

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CONCLUSION AND OUTLOOK

Key findings
- Local consideration of normal force and tangential velocity is mandatory
- Process efficiency can be effectively be influenced by the
  - Angle of immersion $\varphi$
  - Workpiece orientation $\gamma$
- Power equivalent $P$ is a valid qualitative measure for $\Delta m$ and $\sigma^{s5}$

Outlook
- Improve computational approach to gain quantitative normal force values
- Validate findings using a complex geometry

Simulated flow directions
Exemplary representation of the simulation model
Thank you for your kind attention!

REFERENCES


