Final Report

Project name: Effective remanufacturing of hot forging dies - ÅterSmide.

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Abstract

Analysis of tool wear after hot forging

When hot forging components, wear can occur in the tool after a period of use, leading to incorrect geometry in the final component. This necessitates replacing the worn tool with a new one, which is costly. The current approach is to repair the tool using machining that removes the worn surface which is less efficient from a circularity standpoint. A more sustainable approach is to maximize the tool life by carefully adjusting the material and process parameters to slow the wearing process and repair without removing material as much as the cost is justified. Factors such as sliding distance, normal forces between the billet and forging tool, and the hardness of the tool all influence wear during forging. This study focuses on analytics of the process using measurements of the tool conditions and wear simulation based on Archard's law. The tool was analysed using stress, geometry, and hardness measurements. Several strategies to maintain or increase hardness, thereby extending tool life, are proposed. These include adjusting heat treatment before forging, modifying machining parameters, extending cooling time during hot forging, and replacing the current coolant with a more effective one.

Key words: Forging tools, Hammer forging, Wear, FE simulation, Archards Law

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Content

Preface

This publication describes the research carried out in the FFI project "Effective Remanufacturing of Forging Tools – Reforging" (Vinnova, ref. no. 2023-02618). The investigation was carried out in collaboration between Forgex, RISE, KTH and Dibo.

Forgex contributed with a forging tool for hammerforging of an automotive component and also contributed with forging tests. Forgex also contributed with measurement of hardness and simulation of forging. RISE contributed with measurements of hardness, residual stresses, geometry and surface topography. KTH contributed with development of simulation models based on Archards equation. Dibo contributed with knowledge concerning machining and heat treatment.

The authors thank Vinnova for their support and funding of the project.

1 Introduction

When hot forging components, wear may occur in the engraving of the tool after a period of use. This can lead to incorrect geometry of the final component and thereby a need to replace the worn tool with a new tool. This is costly and less efficient in terms of circularity and a better approach is to reuse the existing tool and repair the engraving. One repair method is to re-mill the engraving and make a new countersink. After renewed wear, the repair can then be repeated several times, allowing the tool to be reused in several life cycles.

Wear is the most influential damage mechanism for hot forging tools compared to other damage mechanisms like mechanical cracking, thermal cracking and plastic deformation [1] and this study investigates possibilities for reduction of abrasive wear and thereby extending life in hot forging tools. The analysis was carried out using an industrial test case where the reason for wear was analyzed with support from measurements of residual stress, hardness and geometry before and after forging as well as FE simulation of the tool temperature during the forging process. A simulation model for prediction of abrasive wear based on Archard's law [2,3] was developed and tested.

Section 2 presents the industrial test case and section 3 describes the results from measurements and simulations. Section 4 presents a model for simulation of wear using Archard's equation, and section 5 conclude the investigation and recommend future research.

2 Industrial test case

This study was done using a forging tool for hot forging of a component to the automotive industry, see Fig 1. The tool was manufactured by Uddeholm and the material was Orvar 2M. The tool was machined by Forgex to the correct geometry in the engraving using milling, see Fig 1 and 2.

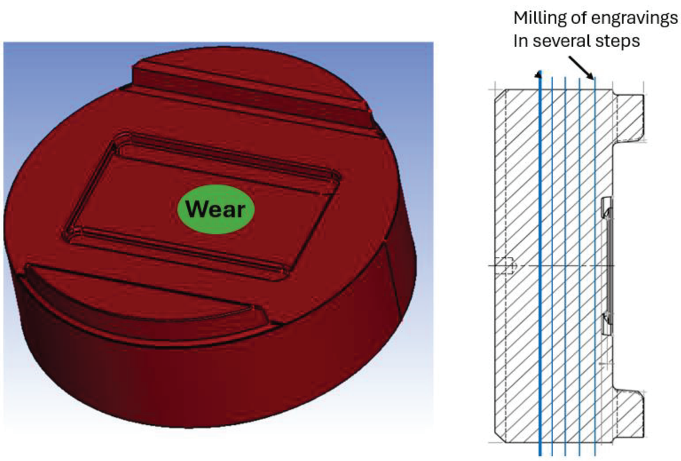

Figure 1 Hot forging tool and repair of engravings in several steps

Before use the tool was heat treated and tempered 2 times to 620°C by a local sub supplier of heat treatment.

Figure 2. Tool with milled engraving

A billet was forged into a component using 3 strokes with a 13-ton counter-forging hammer. The billet material was a precipitation hardening steel V2906 and the billet was heated to 1150°C before forging. The initial tool temperature before forging was 200°C.

During the forging sequence, the tool temperature increased and after the third stroke, the operator sprayed water-based saline solution at the engraving during a short period of time in order to lubricate and cool down the engraving to 200°C.

After forging of 2200 components, geometric irregularities in the shape of pits at the center of the engraving were detected, see Fig 3. This caused out of tolerance geometry failures on the component thickness and the tool had to be repaired.

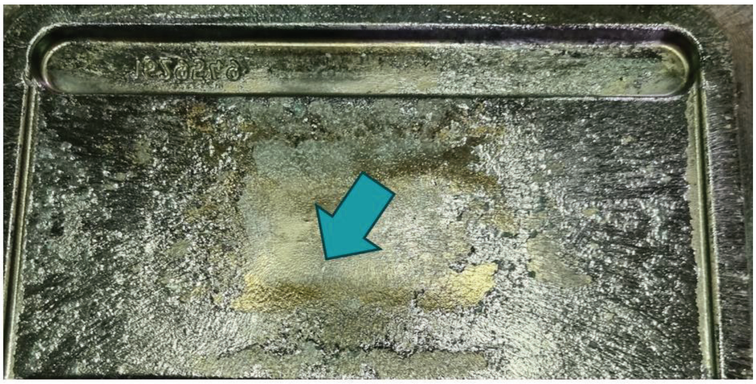

Figure 3. Wear in tool with pits and irregularities in the middle of the engraving

The experimental actions were performed according to below.

1. RISE measured residual stress, geometry and surface topography on a new tool. The hardness of the tool was measured by Forgex to 410 HB.
2. Forgex then forged 2200 components and RISE once again measured residual stress, geometry and hardness on the used tool. RISE also measured geometry and deformations on 6 forged parts no. 100, 1000, 1500, 2000, 2100, 2200.
3. Forgex then repaired the tool by milling the engraving to a depth of 7.5 mm and then measured the hardness of the repaired tool.

4. Forgex then forged another 1000 components and measured the hardness of the worn tool.
5. Forgex repaired the tool again and milled down the engraving 7.5 mm and measured the hardness of the repaired tool.
6. Forgex then forged another 2200 components and then measured the hardness of the worn-out tool.

Table 1 Measurements on different conditions on tool.

Condition of tool	Tool Hardness	Res. Stress on tool	Geom	Tool Topogr.	Tool Temp
1. New Tool	Forgex	RISE	Tool geom RISE	RISE	Forgex
2. After forging of 2200 components	RISE	RISE	Comp geom RISE	-	-
3. After first repair	Forgex	-	-	-	-
4. After forging of 1000 more components	Forgex	-	-	-	-
5. After second repair	Forgex	-	-	-	-
6. After forging of 2200 more components	Forgex	-	-	-	-
7. After third repair	Forgex	-	-	-	-

3 Measurements and simulations

3.1 Residual stress

RISE measured the residual stress profile on a new tool and surface residual stresses on both a new tool and a used tool after forging of 2200 components. The measurements were performed using a XStress Robot equipment.

The residual stress profile measurement showed high tensile surface stresses followed by compressive balancing stresses that decreased to almost zero 0.5 mm below surface, see Fig 4. The high surface tensile residual stresses are most likely introduced during milling of the engraving while the bulk material appear to be stress-free.

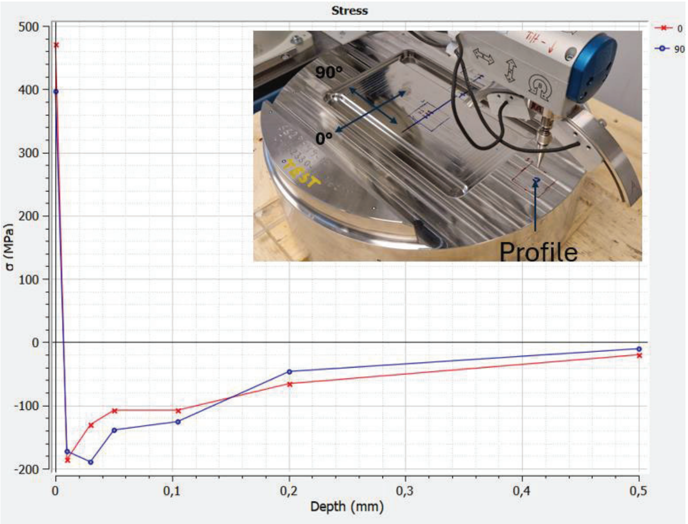

Figure 4 Residual stress profile with high tensile stresses at the surface and low stresses at 0.5 mm depth.

Also, the surface residual stresses measurements showed high tensile surface stresses at several positions, see Fig 5.

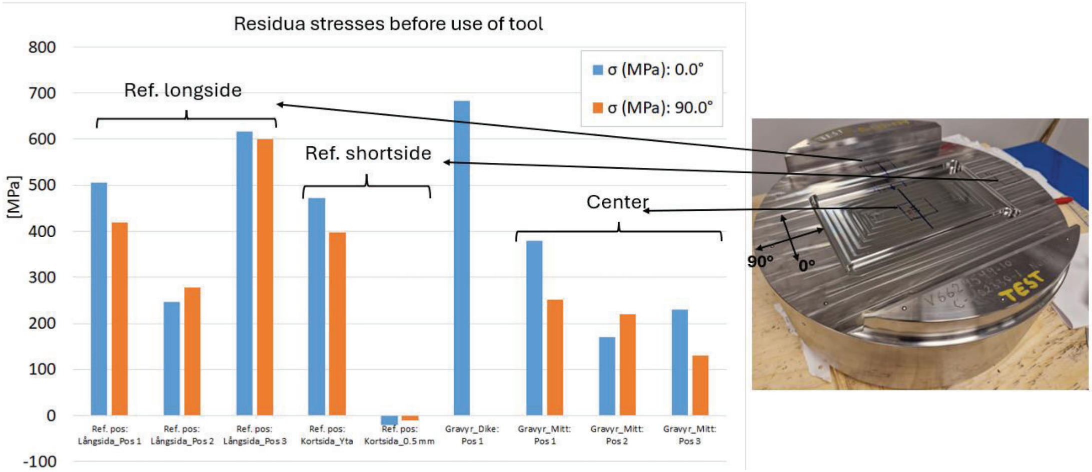

Figure 5 Surface residual stresses at a new tool

The variation in tensile surface stresses may be due to the fact that different machining parameters were used in different parts of the engraving. This was also confirmed by the measurement of surface topography on the engraving that varied according to Fig 6. The measurement of surface topography was carried out by RISE using a SensoFar Neox S equipment. These results show a great variation in surface roughness and texture appearance for the three measured positions on the tool.

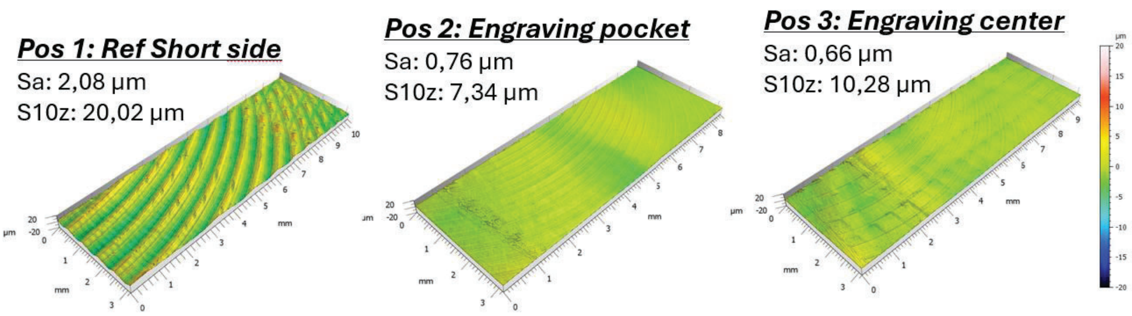

Figure 6 Surface topography on a new tool

RISE measured surface residual stresses after forging of 2200 components at the same positions that was measured before the use of the tool according to Fig 7. The tool was blasted, and the measuring positions were electropolished 0.15 mm before measurements.

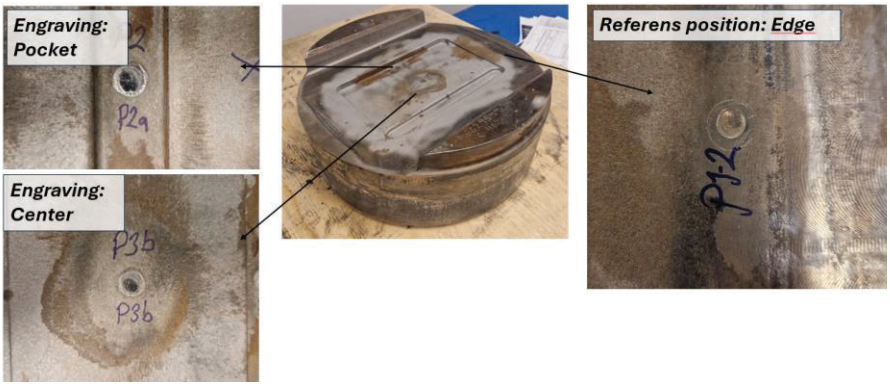

Figure 7 Residual stress measurements on the engraving and at reference position

A comparison of surface residual stresses before and after use is presented in Fig 8.

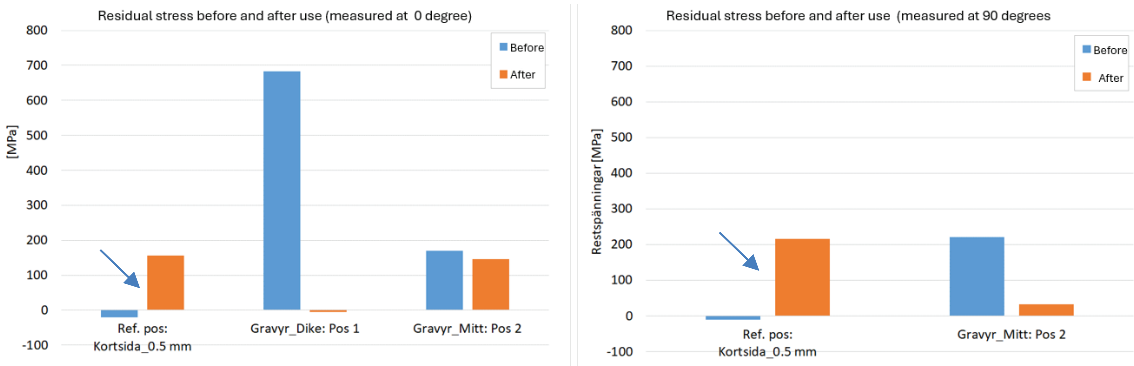

Figure 8 Comparison of residual stresses before and after use, i.e. after forging of 2200 parts

The high tensile surface stresses at the pocket and at the center before use may be a result of machining as described in Fig 4-6.

The comparison before and after use shows that the tensile stresses have decreased significantly for the pocket and marginally for the center position.

The reference position shows increased tensile stresses after use which can be a result from thermal load during use.

3.2 Hardness

The hardness measurements were made both by RISE and Forgex at the center of the engraving, see table 1. RISE used a portable Ernst equipment and Forgex used a portable EQUOTIP equipment. Measurements indicated hardness decline after forging of first 2200 components. The hardness increased after first repair and then maintained stable after forging of another 1000 components. Hardness then declined again after forging of another 22000 components, see Table 2.

Table 2 Measurement of hardness in Brinell (HB)

Condition of tool	HB Center
1. New Tool	410
2. After forging of 2200 components	364
3. After first repair of tool	410
4. After forging of 1000 more components	404
5. After second repair of tool	420
6. Forging of 2200 more components	340
7. After third repair of tool	420

The hardness on a repaired tool and after forging of 1000 and 2200 components are illustrated in Fig 9 below (step 3, 4 and 6). The hardness was reduced by 19 % after forging of 2200 components (step 5 and 6).

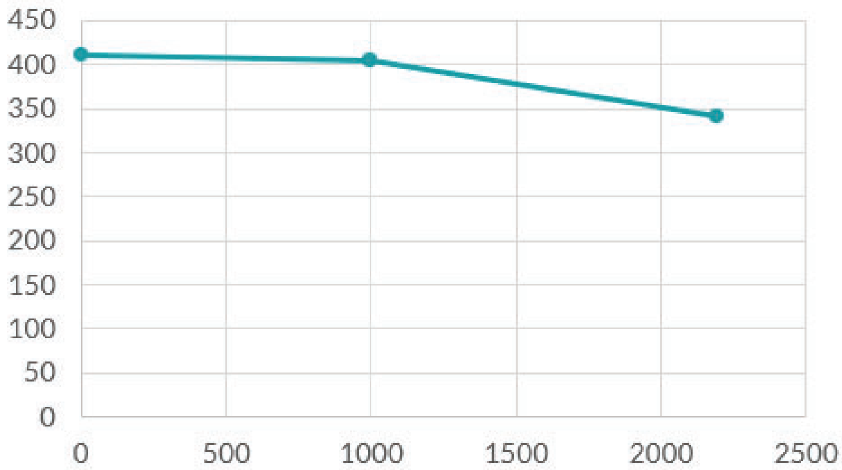

Figure 9 Hardness in Brinell on a repaired tool (step 3) and after forging of 1000 and 2200 components (step 4 and 6).

3.3 Geometry

RISE measured geometry deviations from CAD at the engraving on a new tool and a worn tool after forging of 2200 components. RISE also measured geometry deviations from CAD at component no. 600, 1000, 1500, 2000 and 2200, see Fig 9. The measurements were performed using an optical non-contact 3D scanning at RISE (GOM).

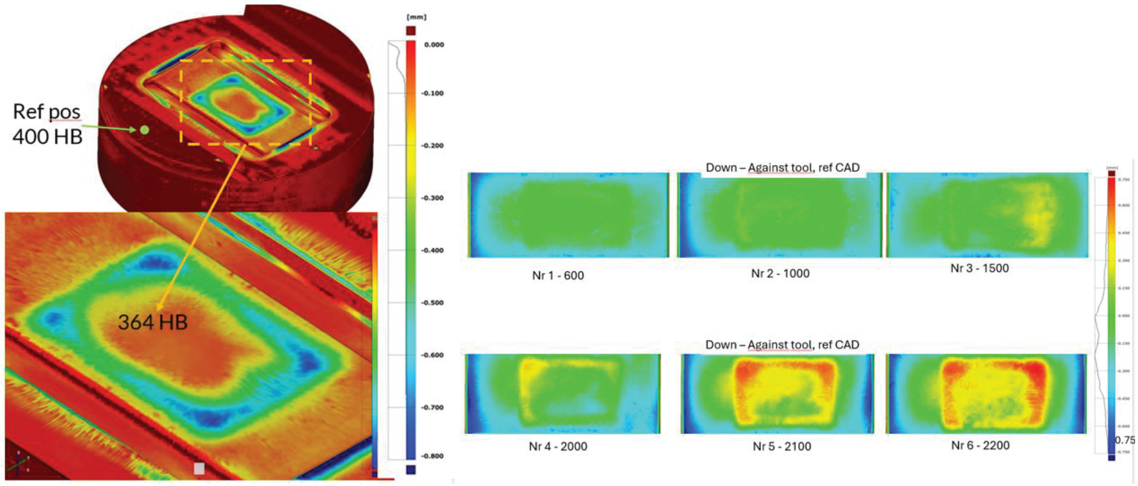

Figure 10 Measurement of geometry and hardness on tool and on the top side of components

The depths of the pits around the center of the used tool were approximately the same as the geometric changes on forged parts after forging of 2200 parts, i.e. a maximum of 0.75 mm (red color at component and blue color at the tool).

The thickness deviations between CAD-model (step 0) and component no 600, 1000, 1500, 2000 and 2200 are illustrated in Fig 11 below. The thickness change was initial small and accelerated after forging 1500 components.

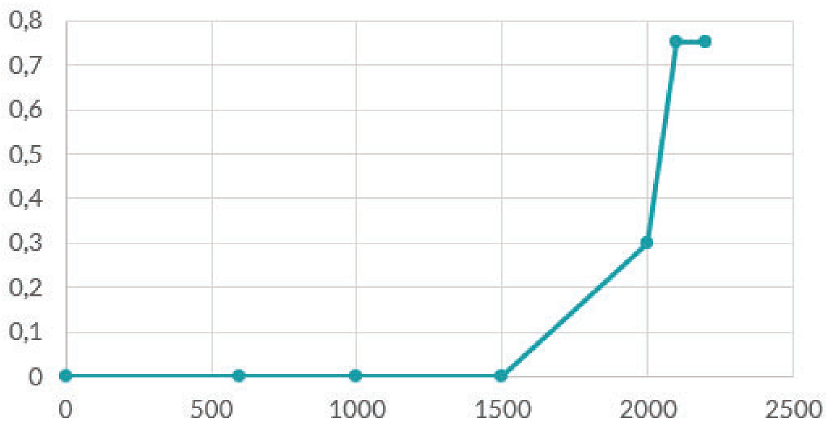

Figure 11 Thickness deviations between CAD-model and component no 600, 1000, 1500, 2000 and 2200

3.4 Temperature

The assessment of temperature was made using forging simulation in QForm which was carried out by Forgex, see Fig 12. The simulation indicated that the temperature at the engraving of the tool varied from 500 after the first stroke to 650 C after the third stroke. The high temperature in the engraving may cause a risk for unintentional tempering, especially if this temperature span is maintained for too long. Also, the hardness decreased after forging of 2200 components and indicated that a tempering had occurred. In order to improve the accuracy of the simulated temperatures, it is recommended in the future to complement simulation with measurements using a calibrated IR camera combined with e.g. a built-in measurement sensor in the engraving.

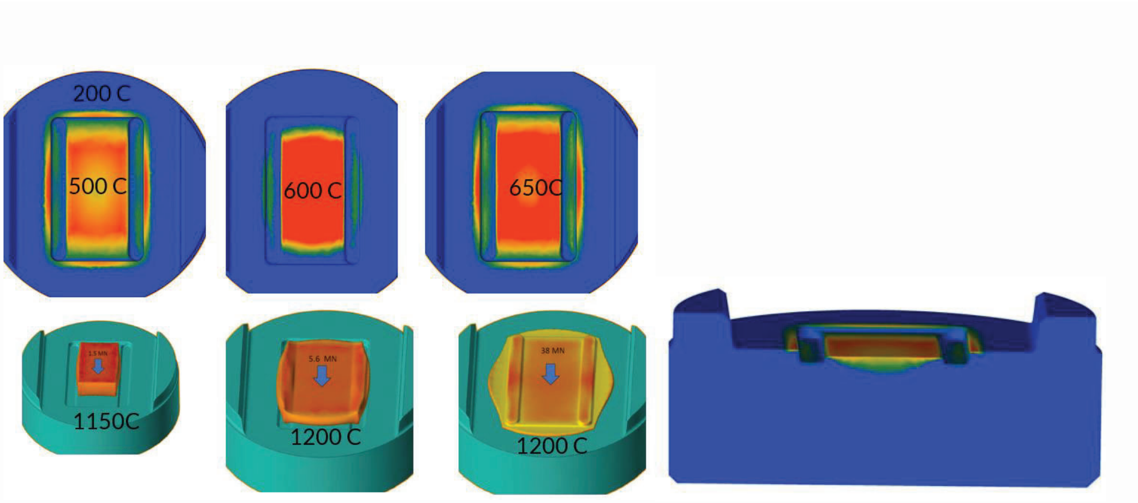

Figure 12 Surface- and cross section temperature in the tool after stroke 1 to 3

4 Archards Law

The simulation of wear and damage to forging tools was carried out using Archard's law of abrasion. The aim was to analyze and predict the wear behavior of the tools, which can help to assess the tool's lifetime and maintenance intervals.

Archard's equation describes abrasion in sliding and shear contact between surfaces. The equation gives a proportional relationship between the volume of material that wears away, the normal force and the sliding distance that surfaces move relative to each other. It is formulated acc. to equation below

$Q = KWL/H$

where

Q = Volume of material worn away
K = dimensionless coefficient of abrasion
W= Normal force between surfaces
L= Sliding distance between the forged blank and the tool engraving in the wear area
H= hardness of the wear area of the forging tool.

The equation shows that the wear is proportional to the normal force and the sliding distance and inversely proportional to the hardness. The FE simulation was performed using Ansys LS-Dyna.

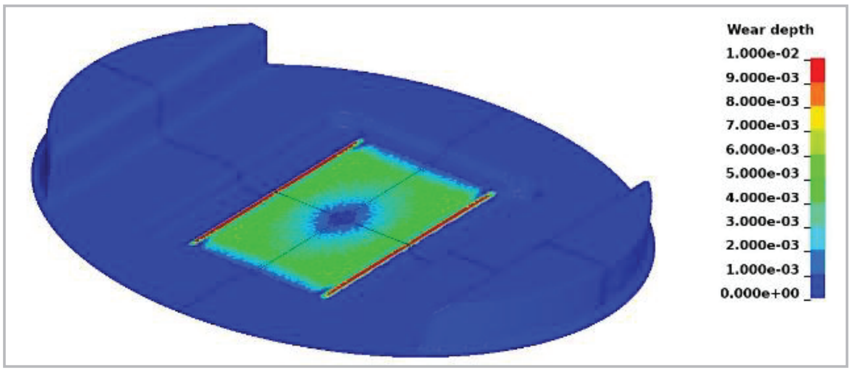

Figure 13 Wear depth calculated using Archard's law

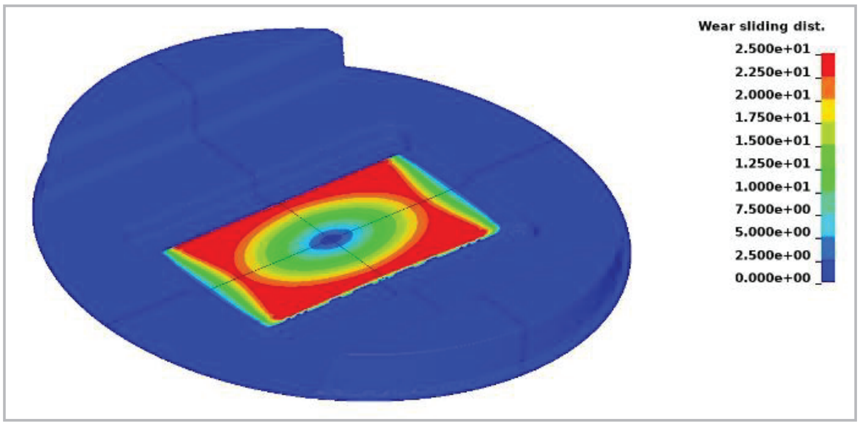

Figure 14 Accumulated slip length in contact interfaces step 2

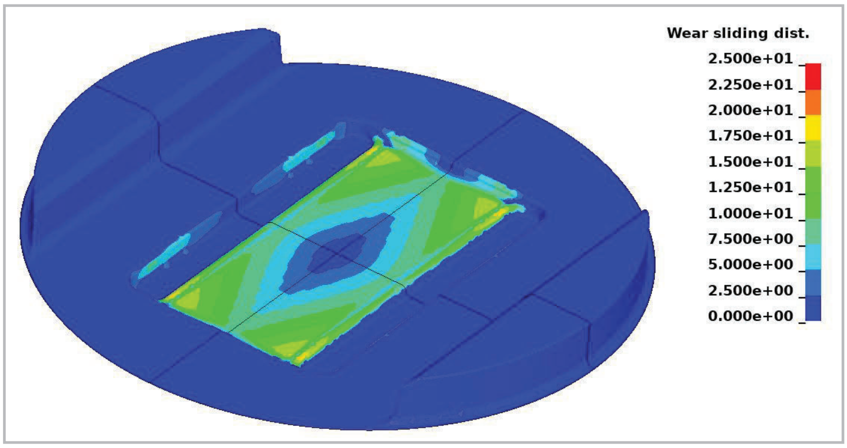

Figure 15 Accumulated slip length in contact interfaces step 3.

The simulation with Archard's law and used material model provides a basic understanding of wear mechanisms in forging tools. To improve accuracy and predictability, it may be beneficial to explore and implement alternative abrasion models depending on specific forging conditions and material selections.

In addition, in order to properly evaluate the effects of abrasion with Archard's law, the coefficient of the material combination in question and the surface condition (such as surface roughness) must be determined. Additional factors that can be considered include strain rate dependence, the proportion of work that is converted into heat and thus affects material behavior, and more.

This combination of models can lead to optimized tool designs and increased service life for forging tools.

For the material behavior of the forging element during the forging process, the Johnson-Cook (J-C) material model of the blank is used.

The J-C model is particularly useful at high deformations and temperatures, common in forgings and is described by the equation below:

$$\sigma = (A + B \cdot \varepsilon^n)(1 + C \cdot \ln \dot{\varepsilon})\left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right)$$

where

s	The current yield stress
E	The plastic elongation
$\dot{\varepsilon}$	The elongation rate
Tm, T_0, T	Melting temperature, reference temperature (room temp) and current temperature
A, *B*, C, n and m	Material constants.

This model takes into account both physical and thermal properties of the material, providing a more realistic simulation of the forging process. The value of the parameters of the J-C equation, namely A, B, C, n and m, for the subject material was determined using optimization. The input for this was taken from a previous process simulation performed by Forgex in QForm.

The material behavior of the tool was modeled with a simpler bilinear material model. The bilinear material model simulates the constitutive relationship between stress and strain for elastic-plastic material. This can be further improved by using the Johnson-Cook (J-C) model, provided that sufficient material data is available or created through experimental samples. It would allow for a more accurate representation of the tooling material's behavior under high temperatures and strain rates. It would also require the dependence of hardness on temperature and plastic deformation, as well as the impact of the strain rate on material behavior

The simulation used Archard's law, which describes the volume of material removed by abrasion. The built-in Archard model in LS-DYNA was used via a script as part of the contact definition between the subject and the tool.

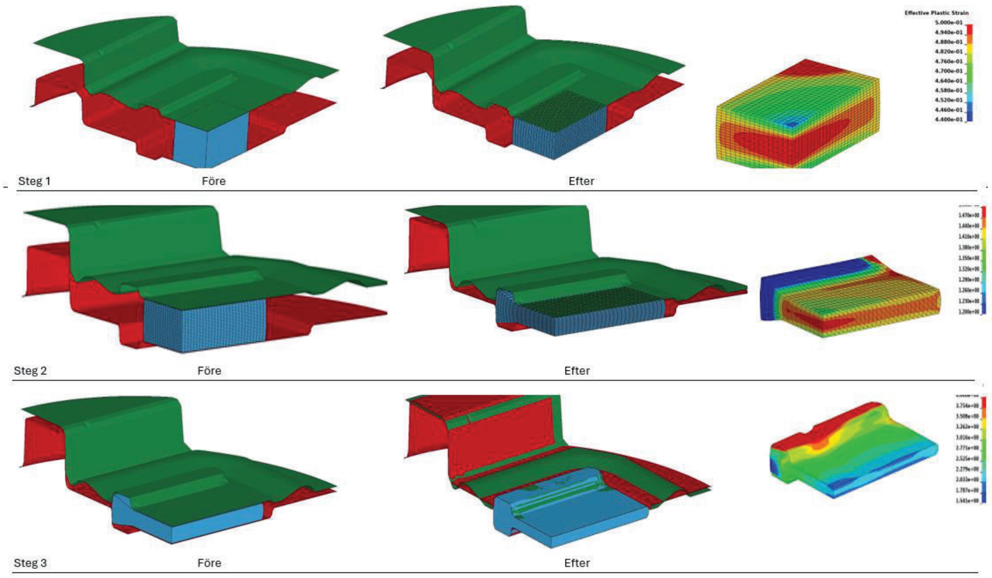

Figure 16 Changes in each step (stroke) were simulated separately

5 Conclusions

According to Archards law the sliding distance, normal forces and the hardness in the engraving will influence abrasive wear in forging tools. This study has investigated possibilities to adjust the hardness according to below.

Modify heat treatment before forging: Before use the tool was heat treated to 1020 C and then tempered twice to 620 C. The possibility to increase the hardness by modifying the heat treatment process parameters for tempering should be further investigated.

Modify milling of the engraving: High tensile surface residual stresses after milling indicate plastic deformation and possible work hardening [4]. Further investigations how machining parameters may influence hardness are recommended. Aso further investigations concerning hardness and bulk stresses in the tool is recommended using tools like the Contour method [5] etc.

Modifying cooling after forging: The hardness measurements indicated that tool hardness declined in the engraving after hot forging of 2200 components. This indicated that tempering had occurred during the forging. Further investigations regarding extension of the cooling time as well as tests with a more efficient coolant are recommended. It is recommended to complement simulation of temperature with measurements using a calibrated IR camera combined with e.g. a built-in measurement sensor in the engraving.

Archards law: Further development of the FE model for wear according Archards law is recommended. Also, possibilities to adjust normal forces and sliding distance should be investigated with support from simulation and Archards law.

The study is summarized in Fig 17 below:

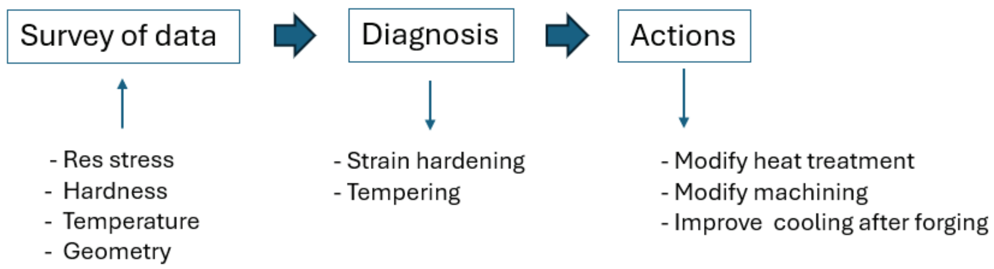

Figure 17 Methodology for analysis of wear at a hot forging tool

6 References

1. Emamverdian, Sun, Cao, Pruncu, Y Wang, *Current failure mechanisms and treatment methods of hot forging tools dies – a review,* Engineering Failure Analysis 129 (2021) 105678, https://doi.org/10.1016/j.engfailanal.2021.105678
2. Archard, Hirst, *The wear of metals under unlubricated conditions* Proceedings of the Royal Society 1956, https://doi.org/10.1098/rspa.1956.0144
3. Hanief, Charoo, *Archard's wear law revisited to measure accurate wear coefficient considering actual sliding velocity,* Materials Today: Proceedings 47 (2021) 5598–5600, https://doi.org/10.1016/j.matpr.2021.03.475
4. Thakur, Ramamoorthy, Vijayaraghavan, *Effect of cutting parameters on the degree of work hardening and tool life during high-speed machining of Inconel 718,* Int J Adv Manuf Technol (2012) 59:483–489,
DOI 10.1007/s00170-011-3529-6
5. Werke, Wretland, Ottosson, Holmberg, Machens, Semere, *Geometric distortion analysis using a combination of the contour method and machining simulation*, 51st CIRP conference of Manufacturing Systems, 2018 Stockholm

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