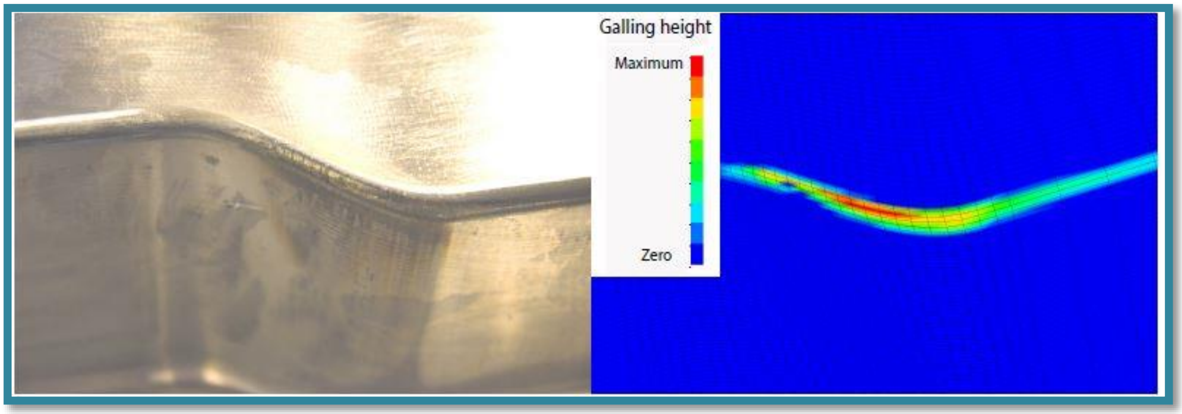
Prediction of die conditions in press hardening

Public report



Project within sustainable production
Author Mats Oldenburg, Liang Deng, Peter Ottosson, Johan Berglund, Kenneth Kjellsson, Mats Sigvant, Greger Bergman
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FFI Fordonsstrategisk Forskning och Innovation

Content

1. Summary

In this project a full-scale press hardening experiment has been established. A thermo-mechanical model for finite element simulations of the press hardening experiment has been established. This experiment and the simulation results provide a deep understanding of the contact conditions occurring in the stamping, which serves as a base to design a test programme for a laboratory test. The dedicated laboratory test, a high-temperature tribometer test, has been developed based on a previous study. This test aims to reproduce the press hardening conditions in laboratory environments. A pair of pins with flat surface is implemented in the test, which enable quantitative galling measurement. The tribological behaviour under the press hardening conditions has been analysed. Based on the galling measurements, a modified Archard model predicting the material built up has been proposed and implemented as a user-defined model in a commercial finite element (FE) program. The galling simulations have been validated by the full-scale press hardening experiment.

Two methods for monitoring product geometry and die conditions have been evaluated. A measurement system of the type Helix H0800 from Perceptron have been evaluated at Gestamp HardTech. Measurements of a number of pre-defined points during press hardening production were successful. However, the limitation with respect to maximum measurement distance of the selected system means that it cannot be mounted close enough to the press. If the system is to be used in future applications the sensor must most likely be mounted in a location after the press.

Optical 3D scanning has been used to determine whether it is possible to detect and quantify adhesive wear in production tooling by means of scanning. By this the capabilities of the equipment and the method to measure the adhesive wear after a production run was clearly demonstrated. The obtained measurements are determined to be both qualitatively and quantitatively satisfactory.

In-situ draw-in measurements by following the blank edge during the process have been performed. The equipment used proved to be able to trace the edge despite the harsh measurement conditions. Between the evaluated forming cycles there were relatively large changes in draw in as well as starting positions. The results of this study do not support the hypothesis that that the draw in is affected by the increasing amount of adhered material on the tools. However, they do not falsify it either. Rather, the results indicate that there are other factors contributing to the changes in draw in at least as much as the galling.

FE modelling is attempted in order to numerically study the influencing parameters from wear on the impact on the blank draw-in during hot forming. At first a morphological modelling concept is used followed by an approach using results from scanning of physical tools with actual adhesive wear.

A PVD coated tool has been evaluated at Volvo Cars. Results after production indicate adhesion of AlSi. A nitrided tool will be evaluated at Gestamp HardTech.

2. Sammanfattning på svenska

I detta projekt har ett fullskaligt presshärdningsexperiment utvecklats. En termo-mekanisk modell för finita elementsimuleringar av presshärdningsexperimentet har etablerats. Experimentet och simuleringsresultaten ger en djup förståelse för de kontaktförhållanden som uppstår vid presshärdning och utgör en bas för att designa ett testprogram för ett laboratorietest. Den utvecklade utrustningen för laboratorietester är en tribometer för studier av högtemperaturtribologi som har utvecklats i tidigare projekt. Detta test syftar till att reproducera presshärdningsförhållandena i laboratoriemiljö. Verktygsmaterialet representeras av ett par platta stift med en rundad framkant och möjliggör kvantitativ mätning av påkletning på verktygen från den Al-Si-baserade beläggningen på den formade plåten. Det tribologiska beteendet under presshärdningsförhållandena har analyserats. Baserat på mätningarna av påkletning har en modifierad Archard-modell som förutsäger materialuppbyggnaden tagits fram och implementerats som en användardefinierad modell i ett kommersiellt finita elementprogram. Simuleringarna av påkletningen på verktygen har validerats baserat på resultaten från det fullskaliga presshärdningsexperimentet.

Två olika metoder för mätning av produktgeometri och verktygstillstånd har utvärderats. Vid Gestamp HardTech har ett mätsystem av typen Helix H0800 från Perceptron utvärderats. Försök med att mäta några fördefinerade punkter på presshärdade komponenter visar att det är möjligt att mäta direkt i produktionsflödet. Det valda systemet har dock en begränsning vad gäller maximalt mätavstånd vilket innebär att mätning i direkt anslutning till en press inte är möjlig.
Mätning av plåtindrag hos Volvo Cars har genomförts av Swerea IVF. Studiens syfte var att undersöka om en skillnad i plåtindrag kunde detekteras mellan början och slutet av en produktionsserie och i sådana fall koppla detta till de påkletningar som uppkom under samma tid. Plåtindraget mättes med en lasersensor och påkletningarna i verktyget mättes med optisk 3d-skanning. Någon trend gällande förändring av indrag kunde inte hittas.
Vid ett antal tillfällen har verktyg 3D-skannats efter en produktionsperiod. Båda verktygshalvorna skannades, varefter de rengjordes från skräp och påkletat material och slutligen skannades de en gång till. De två resulterande datamängderna före och efter rengöring lades sedan samman och de geometriska avvikelserna kunde analyseras. Därmed har utrustningens förmåga och metodens lämplighet för att mäta slitage efter en produktionsperiod säkerställts. De erhållna mätningarna är både kvalitativt och kvantitativt tillfredsställande.
En morfologisk modellering har provats för att studera vilka parametrar som har störst inverkan på plåtens indrag till följd av slitage. Detta ledde till fortsatt arbete med FE-simulering baserat på ett riktigt skannat verktyg som utsatts för slitage. För att använda resultat från scanning på ett robust sätt vid simulering behöver man bearbeta dessa data och

renodla modellen. Dessutom behöver man metoder för att använda delmodeller för att få hanterbara beräkningstider.

Ett PVD-belagt verktyg har utvärderats hos Volvo Cars. Resultatet visar på påkletning. Ett nitrerat verktyg kommer att utvärderas hos Gestamp HardTech.

3. Background

Press hardening, a special type of thermo-mechanical forming process invented in northern Sweden in 1970s, is a technique for producing ultra-high strength steel (UHSS) components through simultaneous forming and hardening of the steel sheet material. This process technique takes advantage of the excellent formability of the hot steel during the forming process and shows negligible springback of the formed part after the quenching process. Nowadays, press hardening with Al-Si coated workpieces are commonly used in automobile industries. However, tool wear is an inevitable problem in mass production. The tool wear in the press hardening processes, especially severe galling, not only decreases the production quality but also increases the maintenance cost. Since the cost of press hardening experiment is expensive, a laboratory test reproducing the press hardening conditions is necessary. Based on the previous work, a high-temperature reciprocating test has been used. However, the set-up of this test involves a boron steel pin sliding in the same wear track in the tool steel disc, which is very different to the sliding process in the press hardening. A dedicated test from a previous project that mimics the press hardening condition was further developed in the present project. Furthermore, quantitative measurement of the galling is an important requirement in the test, which can be used to calibrate the coefficient in an Archard model so as to predict when and where the galling occurs in industrial applications.

4. Purpose, research questions and method

This research aims at developing a predictive tool of wear and galling for the press hardening in order to answer the question: when and where the galling occurs. After achieving the aim, researchers can use the wear modelling to enhance the performance and quality of the produced parts and to reduce the maintenance cost through prolonging the tool life by the use modern surface modification technologies. This research has been performed based on previous knowledge of tribology and numerical modelling. The main methods of the present research include:

1. Perform a full-scale experiment of the press hardening processes, which include a typical geometry of press hardened parts.

2. Study the tribological behavior in the tool-workpiece pairs with Al-Si coated boron steels.
3. Develop a predictive model for the tool wear (galling) of the press hardening based on the tribological results.
4. Validate the predictive model by the full-scale press hardening experiment.
5. Establish methods for monitoring product geometry and die conditions.
6. Evaluate tool enhancements/coatings for optimal performance in press hardening of Al-Si coated boron steel.

5. Objective

This research is aimed to enable multiphysics-based process modelling of thermal mechanical sheet metal forming that accounts for tool wear as well as material transfer from blanks to tools, i.e. galling. The application of Al-Si coating on the boron sheet steel and the consequence concerning tool wear and galling in the forming process are of special interest and have been focused during this project. This project needs to establish and develop a model based on simulative wear tests to predict tool wear/galling to evaluate the tool life. This modelling can eventually lead to better competitiveness for Swedish industries, including those of material suppliers as well as component manufacturers and end users in the automotive industry, working with thermo-mechanical sheet metal forming technologies.

6. Results and deliverables

6.1 Modelling of tool wear

The galling development at the interface between workpieces and stamping tool steel is evaluated by means of the high-temperature tribometer test. Based on the analysis of the tribological behaviour of the laboratory test, the main wear mechanism has been identified in the press hardening conditions. At the temperature between 750 °C and 600 °C, the main wear mechanism is adhesive wear with severe galling accumulation. At 500 °C, the galling is negligible and abrasive wear is the predominant wear mechanism. Figure 1 presents galling growth rates in this tribological test. Here the galling growth rate is defined as:

$$\mathrm{g} = \frac{V}{Fs}$$

where g is the galling growth rate in $[\frac{m^3}{Nm}]$, V is the galling volume in $[m^3]$, F is the normal load in $[N]$ and s is the sliding distance in $[m]$.

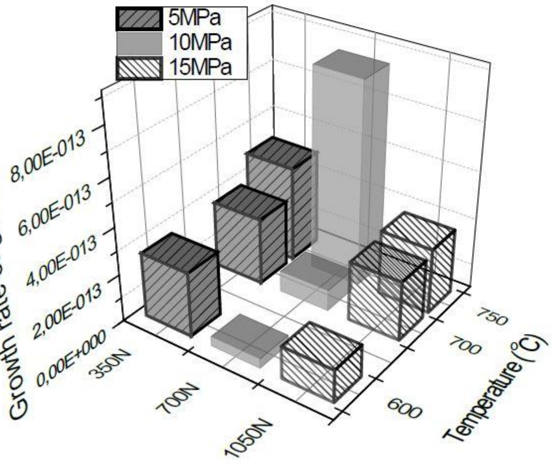

Figure 1. Galling growth rates in the tribological test.

The analysis of the tribological behaviour concluded that the galling growth rate increased with increasing test temperature. At the test with 10 MPa, the transferred layer on the specimen was compacted and became a load bearing surface. The growth rate of galling is used to calibrate the Archard wear model. The physical meaning of the growth rate of galling in the model is the possibility of the wear particle generation and consequent adhering on the tool steel. The tribological study of the present test deepens the understanding of the galling evolution during the extended sliding process.

The galling result of the high-temperature tribometer test is used to calibrate the galling rate in the Archard wear model. The galling model based on the modified Archard wear model is implemented for the full-scale press hardening experiment. The measured galling result in the stamping tool is compared with predicted galling in the FE simulations. The galling simulation precisely predicts the severe galling positions in the stamping tool, as seen in Figure 2. The galling simulation can be used by press hardening part manufacturers to estimate the tool maintenance interval and to optimize the process parameters.

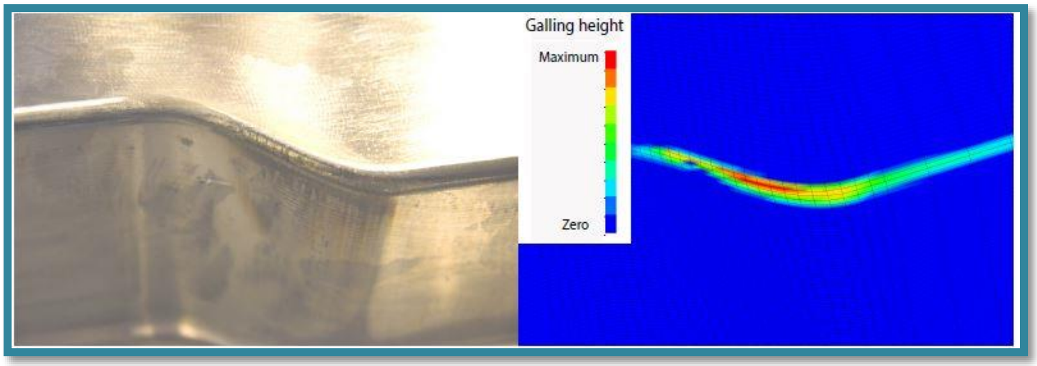

Figure 2. Comparison of the measured and predicted galling in the stamping tool.

The evolution of galling profiles during the continued strokes is related to the varying contact conditions during the forming process, which is different to the constant conditions in the high-temperature tribometer test. The discrepancy between the measured and calculated galling profiles may be attributed to the effect of loose wear particles at the tool-workpiece interface during the continued strokes, which is not taken into account by the present galling simulation.

6.2 In-line measurements of product geometry at HardTech

The aim is to develop a method to measure the geometry of all details in-line after the press hardening and to predict when parts will be out of tolerance and/or when the tool needs maintenance.

An equipment for geometry measurements was rented for six months from the company Perceptron. The system was of the type Helix H0800. The equipment was mounted in the research line at Gestamp HardTech Luleå and positioned according to Figure 3.

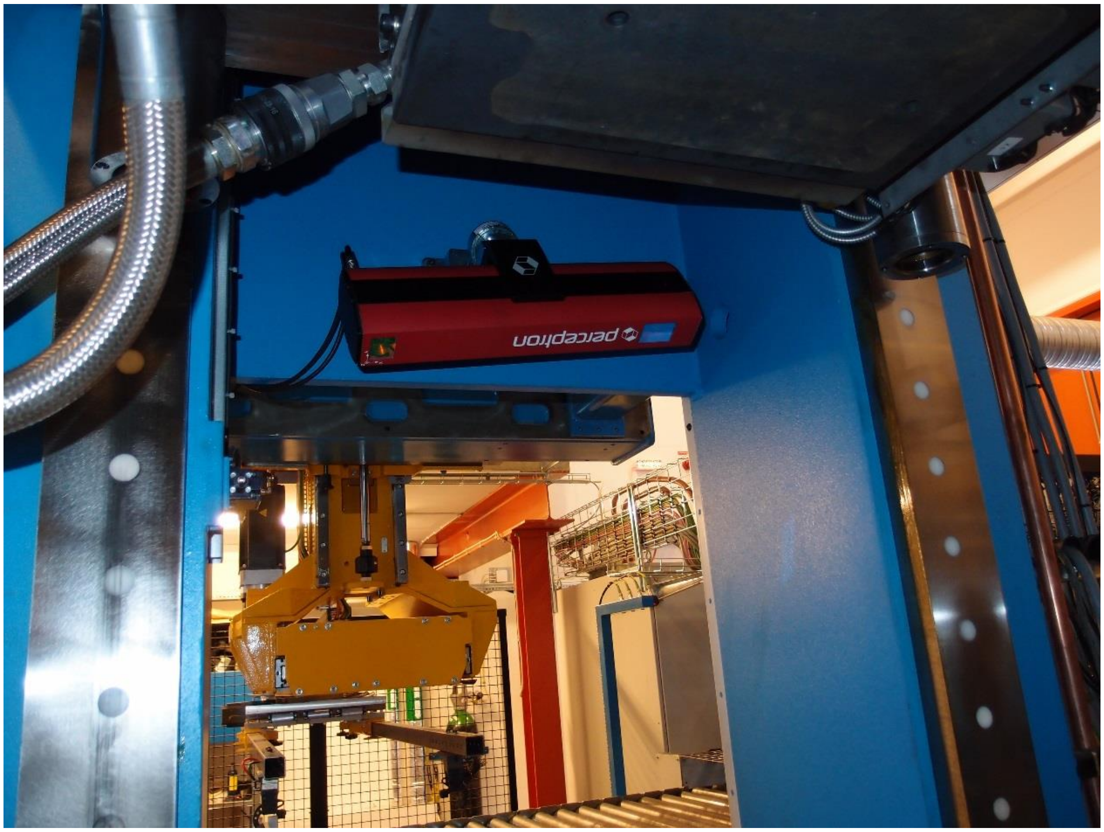

Figure 3. The sensor mounted in the press.

The system was evaluated during production of some prototype parts in the research line. The system was set to measure and evaluate a pre-defined number of points on the trim line of the product. In the first set of tests a flat blank was measured when positioned in the tool. This was only done to evaluate the accuracy and repeatability of the system. A picture of the flat blank positioned in the tool with the measurement points is shown in Figure 4. The repeatability was acceptable, less than ±0.1 mm for each measured point. The measurement time is also a factor that was evaluated and for the set up with the flat blank each point took approximately 0.4 s to measure. The produced product and the points that were measured are shown in Figure 5. To test the possibility to measure all the points during production, three parts were produced with approximately 10 seconds interval between each part. The test showed that all the points could be measured with sufficient accuracy within the cycle time of the press. The sensor was then moved to the other side of the press to do more tests but there were some limitations in the possibilities to mount the sensor in a location so that the tool was within the sensor maximum measurement distance.

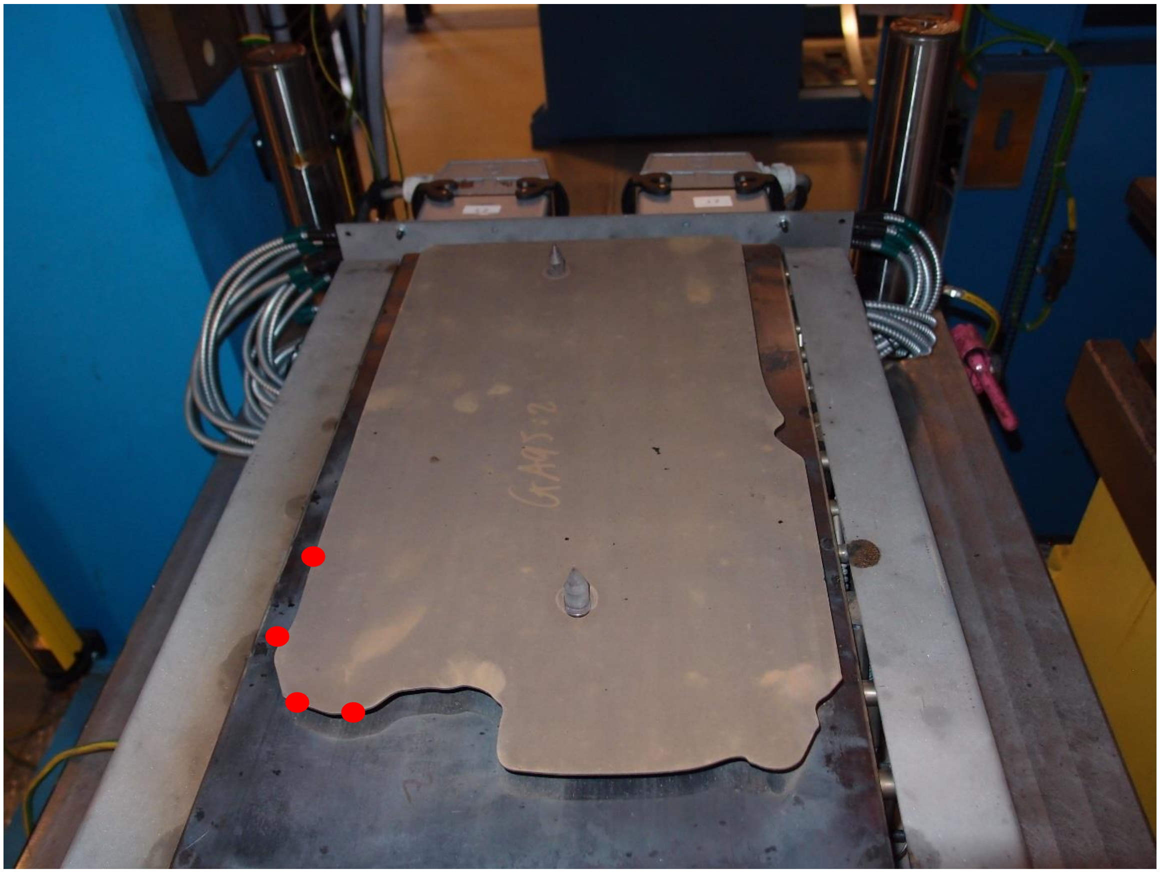

Figure 4. Flat blank for initial tests. Measured points marked with red dots.

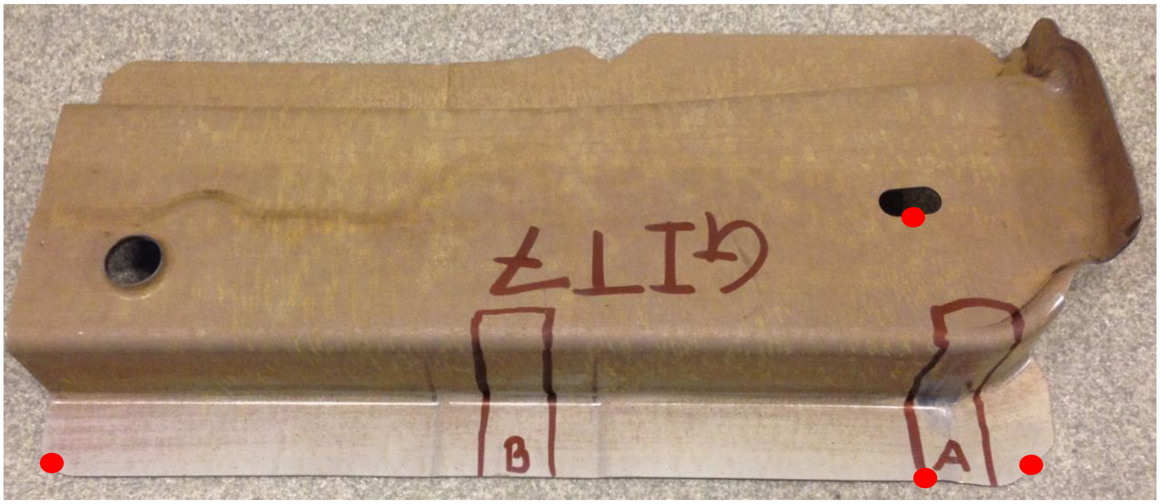

Figure 5. Measured part with measurement points marked with red dots.

The tests performed in the research line showed that the sensor was able to measure specified points on both a flat blank and a formed product with sufficient accuracy and speed. The major issue was the maximum measurement distance that according to the specification is 1400 mm for this type of sensor. If the sensor is to be mounted in the press and measure parts in the tool this is a limitation since there is no room for a sensor as close to the tool as 1400 mm. Another disadvantage with the tested system was the software, which was experienced as non-intuitive and somewhat difficult to work with. It was also found that the possibilities to export the data files are limited as well as connectivity with other systems. Further trials were aborted due to the limitations in measurement distance and the possibility to mount the sensor in HL9 in Luleå. The conclusion is that the system works as expected regarding measurement accuracy and speed but not regarding software and export of data. If the system is to be used in further applications the sensor must most likely be mounted in a location after the press where it can be moved into position by a robot or similar.

6.3 3D-scanning of production tools for detection and quantification of wear

Optical 3D scanning has been used to determine whether it is possible to detect and quantify adhesive wear in production tooling by means of scanning.

Optical 3D scanning with ATOS III is touch-free and scans the object with 8 million points in each capture. The system is easy to use and provides high accuracy. The system is also mobile which allows for great flexibility. The measuring range of the equipment is 320 x 240 x 240 mm, but as a system of reference points is built up as the system constantly references the scan result, you can move the equipment around the object and gradually fill it with more measurement points. This builds a "whole" model in the form of a point cloud. The software then merges the various scan results and automatically picks out duplicate points. This scan result is then analyzed and can be compared to e.g. a CAD-model or properly evaluated in other ways. In our case we compared the tool before cleaning with the tool after cleaning instead of a CAD-model.

The subject to be 3D scanned is prepared with reference dots consisting of a white circle on the black bottom. The white circle is 3 mm in diameter. For as accurate a result as possible, these reference dots were photographed using a Tritop system. This meant that the reference dots had interlocked before the actual 3D scan. Hence, you could start scanning anywhere in the tool without starting in the middle of the measurement area, then going out the edges, etc.

All measurements have been made on site at Volvo in Olofström. A total of six measurements trip were made a number of months apart. From the third measurement occasion, a Tritop system was used. Thus the reference points were taken for the 3D scanning of the mold tool itself. This is to ensure that the scan results have the best possible accuracy when the measurement area is greater than 320 mm which is the measurement volumes used with this ATOS system.

Each 3D scan results in a point cloud that depicts the actual outcome of the tool halves. Measurement accuracy is considered to be very high, of which all results can be seen as real, relevant information. After both tool halves were 3D scanned, the tools were cleaned from adhesions. The procedure with scanning was then repeated with 3D scanning of the cleaned tools.

The results of the 3D scan were evaluated in GOM's software GOM Inspect. The two scans from pre- and post-cleaning were added to each other, of which a color scale deviation analysis was projected on the first scan before cleaning. In this way, it is possible to study the height of the galling as well as the tool they encountered.

This clearly demonstrates the capability of the equipment and the method to measure the adhesive wear after a production run. The obtained measurements are both qualitatively and quantitatively satisfactory.

6.4 In-line measurements of draw-in at VCC

In hot stamping, adhesion of sheet material and sheet coating onto the forming tools, e.g. galling, is a common problem. Eventually parts with different types of damages and out-of-tolerance geometry are produced.

Simulations have shown a relation between small changes of tool geometry, similar to changes caused by adhered material, and changes of sheet draw in. Realistic levels of adhered material should cause a detectable change of draw in according to previous studies.

The objective of the present study was to experimentally investigate if a difference in draw in could be detected during production of a batch of automotive parts using hot stamping and if so, also evaluate the relation between the amount of adhered sheet material on forming dies and the change of draw in.

The draw in was measured using a laser sensor, Keyence LJ-V7200, during the production of sheet metal parts and the tool surfaces were measured using an optical 3d scanner, ATOS III Triple Scan, before and after cleaning of the tool. The cleaning is a regular maintenance procedure to remove any adhered material from the tool surfaces.

The laser sensor was mounted in a custom built adapter with protection for the sensor from vibrations and heat radiation. The sensor was mounted so that the position of the sheet edge could be detected during the entire forming cycle, including the quenching sequence. See Figure 6 for an example of measured data at the beginning of a forming cycle. For every studied forming cycle the position of the sheet edge was measured in the beginning and in the end. From these positions the draw in was calculated for each studied cycle individually.

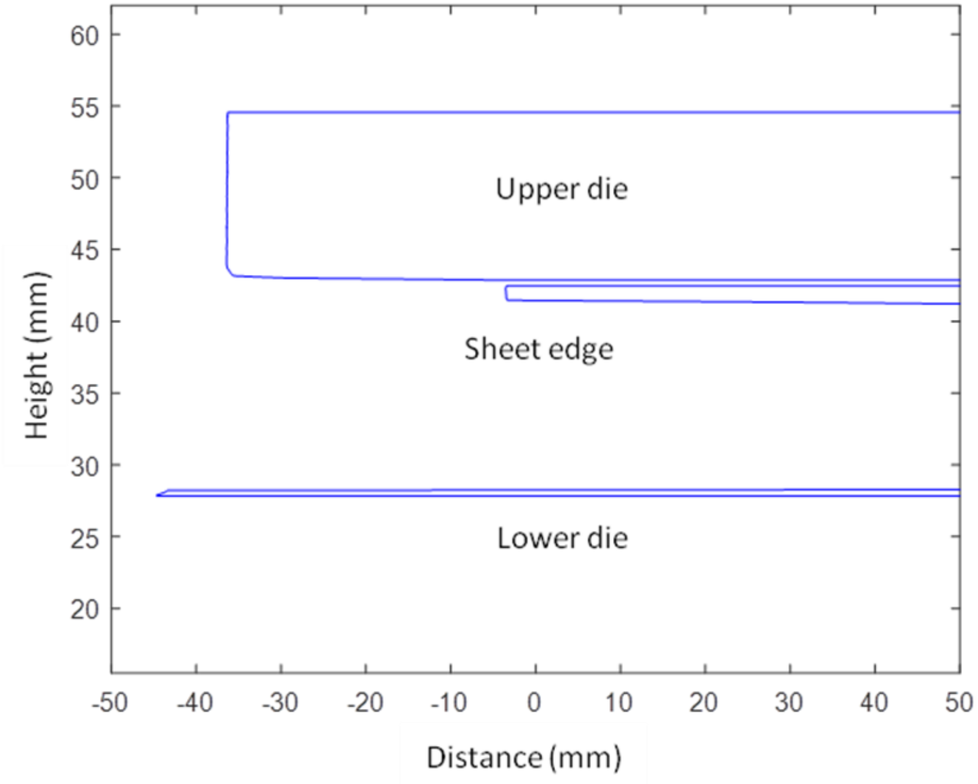

Figure 6. Measurement from laser sensor.

In the 3d scanning results adhered material could be found in areas were the draw in was measured. The adhered material was in the 0.05-0.08 mm range in thickness. Spots with thicker layers of adhered material (>0.1 mm) was also found in nearby areas of the tool.
Between the evaluated forming cycles there were relatively large changes in draw in as well as starting positions. However, no significant trend in the changes could be found. The hypothesis was that the draw in was to be affected by the increasing amount of adhered material on the tools. The results of this study do not support this hypothesis. However, they do not falsify it either. Instead, the results indicate that there are other factors contributing to the changes in draw in at least as much as the galling. There are also lots of sources of variation and possible measurement errors coming from the experimental set up which have not been thoroughly evaluated.

6.5 Using FE modeling to determine effects from wear

A morphological modelling is attempted in order to numerically study the influencing parameters from wear on the impact on the blank draw-in during hot forming of boron steel. This lead to a continued work with FE simulation based on a real scanned tool that is subjected to wear.

The effort is realized by using parametric changes of the geometry of a simplified version of the model for the dog bone tool to create understanding of most influencing parameters. Both adhesive and abrasive wear is modelled with the same parameterisation, albeit with opposite sign. The model of galling represented by a truncated cone on a flat area is described. The aim is to have the same change of volume for the different changes. The parameterised model were run in a Design of Experiments (DoE) where the response is the draw in of the blank edge on a single node and the geometrical parameters are the variations; wear on radius, galling on radius, galling under blank holder and galling both on radius and under blank holder. The DoE result is subjected to a Global Sensitivity Analysis (GSA) which appoints friction as the dominant parameter.

There are simplifications that calls for caution when interpretating these results. Further work without the simplifications can be suggested to secure the conclusions. Another possibility is to perform FE simulation based on a real scanned tool that is subjected to real wear. The latter has been attempted as described below.

In this work, the effect on the draw-in because of the galling or adhesive wearing on both the punch and the die is studied. The tools are scanned in two different situations: before and after cleaning as described in the section 6.3 3D-scanning of production tools for detection and quantification of wear.

The stl-file resulting from the scanning contains the obtained coordinates of the scanned part in terms of nodes with a connectivity that constitutes a triangular mesh. This mesh is not as smooth as one desires in order to base a FE simulation on. In addition, the element size is so small that it will severely affect the time step size thus prolonging the computational time for the analysis. Another issue that can cause trouble in an FE analysis directly based on the scanning is that some of the scanned coordinates lies somewhat above the mean surface height which might cause contact instabilities in the FE simulation because of the sharp point. Because of this a post processing of the scanned result was performed by Tebis Scandinavia AB, confer Figure 7. Only a small section of the tool were the galling was distinct were used to keep the size and complexity of the problem low. Tebis got the .iges and .stl files and meshed them using their software in order to get a high-quality mesh.

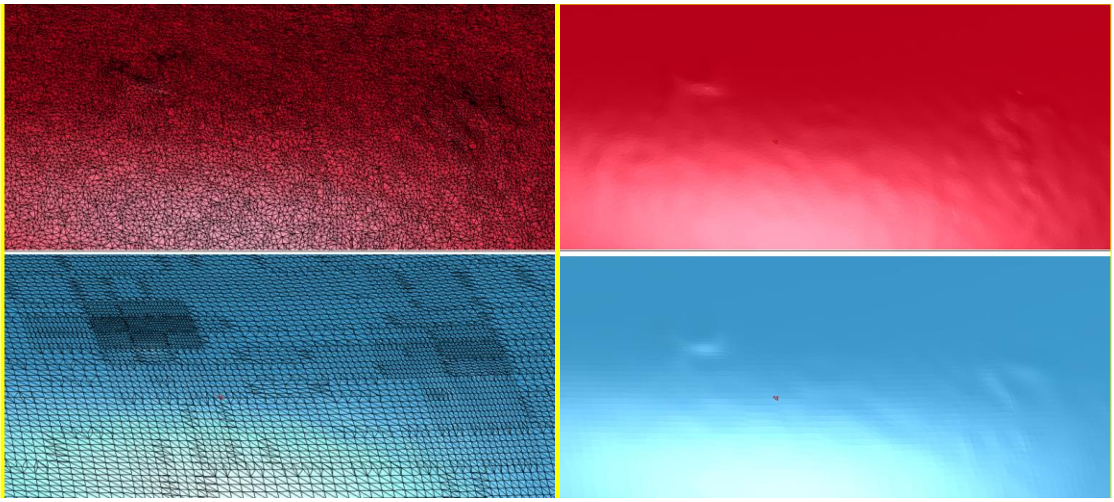

Figure 7. Same area of tool with galling. Upper left and right images showing stl-file from scanning with and without mesh highlighted. Lower left and right images showing resulting mesh from Tebis with and without mesh highlighted.

The forming process has been implemented into the FE simulation using LS-PrePost v4.3. The model is made based on the nominal geometries of the tools. The blank has the same shape as in production. Figure 8 shows the setup of the simulation with all the parts involved.

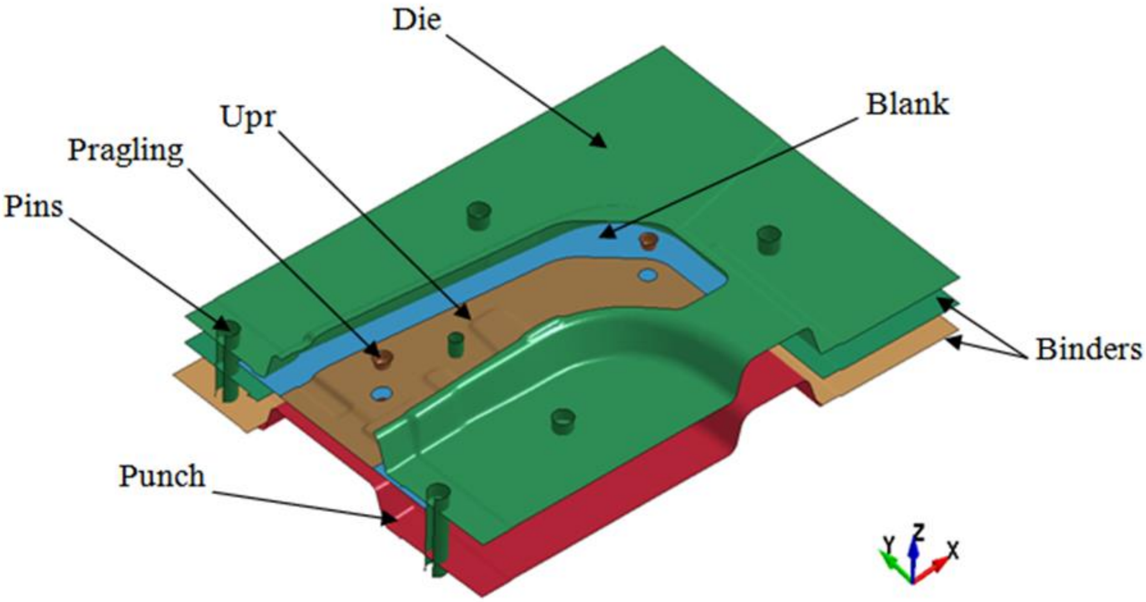

Figure 8. Setup of the forming simulation with its different parts marked.

The material model used in the forming simulation is found under the keyword *MAT_UHS_STEEL (244) in LS-DYNA. The input data to this model is obtained from

LTU's in-house test results. Contact conditions with suitable friction coefficient were set-up. The mesh size matching between tool and blank were found to be crucial for this set-up to be executable.

In order to keep the size of the problem sufficiently small as described above a sub modelling approach was used. By selecting the interface between the intended sub model and the full model the interface movements can be obtained from the analysis of the full model. Then the sub model can be analysed with boundary condition for the interfaces that ensures correspondence in a global sense even though the mesh resolution and tooling in the local model is altered. This will significantly reduce the computational time to run the simulation while maintaining the accuracy of the results obtained.

To enable assessment of the usefulness of using scanned results from actual tool wear it is necessary to compare with simulation results obtained without galling defects on the tools. Hence the nominal model is used with the same sub modelling approach, see Figure 9. Even better though would be to use a model based on scan result without adhesive wear. This, however is left for future studies.

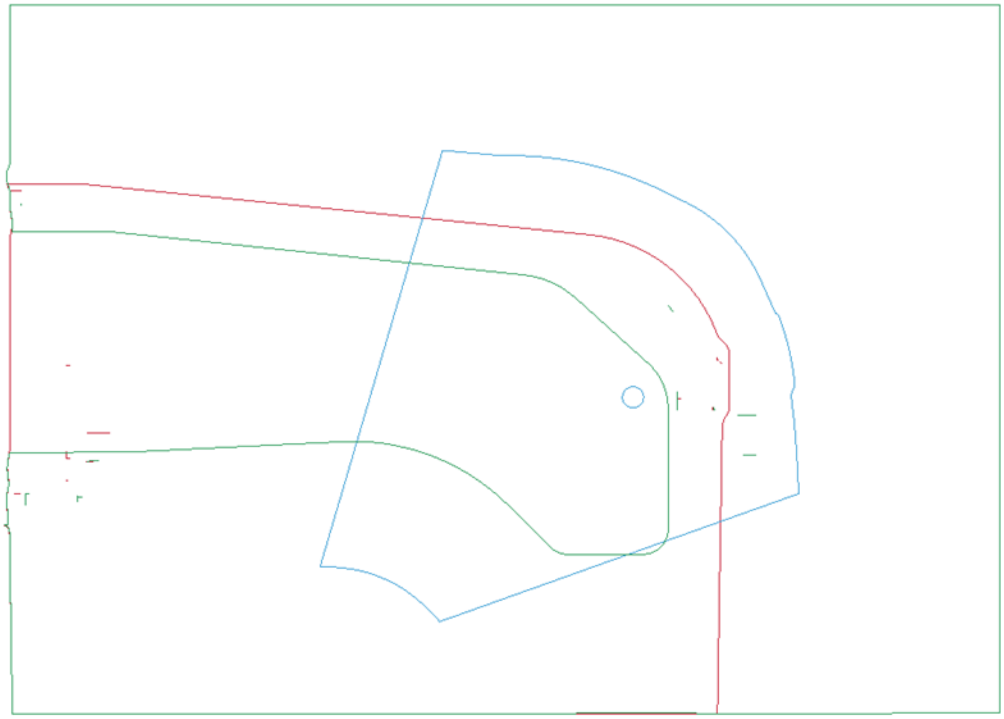

Figure 9. Sub modelling of the nominal geometry of the die (green), punch (red) and blank (blue).

Due to the complexity of this approach in combination with the many parameters involved it is difficult to determine the origin and nature of the varying outcome in terms of resulting draw-in of the blank.

For instance the positioning of the individual tool parts can affect the outcome of a result comparison between scanned tools before and after use and nominal tooling.

Also the detailed modelling required for using the results from scanning is calling for improved pre-processing tools to take advantage of the details in the scanned geometry without having to use additional software which increases the complexity.
However the method to convert stl to FE mesh is adequate and the sub modelling is useful to economize with computational resources.
So far no final conclusion regarding the effect on draw-in exists from this effort. But some further work will be conducted to enable conclusions and suggestions for continued physically based modelling. The outcome of this will be communicated within the project group.

6.6 Tool enhancements at VCC

Adhesion and wear is a problem in press hardening. The AlSi layer sticks to the surface and can in some cases be very hard to remove. Most common today is only hardened steels, no surface treatment. PVD coating is continuously being developed and will probably be used more in the future. This choice of PVD coating is recommended from the coating company, tests has been made with good results in USA and ASIA. New steels have been manufactured, polished and PVD coated. Two steels in total, one in the upper die and one in the lower die, same corner in the die.

Results before PVD coating, new steels:
The surface roughness is much smoother than ordinary production steels in press hardening, the steels are between Ra 0.1 to 0.3. This is recommended from the coating company.

Result after production with PVD coated steels:
PVD coating is in place and not damaged but has a lot of adhesion and it is AlSi (we have tried to detect iron or damage areas in the PVD layer with copper sulfate (CuSO4) but no iron is detected). The adhesion demands mechanical work, impossible to wipe away and grinding stones cannot be used. The operator at maintenance feels that the adhesion on the PVD layer needs more work compared to uncoated surface. Could be due to that they need to be more careful or that they cannot use stones.

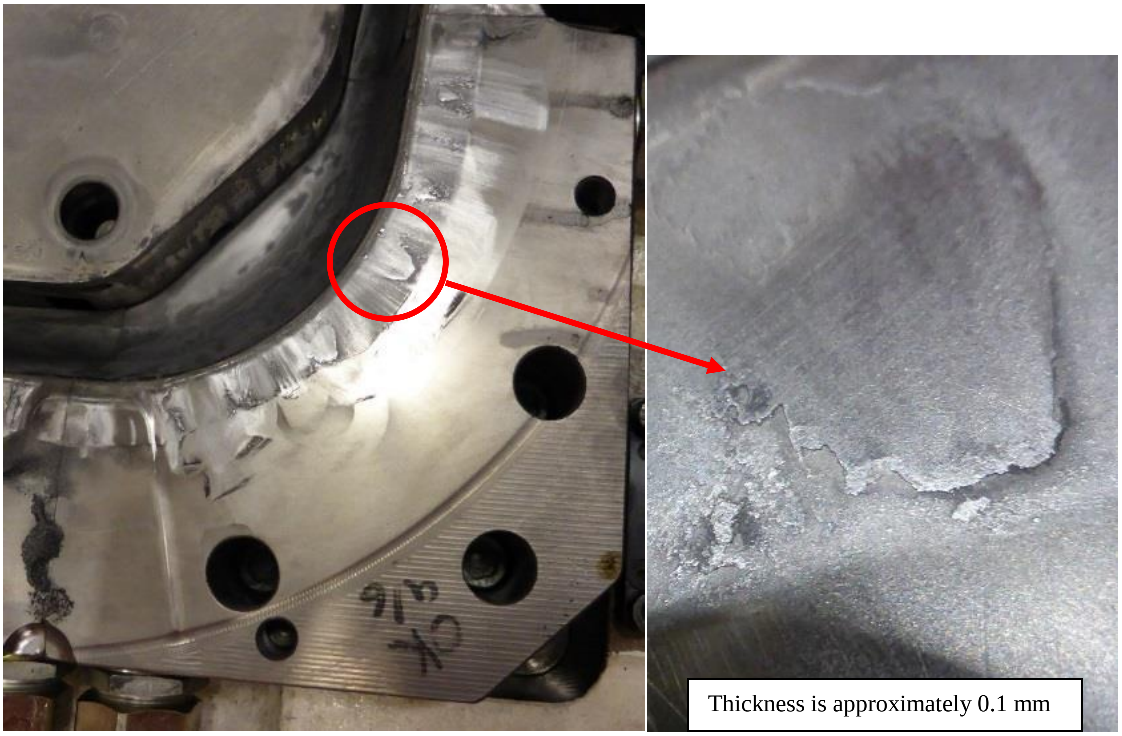

Figure 10. Result after production with PVD coated steels.

6.7 Tool enhancements at HardTech

The tool enhancement chosen by Gestamp HardTech for evaluation is nitriding. An identical tool setup as the one used for the full-scale press hardening experiment have been manufactured and nitrided. The test has unfortunately not been conducted due to time constraints in the research line at HardTech. We plan to run the test as soon as possible during 2018 and distribute the results within the project consortium.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	By publications and the cooperation with the companies in the project
Be passed on to other advanced technological development projects	X	Within the companies and possible future research projects
Be passed on to product development projects	X	Within the participating companies
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

The dissemination is accelerated by the continuous research cooperation between LTU and the participation industries and institutes. The industrial use of the results is facilitated by the infra-structure of simulation models and product development processes that has been built up in several previous VINNOVA/FFI-projects.

Swerea IVF is hosting the industrial network Plåtforum. In the second newsletter of 2015 there was a feature article describing the project, the background and the ambitions. In a newsletter during 2018 the project results will be published in a new article. The project results will also be disseminated through a coming seminar that will be arranged by Plåtforum.

7.2 Publications

- Liang Deng, Modelling of wear and galling in press hardening simulations, PhD. Dissertation, Department of Engineering Sciences and Mathematics, Luleå University of Technology, 2017.
- Liang Deng, Leonardo Pelcastre, Jens Hardell, Braham Prakash and Mats Oldenburg. A tribological test under press hardening conditions for galling research, In: Oldenburg, M. and Steinhoff, K. and Prakash, B (Eds.). Hot Sheet Metal Forming of High-Performance Steel, CHS2: 6th International Conference, Verlag Wissenschaftliche Scripten, pp. 453-460, 2017.
- Liang Deng, Leonardo Pelcastre, Jens Hardell, Braham Prakash and Mats Oldenburg. Experimental evaluation of galling under press hardening conditions, to be submitted.
- Liang Deng, Leonardo Pelcastre, Jens Hardell, Braham Prakash and Mats Oldenburg. Numerical investigation on the galling in a press hardening experiment with Al-Si coated workpieces, to be submitted.

8. Conclusions and future research

The high-temperature tribometer test program has been performed under press hardening conditions. The galling result has been used to calibrate the coefficient in the modified Archard model for galling simulations. The analysis of the wear mechanisms in the laboratory test provides a possibility to establish a wear and galling process map based on the improved test procedure for the laboratory tests. The severe galling accumulation at the leading edge of the pin occurs early in the test with a high load. An improved test programme including an elaborate choice of interrupted sliding distances and high loads for the understanding of galling evolution is necessary. Furthermore, grinding direction in a real stamping tool is not unidirectional due to the complex geometry of stamping tool. The influence of varying grinding directions on the galling is of interest. However, a parallel grinding direction to the sliding direction is employed in the present tests.

The galling simulation based on the modified Archard model predicts when and where the galling occurs on the stamping tool. The predicted position of severe galling matched well with the galling measurement of the full-scale press hardening experiment. The present galling simulations assumes a linear relation between the galling amount and sliding distance. According to the measurement of worn tools, the galling profiles may be affected by wear particles during the repeatedly strokes in the press hardening process. In future work, the effect of wear particles on the galling evolution during the extended sliding distance of laboratory test correlating with the strokes of press hardening could be taken into account. Furthermore, the influence of physical factors, such as strain of the workpiece, tool surface roughness and grinding direction on tool wear could be numerically and experimentally studied with an extended range of material combinations of interest to industries. A worn stamping tool based on the predicted worn profile with a proper extrapolation of a big number of strokes could be used in the galling simulation to study the influence of galling on the production quality in terms of the final product shape, concentrated contact conditions and the thickness change in the blanks.

Measurements of the product geometry at Gestamp HardTech during press hardening production is possible. A number of specified points were measured with sufficient accuracy and speed. The limitation with respect to maximum measurement distance of the selected system means that it cannot be mounted close enough to the press. If the system is to be used in future applications the sensor must most likely be mounted in a location after the press.

The result from 3D scanning of tools before and after production clearly demonstrates the capability of the equipment and the method to measure the adhesive wear after a production run. The obtained measurements are both qualitatively and quantitatively satisfactory thus both results and method can be useful for modeling and analysis of adhesive wear in the future.

The simplified geometrical modelling of wear demonstrates a capability to study influencing parameters and their respective importance. From this limited study it is found that friction constitutes the dominant contribution to varying draw-in. However more work is needed to secure the results, including modelling review as well as evaluating more parameters and possibly extended parameter ranges. If, however the result still holds after a more thorough reworking it supports the importance of having an elaborate friction model when studying the effects from wear. FE simulation based on a real scanned tool that is subjected to real wear is performed. So far no final conclusion regarding the effect on draw-in exists from this effort. However future work with comparing results from FE simulation based on scanning with corresponding results obtained with the implemented wear model used to model the same forming process is suggested.

In-situ draw-in measurements by following the blank edge during the process have been performed. The equipment used proved to be able to trace the edge despite the harsh measurement conditions. Between the evaluated forming cycles there were relatively large changes in draw in as well as starting positions. However, no significant trend in the changes could be found. The hypothesis was that the draw in was to be affected by the increasing amount of adhered material on the tools. The results of this study do not support this hypothesis. However, they do not falsify it either. Instead, the results indicate that there are other factors contributing to the changes in draw in at least as much as the galling. There are also lots of sources of variation and possible measurement errors coming from the experimental set up which have not been thoroughly evaluated.

Tests with PVD coated tools at Volvo Cars show large amounts of galling.

9. Participating parties and contact persons

Name	Affiliation	Email	Phone
Mats Oldenburg	Lulea University of Technology	mats.oldenburg@ltu.se	+46 920 491752
Liang Deng	Lulea University of Technology	liang.deng@ltu.se	+46 72 2072088
Peter Ottosson	Swerea IVF	peter.ottosson@swerea.se	+46 70 7806069
Johan Berglund	Swerea IVF	johan.berglund@swerea.se	+46 70 7806050
Lluis Perez Caro	Swerea IVF	lluis.perez.caro@swerea.se	+46 768 997550
Kenneth Kjellsson	Volvo Car Corporation	kenneth.kjellsson@volvocars.com	+46 454 264930
Mats Sigvant	Volvo Car Corporation	mats.sigvant@volvocars.com	+46 454 265368
Greger Bergman	Gestamp HardTech	gbergman@se.gestamp.com	+46 920 474205
Christer Allard	Gestamp HardTech	callard@se.gestamp.com	+46 920 474320

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