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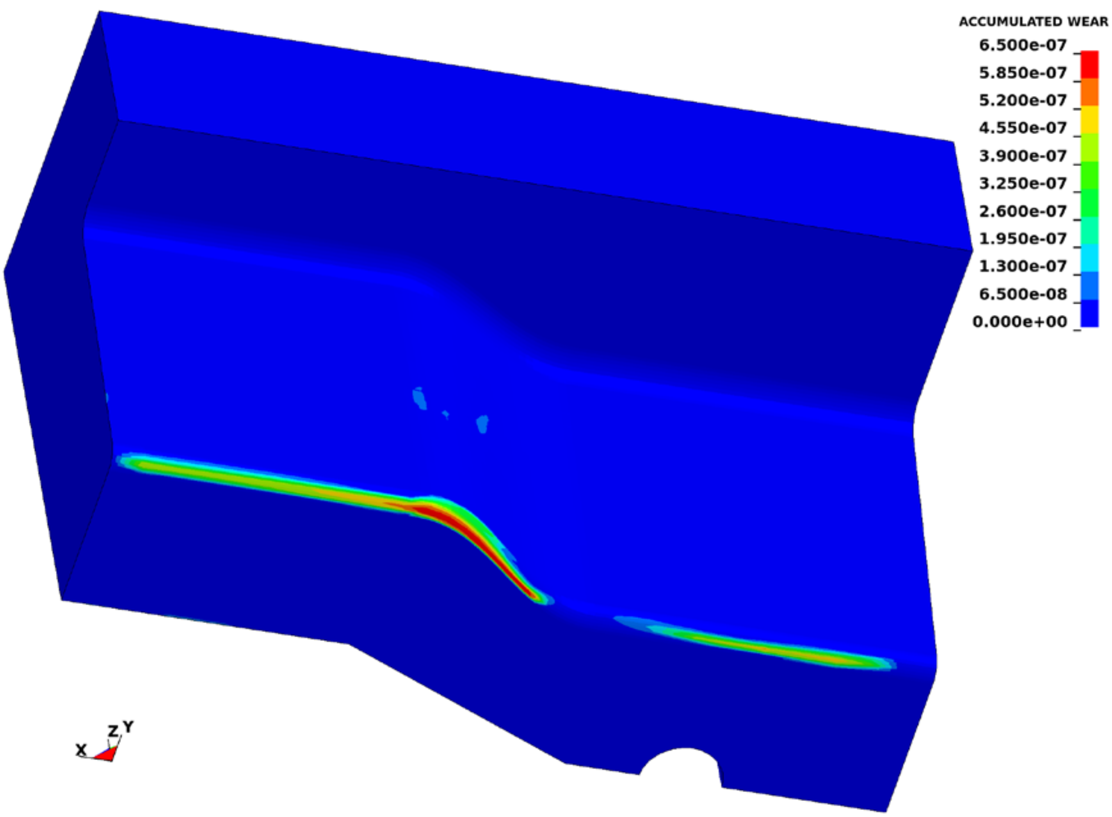
Modelling thermomechanical processes for enhanced productivity and quality
Prediction of tool wear



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Cover figure: Accumulated wear in metres on a quarter of the numerical deep drawing model.

1. Executive summary

Predictive process models for thermo-mechanical forming processes like press hardening have been developed during this project. Simulative, tribological experiments were carried out on uncoated and surface treated/coated tool steel materials sliding against uncoated and Al-Si coated 22MnB5 steel. The tool coatings seem to significantly reduce wear, but further analysis of the specimens is needed in order to confirm this. However, results for uncoated tools differed markedly from friction coefficients observed in reciprocating tests due to the difference in experimental setup as the simulative tests represent the conditions prevalent in press hardening. The results were used to propose two modified Archard wear models in which the wear coefficient was set as a function of temperature, pressure and sliding velocity. The two tool wear models were implemented in the finite element (FE) simulations.

FE simulations revealed mean contact pressure values that agree very well with measurement results taken from real stamping cases. Geometry updating for the prediction of tool wear has also been integrated in FE simulations, as it is thought to affect contact conditions after a number of drawing strokes. Wear depths calculated from the simulative tests were higher than the values based on the reciprocating tests, which implies that the wear prediction is sensitive to the choice of laboratory test setups.

The combination of FE simulation and simulative tribological testing has created a unique platform that can quickly and cost efficiently assist in optimisation of tool steel compositions as well as the design of surface coatings for high temperature applications. This strengthens the position of Swedish industry engaged in thermo-mechanical forming processes as well as those in tool steels and surface modification technologies as all research results have been or will soon be published in conference contributions, journal articles and two Licentiate theses.

2. Background

Press hardening is usually employed in automotive industry for manufacturing of complex shaped structural and safety components from advanced high-strength steels. This special type of thermo-mechanical forming process invented in northern Sweden is characterised by simultaneous forming and hardening of the steel sheet material. Blanks are punched from rolled sheet material. When heated to the forming temperature, the steel sheet is subjected to oxidation and complex oxide layers form. The blank is then transferred to the forming tool and forming into the desired shape occurs when the tool closes as illustrated in Figure 1.

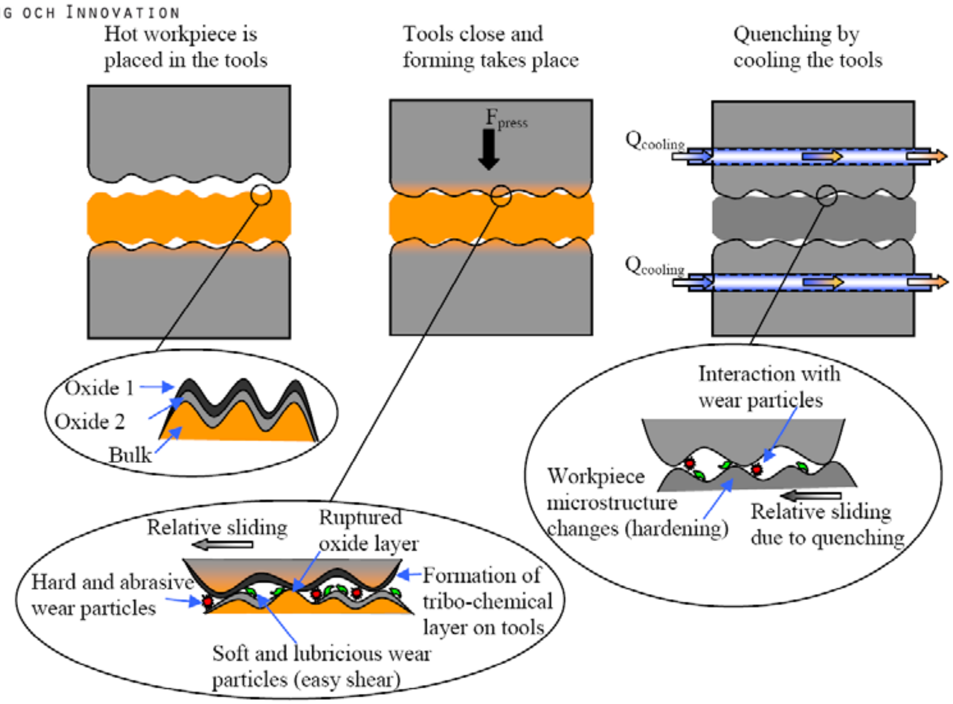


Figure 1: Schematic of thermomechanical forming process showing how tribological conditions change during one process cycle.

The harsh contact conditions in thermo-mechanical forming processes such as the elevated temperature, the changes in temperatures due to cooling of the tools, phase transformations, the repetitive mechanical loading and the relative motion between tool and blank lead to wear developing on the forming tool and reducing its lifetime. A predictive approach to tool wear is needed in order to extend the service life of tools.

Previous research at Luleå University of Technology has focused on the prediction of material and process response as well as the final material state and properties of the material. For that, numerical simulations, e.g. finite element (FE) simulations for the analysis of large deformations including thermo-mechanical coupling and modelling of friction and heat transfer at the contacting interfaces, are employed. These results have enabled simulations of a complete thermo-mechanical process such as press hardening and developed models and methods have been implemented in the commercial FE-code LS-DYNA, which is widely used in industry for forming and crash simulations.

3. Objective

The wear occurring in press hardening shortens the lifetime of stamping tools. Therefore, this research aims at creating a predictive model for high precision simulations of thermo-mechanical forming that accounts for tool wear, related geometry changes and tool life.

The contact conditions in the press hardening process can be analysed with help of FE-simulations. Then, corresponding laboratory experiments programs can be developed. In order to study the wear behaviour appearing on stamping tools during a press hardening process, a dog-bone shaped drawing prototype was established to determine the critical area of tool wear and its corresponding wear level. The FE simulations can unveil the contact conditions in the stamping tools instead of the difficulties in measuring on the work site. However, some numerical variables such as mesh quality, element size and penalty factor are expected to affect the results.

4. Project realization

The aforementioned interdisciplinary research tasks were accomplished through close collaboration between the divisions of Mechanics of Solid Materials and Machine Elements at Luleå Univeristy of Technology, the employer of press hardening Gestamp Hardtech, the tool steel supplier SSAB and the surface coating companies Oerlikon Balzers Sandvik AB and Ionbond Sweden AB as well as the research institute Swerea Mefos.

4.1. Tribological studies

In order to study the behaviour of the bulk material of the tool, tribological studies at elevated temperatures were carried out using the standard test setup of the Optimol SRV high-temperature reciprocating sliding friction and wear tester. In this machine, an electromagnetic drive oscillates an upper specimen over a stationary lower specimen as shown in Figure 2. The upper specimen is loaded against the lower specimen by means of a spring deflection loading arrangement. The friction force is measured by using a pair of piezoelectric transducers. A computerised data acquisition and control system is utilised to control, monitor and measure the different parameters during the tests.

The test parameters used in this study are listed in Table 1. The tests were performed with a view to obtain steady state friction values at different temperatures. After cooling, the specimens were weighed and wear of the specimens was determined through weight loss.

Table 1: Test parameters used in the high temperature reciprocating tests

Test parameters	Value
Load [N]	31
Pressure [MPa]	10
Temperature [°C]	40, 200, 400, 600, 800
Frequency [Hz]	25
Stroke length [mm]	4
Duration [min]	15
Atmosphere (1 atm)	air

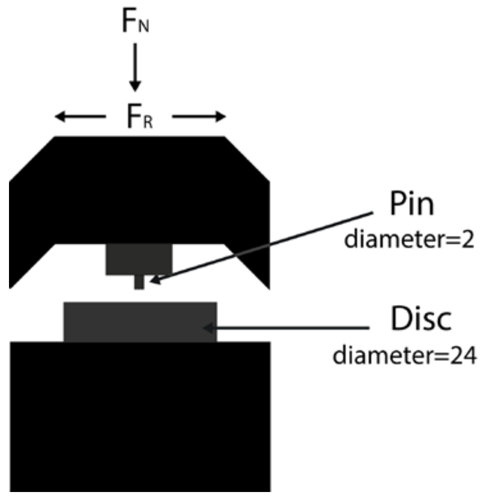


Figure 2: Configuration in the reciprocating test; all dimensions are in millimetres

FE simulations were used to identify the experimental parameters to be employed in the Ducom TR-20M-47 high temperature tribometer. The test parameters including the tool and workpiece temperatures that were based on the FE simulations ensure the reproduction of the actual wear mechanisms encountered during press hardening. Specific emphasis was laid on developing temperature and pressure dependent wear mechanisms maps as the tool life is highly governed by the dominant wear type.

The basic configuration of the high temperature tribometer is shown in Figure 3 and involved a pair of tool steel pins that were loaded against the workpiece strip surfaces (one from each side) and subsequently slid along the length of the strip. In order to enable long sliding distances to induce accelerated wear on the tool steel specimens, an automated pick and place mechanism fed in new strips from a tray containing 10 strips. This allowed to achieve a total sliding distance of 5.5 m and to obtain measureable wear.

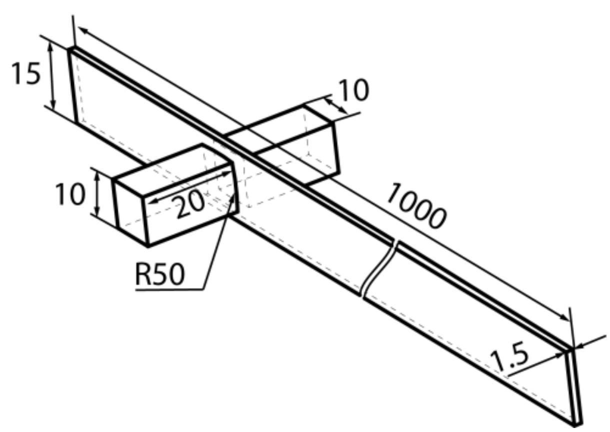


Figure 3: Configuration in the simulative tests; all dimensions are in millimetres

The employed contact pressures, sliding velocities and tool temperatures were based on mean values of a simplified numerical strip drawing or the numerical quarter deep drawing model. The tool coatings were used at the suggestion of the coating companies.

4.2. Basic setup for the deep drawing model

As mentioned before, the numerical model was built on a quarter of the whole press hardening (dimensions can be found in Figure 4) using LS-DYNA, where the gap distance between the holders and the upper tool was maintained at 2 mm, 3 mm, 4.6 mm and infinity (no holders) until the upper tool moved to its final position, then the holders would move back to the blank with a load of 100 000 N, also called closure. The workpiece with a thickness of 1.6 mm was meshed by rectangular shell elements using Belyschko-Tsay formulation in the size of 2 mm and the tools were modelled by eight-node solid elements as rigid bodies. In order to reduce the number of elements, the tool element size gradually coarsened from 1 mm to 8 mm along the direction from a depth of 5 mm to the thermal contact interface to the tool bulk. The material model 'MAT_UHS_STEEL', a thermo-elastic-plastic constitutive model developed by Åkerström, Bergman and Oldenburg at Luleå University of Technology, was employed.

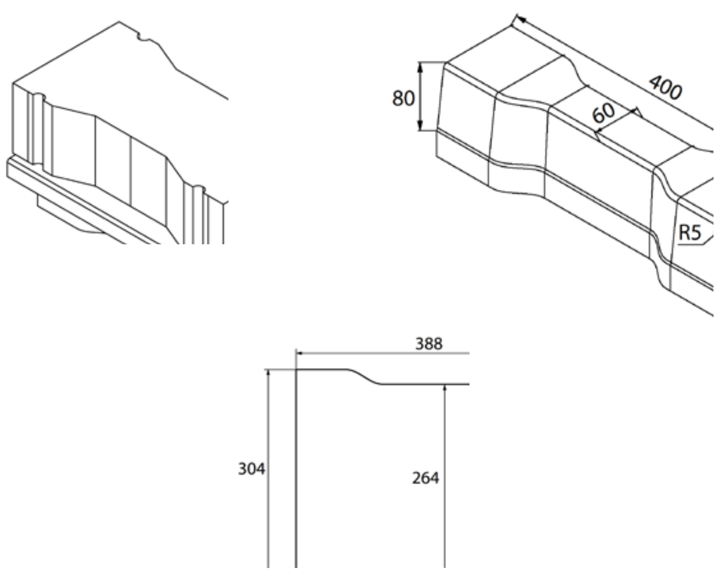


Figure 4: Geometry measurements of stamping tools and blank, all dimensions in millimetres.

4.3. Tool wear modelling based on laboratory experiments

Two predictive wear models designed for the accumulated sliding wear between boron steel and tool steel were implemented in the current FE simulation to predict the wear depth in press hardening and both of them considered the high temperature effect on tool wear. The first wear model was based on Archard's wear model and its wear coefficient was calibrated by the reciprocating tests performed at elevated temperatures (see Figure 2) with the constant test parameters found in Table 1. The relation between the wear depth and the contact conditions in terms of pressure and sliding velocity were determined by using following equation:

$$\mathrm{d} = \frac{V}{A} = K\frac{W}{H}\frac{1}{A}L = \int K(T)Pvdt \quad (1)$$

where V is the worn volume, L is the sliding distance, A is the real contact area determined by the load W divided by the hardness H, P is the pressure and v is the sliding velocity.

The second wear model was obtained from simulative tests conducted at a constant high temperature of the strips with varying pressure and velocity (see Figure 3), where the wear rate is assumed to have a bilinear relation to pressure and velocity. The varying pressures (15.9 and 47.7 MPa) and the velocities (0.01 and 0.1 m/s) used in the simulative tests were based on the FE simulation of the press hardening, which make the experiments mimic the real press hardening. These four combinations of pressure and velocity determined the relationship between the wear depth and the contact conditions. However, only the boundary wear rate was used if the contact conditions exceeded the test ranges. The wear depth was calculated according to following equation:

$$\mathrm{d} = \int \dot{w}(P,v)vdt \quad (2)$$

where $\dot{w}$ is the wear rate, P is the pressure and v is the sliding velocity. Furthermore, the possibility to adapt the geometry of the tools to the expected wear was implemented. With this strategy, the changing conditions during progressive wear can be taken into account in the prediction of tool life.

5. Results and deliverables

5.1. Contribution to FFI-objectives

One of the programme objectives is to reduce all losses in the production processing and also to reduce the environmental impact of the manufacturing process. This project has increased the knowledge in the field of virtual manufacturing processing which has made it possible to perform more accurate forming simulations. This reduces the cost and especially the time for the development of new hot stamped components for the automotive industry.

5.2. Frictional and wear behaviour

In the reciprocating tests, the coefficient of friction reached a steady state value of about 1.34 at 40 °C, as illustrated in Figure 5. This increase in the coefficient of friction at 40 °C was a result of the continuous removal of the natural oxide layer leading to the occurrence of metal to metal contact and the deformation or removal of surface asperities leading to a larger real area of contact. The appearance of metal to metal contact was further confirmed by adhesive wear features on the worn surfaces of the disc depicted in Figure 6. Additionally, the tests performed at 40 °C showed fluctuations in the friction coefficient owing to ploughing. This type of severe adhesion led to local seizure between the two rubbing surfaces. Therefore, the coefficient of friction increased, seen as rising peaks in Figure 5, until a fragment of adhered material got stuck in its ploughing track and detached from the surface leading to a decrease in friction.

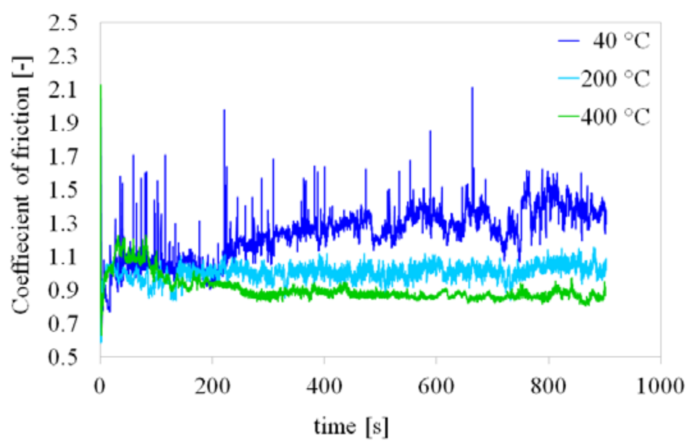


Figure 5: Coefficient of friction as a function of time at 40 °C, 200 °C and 400 °C as measured in the reciprocating experiments

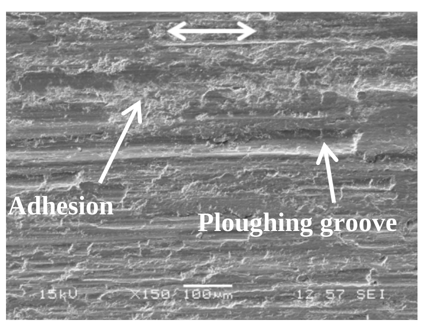


Figure 6: SEM image of the tool steel disc exposed to 40 °C; double arrow indicates sliding directions

The simulative tests were performed on the Ducom TR-20M-47 high temperature tribometer. The test parameters including the tool and workpiece temperatures were based on FE simulations. Figure 7 shows the coefficient of friction as a function of sliding distance obtained for uncoated tool pins sliding against uncoated and Al-Si coated boron steel strips. It can be seen that a higher load leads to a lower and more stable coefficient of friction independently of the applied sliding velocity or material. In Figure 8, the average coefficient of friction of uncoated tool pins sliding against uncoated and Al-Si coated boron steel strips under different loads and sliding velocities shows an excellent reproducibility of results.

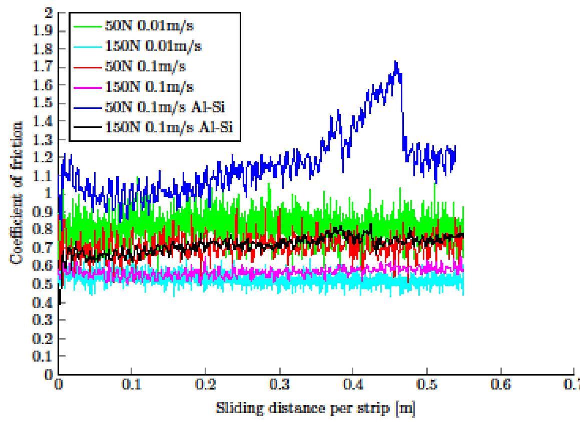


Figure 7: Coefficient of friction as a function of sliding distance for uncoated tools

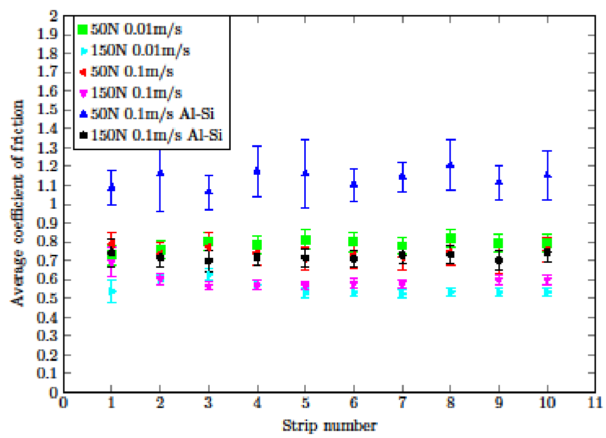


Figure 8: Average coefficient of friction of uncoated tool pins sliding against uncoated and Al-Si coated boron steel strips under different loads and sliding speeds

Tribological studies have also been conducted on surface treated/coated tool steel pins sliding against uncoated and Al-Si coated 22MnB5 steel with a view to explore the potential of surface engineering in controlling friction and minimising wear at elevated temperatures.

As mentioned earlier, the specific wear rates obtained in the reciprocating tests were normalised to the apparent contact area in that specific test setup (see Figure 2) and the resulting wear coefficient represented the wear behaviour in that wear model at temperatures of 40 °C, 200 °C and 400 °C. Figure 9 shows the wear coefficient as a function of temperature and it exhibited a proportional relation between the wear depth and the contact conditions in terms of pressure and sliding velocity.

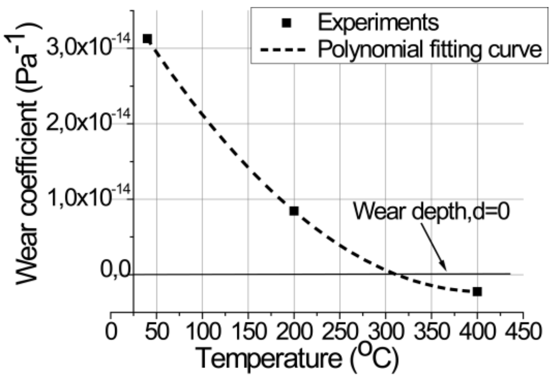


Figure 9: Wear coefficient used in the reciprocating wear model and wear rate

As mentioned in the previous chapter, simulative tribological tests were carried out on the Ducom TR-20M-47 high temperature tribometer. Uncoated tools were run against ten sequentially tested, uncoated and Al-Si coated 22MnB5 strips.

The second wear model was obtained from these simulative tests, see Figure 10. However, these results differed markedly from friction coefficients observed in the reciprocating tests due to the difference in experimental setup as simulative tests are designed to mimic the conditions in the real application. Wear would usually be higher in reciprocating sliding tests due to much severer contact conditions appearing in these types of experiments.

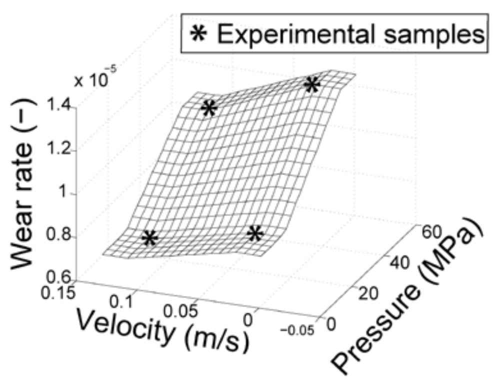
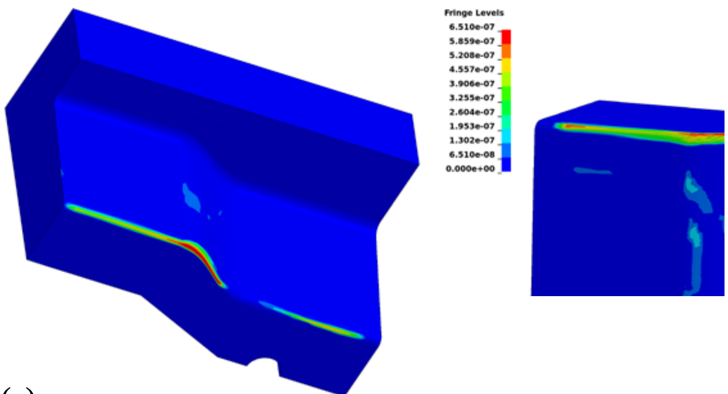


Figure 10: Wear rate used in the simulative wear model

5.3. Numerical simulation

Figure 11 shows the distributions of the wear depth, whose wear model was supported by the tribological tests. It was noticed that the wear mainly concentrated on the radius of the stamping tools and the lateral surface of the transition part also experienced wear during the drawing process.



(a) (b)

Figure 11: Distributions of wear depth in meters on stamping tool with the gap of 4.6mm after one stroke: (a) upper tool; (b) lower tool

Table 2 shows the results from FE-simulations with different blank holder gaps. TW means the wear depth in m calibrated with tribological tests and RW indicates the one calibrated with the reciprocating tests. Obviously, max, mean and SD are substitutions for maximum, mean and standard deviation, respectively.

Table 2: Wear depths on stamping tool with different gap distances

	TW, max	TW, mean	TW, SD	RW, max	RW, mean	RW, SD
G inf, U	6.5e-7	1.1e-7	1.5e-7	5.7e-8	6.3e-9	1.0e-8
G4.6, U	6.5e-7	1.3e-7	1.5e-7	6.0e-8	6.7e-9	9.2e-9
G3, U	6.5e-7	1.4e-7	1.5e-7	4.8e-8	7.2e-9	9.0e-9
G2, U	6.7e-7	1.5e-7	1.6e-7	5.4e-8	6.7e-9	8.9e-9
G inf, L	3.2e-8	4.7e-9	5.0e-9	2.2e-9	1.9e-10	2.7e-10
G4.6, L	2.8e-8	6.1e-9	4.9e-9	5.7e-9	2.3e-10	2.5e-10
G3, L	3.8e-8	9.0e-9	7.4e-9	4.8e-9	3.5e-10	3.6e-10
G2, L	2.6e-8	4.5e-9	3.7e-9	1.9e-9	1.7e-10	1.9e-10

Table 2 shows that the wear depths calculated by the RW wear model were one order of magnitude smaller than the values from the TW wear model since the disc made of tool material in reciprocating tests was heated up from the base and its sliding surface was probably harder than the heated strips used in tribological tests. Furthermore, the wear depths in the upper tools based on both wear models were higher than the values in the lower tools, which were observed to correspond to the sliding distance. Generally, the model with smaller gap distance led to more wear depth but the lower tool with a gap of 2 mm was an exception.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The results of this research project have been disseminated orally through presentation at several international conferences and have been or will be circulated in written through journal articles and Licentiate theses. Furthermore, the Division of Mechanics of Solid Materials at Luleå University of Technology has had a long and successful cooperation with Gestamp HardTech AB concerning modelling and simulation of press hardening. This research has led to the possibility of further developing, improving and evaluating material models and analysis methods for numerical simulations of the simultaneous forming and quenching process.

A complete thermo-mechanical material model for simulation of press hardening and similar processes is implemented in the commercial FE code LS-DYNA and is used by Gestamp Hardtech AB in the product development process to adjust component and tool geometry. The wear models are now also implemented in LS-DYNA.

6.2 Publications

L. Deng, S. Mozgovoy, J. Hardell, B. Prakash and M. Oldenburg, Implementation of wear models for stamping tools under press hardening conditions based on laboratory tests, 1st International Conference on Hot Stamping of UHSS: August 21 – 24, 2014, Chongqing, China.

L. Deng, S. Mozgovoy, J. Hardell, B. Prakash and M. Oldenburg, Simulation of tool wear in press hardening, 11th World Congress on Computational Mechanics: July 20 – 25, 2014, Barcelona, Spain.

S. Mozgovoy, J. Hardell, L. Deng, M. Oldenburg and B. Prakash, Effect of temperature on friction and wear of prehardened tool steel during sliding against 22MnB5 steel, *Tribology*, 2014, **8**, 65 – 73.

L. Deng, S. Mozgovoy, J. Hardell, B. Prakash and M. Oldenburg, Press-hardening thermo-mechanical conditions in the contact between blank and tool, 4th International Conference Hot Sheet Metal Forming of High-performance Steel CHS2: June 9 – 12, 2013, Luleå, Sweden.

S. Mozgovoy, J. Hardell, L. Deng, M. Oldenburg and B. Prakash, Effect of temperature on friction and wear of prehardened tool steel during sliding against 22MnB5 steel, 3rd International Tribology Symposium of IFToMM (ITS): March 19 – 21, 2013, Luleå, Sweden.

7. Conclusions and future research

Tribological studies were conducted on uncoated and surface treated/coated tool steel pins sliding against uncoated and Al-Si coated 22MnB5 steel with a view to explore the potential of surface engineering in controlling friction and minimising wear at elevated temperatures. An advantage of the tool coatings seems to be a significant reduction in wear, but further analysis of the specimens is needed in order to confirm this for each coating individually. However, results for uncoated tools differed markedly from friction coefficients observed in the reciprocating tests due to the difference in experimental setup as simulative tests mimic the conditions in the real application. The simulative tests exhibited a lower coefficient of friction due to an inferior severity of the contact and a reduced occurrence of adhesion owing to an oxide scale on the workpiece. Wear was lower in the reciprocating sliding tests due to lower tool temperatures appearing in these types of experiments.

The combination of FE simulation and simulative tribological testing has created a unique platform that can quickly and cost efficiently assist in optimisation of tool steel compositions as well as the design of surface coatings for high temperature applications.

When it comes to coatings for hot working tools, it is generally known that the performance of tool coatings is not satisfactory in many cases concerning press hardening. On one hand, coating companies like Oerlikon Balzers Sandvik AB or Ionbond Sweden AB need to evaluate the performance of newly developed or modified and improved coatings for press hardening. On the other hand, tool steel suppliers like SSAB also need to evaluate the performance of further or newly developed tool materials. Data should be generated in order to increase knowledge about the tribological behaviour of tool steels sliding against workpiece materials.

8. Participating partners and contact persons

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