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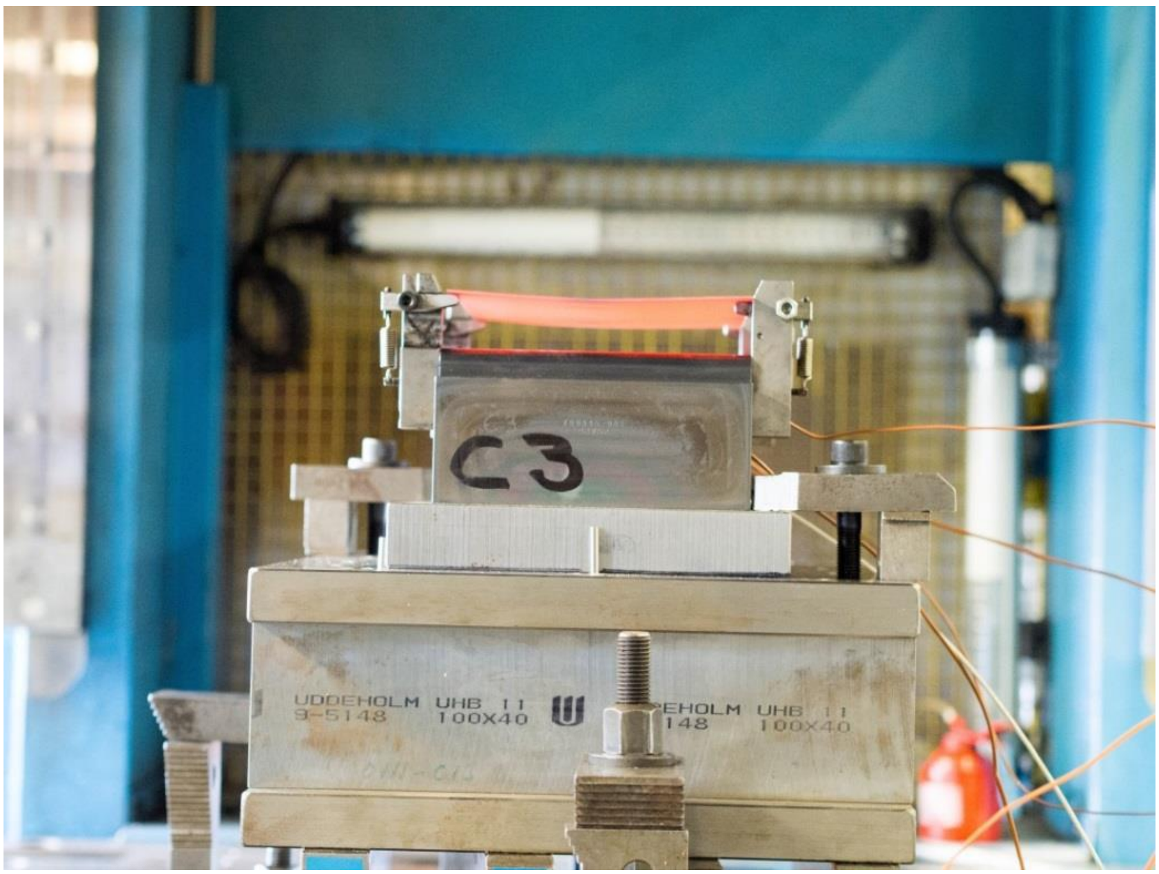
FORSKNING OCH INNOVATION

Analysis for robust sheet forming processes at high temperatures – Hotform



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Program: Sustainable Production

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1. Summary

The Hotform Project set out to obtain robust physical data on the hot forming process for use in improving the quality of finite element simulations used in the design and verification of parts and tooling for manufacturing press hardened auto body components.

New information was obtained on the microstructure and processing of pressing hardening steels, along with information on the thermophysical and thermoelastic properties of tools and sheet materials. A number of new and novel laboratory and semi-industrial scale test methods were developed which yielded new information on friction in the hot forming process, as well as heat transfer and formability of sheet steels at elevated temperatures. The Project was able to deliver a large body of measurements and process data obtained at laboratory and semi-industrial scale related to the hot forming process, including:

1. For four modern hot formable steels:

    a. Catalogue of annotated microstructures and corresponding micro hardness measurements
    b. Continuous cooling diagrams (CCT) and fractional transformation diagrams (CFT) detailing phase transformation temperatures and kinetics
    c. Heating and cooling thermal expansion coefficients
    d. Thermo-physical properties measurements
    e. Thermo-physical properties calculations and tabulations under assumed stamping conditions
    f. Measurements of deformation behaviour in uniaxial tension

2. For each of the three tool materials used in the project:

    a. Thermo-physical properties measurements
    b. Thermal expansion coefficient measurements

3. Development of a method for evaluating biaxial deformation behaviour of sheet steels at hot stamping temperatures using gas pressure deformation

4. Development of a hot tensile testing method utilizing the Aramis strain measurement system for simulating hot forming in a standard tensile testing frame

5. Design and manufacture of a tool for forming limit curve testing in a semi-industrial scale press using the Aramis strain measurement system

6. Detailed analysis of the structure and composition of Al-Si coatings after heating to austenitisation temperatures in both convection and induction heating processes

7. Development of a robust hot bending-under-tension test method for evaluating the tribology and friction behaviour

8. Measured friction coefficients for 12 different combinations of tool material, tool surface roughness and three different types of surface coating at hot forming temperatures

2. Background

The demand for lighter, higher strength vehicle bodies is driving the rapid expansion of the use of hot formed and press hardened advanced high strength steels. Current predictions suggest that the body-in-white of future passenger vehicle will contain up to 35% press hardened material and hot formed steel by weight. This increased use of hot formed steel in auto bodies marks the transition of press hardening from an important niche production technology for a limited number of critical body structural elements, and into a more general purpose, high volume forming process. Furthermore, techniques such as tailor welded and rolled hot forming blanks made from press hardening steels of different strengths, hardenability levels and thicknesses are being more widely applied to improve crash worthiness, save weight and reduce costs.

This expansion of the volume and complexity of hot formed parts has increased the demands for accurate simulation tools for panel and tool design and verification. Building accurate and robust simulations of the hot forming process requires a detailed understanding of and high quality, quantitative data for a number of key features of what is a technologically very complex process, including:

- The physical metallurgy, microstructure and properties of modern hot formable steels during and after the hot stamping process
- The thermophysical properties (thermal diffusivity, thermal expansion) of modern sheet steels and modern tool materials used in the hot stamping process
- The constitutive behaviour (strength, work hardenability, anisotropy) of the sheet material during forming
- Real temperature-time histories of the formed sheet during hot forming, and heat transfer between sheet and tool in the pressing and hardening operation
- The behaviour of the Al-Si coating applied to modern hot formable steels during heating and forming
- The role of tool material and surface finish and the influence of different classes of surface coatings on heat transfer and friction and the tribology of the hot forming

The answers to these questions can be distilled down into a series of technical parameters and material data which are required for use in finite element simulation and computer aided design tools. The project aimed to develop methods and conduct experiments which would provide these technical parameters as a way of improving the productivity, quality, and usefulness of computer aided design and simulation tools for the hot stamping process.

3. Aims

The overall goals of the project were as follows:

1. Increase understanding of key technical features of the hot forming process
2. Develop new experimental methods for the analysis of hot forming to yield critical data for improved computer aided design and simulation of hot formed parts
3. Enhance hot forming simulation accuracy
4. To shorten lead times for hot forming tool design, verification, and production
5. To maximize the efficiency of the forming tools relative to their cost
6. To increase the productivity of the hot forming process

4. Implementation

The consortium selected four commercially available press hardenable steels which are used singly or in tailor welded blanks

Arcelor Mittal Usibor 1500P AS150 Al-Si metal coated boron steel
Arcelor Mittal Ductibor 500 AS150 Al-Si metal coated microalloyed steel
Thyssen Krupp MBW1500 AS150 Al-Si metal coated boron steel
Thyssen Krupp 500 AS150 Al-Si metal coated microalloyed steel

Volvo Car procured approximately 500 kg of cut sheet from each of these grades A further coil of 50mm wide Usibor 1500 material was provided by Arcelor-Mittal to the project for use in the KIMAB hot bending-under-tension machine. A range of metallurgical, mechanical and thermophysical analyses were performed on these steels to develop a material data of the technical parameters required for finite element simulation of the hot forming process.

Three different tool materials, two different surface roughness and four different post machining surface treatments were selected for evaluating heat transfer and frictional properties of the hot forming process with different tool types. The resulting matrix contained 12 different combinations of material, surface finish and treatment (shown in Figure 1). Tools for press trials and friction testing were manufactured by the consortium from this matrix for use in the project.

Tool Material	**Surface treatment**							
	Uncoated		Nitrided		Balinit Alcrona Advanced		Balinit Lumena Advanced	
Orvar Supreme	0.1 Ra	0.4Ra	0.1 Ra	0.4Ra	0.1 Ra	0.4Ra	0.1 Ra	0.4Ra
Unimax	0.1 Ra	0.4Ra						
QR090	0.1 Ra	0.4Ra						

Figure 1: Matrix of tool materials and surface finishes used for manufacturing tooling

4.1 The project consortium and roles within the project

The project consortium consisted of nine partners, including two industrial research organisations, a university and six industrial companies. The complete project consortium comprised of the following actors:

Vinnova funded research partners
Swerea KIMAB AB, *coordinator*
Tekniska Högskolan i Jönköping
IUC i Olofström AB

Participating partners
AP&T Automation and Tooling AB
Dynamore Nordic AB
Oerlikon Balzers Sandvik Coating AB
Uddeholms AB
Volvo Lastvagnar AB
Volvo Personvagnar AB

The roles and activities by each partner within the project consortium can be summarised as follows:

Swerea KIMAB AB
Swerea KIMAB acted as coordinator in the project. KIMAB performed dilatometer analysis on hot formable sheet steels to establish CCT and fraction transformation diagrams, thermal expansion coefficients, microstructure analysis, and microhardness measurements. KIMAB developed novel laboratory scale simulation methods for evaluating friction and tribological features of the hot forming process, and for measuring deformation under biaxial states of stress at high temperatures. KIMAB also assisted in the planning, instrumentation, and execution of the pressing trials held at AP&T, and processed the results obtained from them.

IUC i Olofström AB
IUC Olofström developed two methods of measuring the deformation behaviour during simulated hot forming using the Aramis strain measurement system. One allowed hot tensile tests to be performed through a thermal cycle similar to that in commercial plant. The other utilizes a new tool design for use in a semi industrial press for evaluating forming limit curves at temperatures up to 600°C.

Tekniska Högskolan i Jönköping
Jönköping University performed measurements of thermophysical properties of both sheet and tool materials, and delivered a package of numerical results and equations for these properties.

Volvo Personvagnar AB
Volvo Cars provided requirements and specifications for material and process data, and procured sheet materials from Arcelor-Mittal and Thyssen-Krupp for use in the project. Volvo also provided high temperature uniaxial tension test data for the sheet steels. Volvo cars are implementing the results and know-how of the project into their computational tools for simulation of the hot forming process.

AP&T Automation and Tooling AB
AP&T coordinated the design and executed the manufacture of the tools for pressing and bending-under-tension trials, and ran a large campaign of press trials with the experimental tools for temperature measurement at their Blidsberg factory.

Uddeholms AB
Uddeholm Tooling provided three different tool steel materials to the consortium for analysis and for manufacturing tools for pressing trials at AP&T and laboratory scale bending under tension pins at KIMAB. Uddeholm also provided advice to the consortium about suitable heat treatment and processing for each tool steel during the manufacturing processes.

Oerlikon Balzers Sandvik Coating AB
Oerlikon Balzers performed finish polishing and surface coating on the experimental forming tools and pins using in the project. Oerlikon also provided advice to the consortium regarding the desired surface finish of the tools where coatings would be applied.

Dynamore Nordic AB
Dynamore Nordic followed the project and will implement the results and know-how of the project into their computational tools for simulation of the hot forming process

Volvo Lastvagnar AB
Volvo Trucks are integrating the results and know-how of the project into their design processes for hot formed components and tools

The base report for the project was submitted to Vinnova on the 9th of October 2012, and the kick-off meeting held on the 28th of November 2012. During the course of the project, the consortium met on twelve occasions to plan the work in the project and review progress and results. Progress reports were submitted to Vinnova in July 2013, September

2013, and April 2014. In February 2014, the consortium elected to request a six month extension in the project, mainly to mitigate the cumulative effects of availability of material and equipment required to perform some of the experimental work. This request was approved by Vinnova on the 5th of March 2014. The project final meeting was held on the 26th September 2014.

5. Results

The major results in the project came in the form of a large database of material data for both sheet and tool materials, and new physical simulation methods for measuring features of the contact between Al-Si coated press hardenable steel sheets and different types of tool materials. From these test methods, friction coefficients and heat transfer coefficients were derived and related to process variables in the hot forming process.

Material data for hot forming sheet steels and tools
A database of material properties for four common hot formable steels and three common hot forming tool materials, including

1. For each of the four sheet steels used in the project:
    a. Catalogue of annotated microstructures and corresponding micro hardness measurements under different simulated hot stamping conditions
    b. Continuous cooling diagrams (CCT) and fractional transformation diagrams (CFT) detailing phase transformation temperatures and kinetics
    c. Heating and cooling thermal expansion coefficients
    d. Transformation strain calculations
    e. Thermo-physical properties measurements (heat capacity, thermal conductivity, thermal diffusivity)
    f. Thermo-physical properties calculations and tabulations under assumed hot stamping conditions
    g. Measurements of deformation behaviour in uniaxial tension
2. For each of the three tool materials used in the project:
    a. Thermo-physical properties measurements(heat capacity, thermal conductivity, thermal diffusivity)
    b. Thermal expansion coefficient measurements

Temperature measurements and contact heat transfer conditions between tool and blank

A novel tool design was developed by the project consortium for measuring the temperature of the tool and blank during pressing using a combination of in-situ optical pyrometry and contact thermocouples. Twelve tools using different tool steels, and surface treatments were manufactured from this design and using in a large campaign of pressing trials. The resulting temperature data was analysed using an inverse method to yield heat transfer coefficients. An illustrated of this process and examples of the results obtained are shown in Figure 3.

<u>Laboratory scale measurement of friction between the tool and blank under simulated press hardening conditions</u>

An existing bending-under-tension test method for evaluating the tribology and friction of cold forming processes was adapted for simulating the hot forming process. A planar induction heating system and temperature control automation was developed to allow the temperature of the test piece to closely follow that of full-scale commercial hot stamping line furnaces. Detailed analysis of the structure and composition of Al-Si coatings after heating to austenitisation temperatures in both convection and induction heating processes was performed to confirm that the coating microstructures obtained by induction heating were comparable to conventional convection heating systems used in industry.

Using this test method, measured friction coefficients were obtained under typical forming conditions for 12 different combinations of tool material, tool surface roughness and three different types of surface coating. It was found that adhesive contact dominates the sliding friction between sheet and tool between 600°C and 700°C with the coating in compression, leading to surprisingly high friction coefficient values. An illustration of this test and example results are shown in Figure 4.

<u>New laboratory scale test methods for simulating the hot forming process</u>

A number of novel laboratory scale mechanical test methods were developed and trialled in the project with the objective of generating data for forming curves and limit diagrams. These included:

1. Development of a method for evaluating biaxial deformation behaviour of sheet steels at hot stamping temperatures using gas pressure deformation with the Autogrid strain measurement system
2. Development of a hot tensile testing method utilizing the Aramis strain measurement system for simulating hot forming in a standard tensile testing frame
3. Design and manufacture of a tool for forming limit curve testing in a semi-industrial scale press using the Aramis strain measurement system

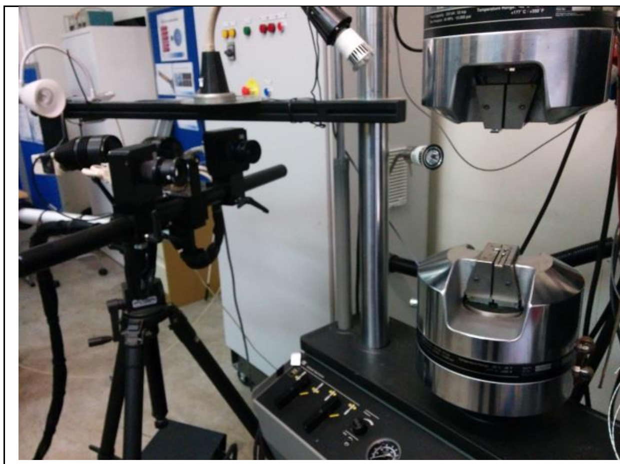
Some of these test apparatuses are shown in Figure 2.

5.1. Contribution to FFI goals

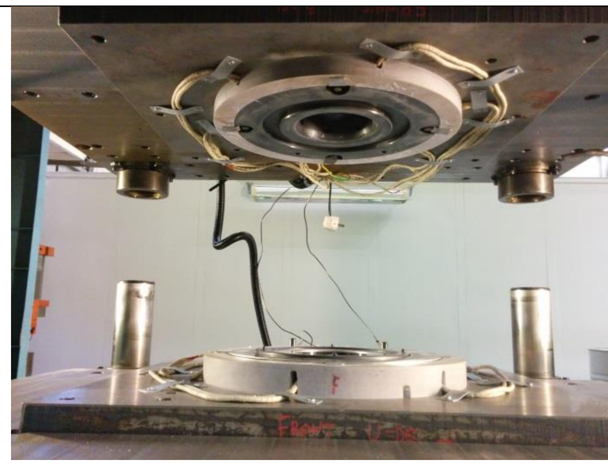
The research consortium in the project is a truly vertical one, including material suppliers, an equipment supplier, two vehicle manufacturers (including a press hardening line operator), and an analysis software supplier. The composition of this consortium is such that the results obtained in the project have been disseminated to the complete supply and operation chain within the Swedish automotive industry, and rapid implementation and exploitation of the project results is already underway. As such, the project satisfies the FFI program goal of ensuring that new knowledge is generated and implemented, and that existing knowledge is implemented in industrial applications.

The results and data produced in this project are also being used to directly support the start-up and operational activities of the two new hot forming lines at the Volvo Personvagnar plant at Olofström, Sweden. Because of this, the project has contributed to the FFI program goal of contributing to concrete production improvements made to the participating companies.

Figure 2: Equipment and test methods developed for evaluating hot formability of commercially available press hardening steels



(a) Hot tensile testing system using the Aramis strain measurement system for evaluating deformation behavior at pressing temperature, developed at IUC Olofström

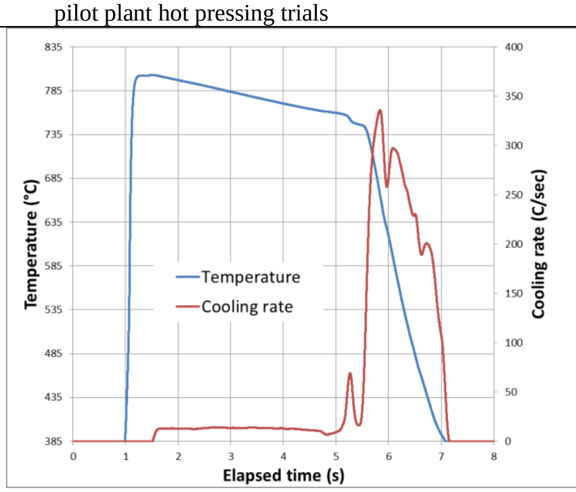


(b) Hot biaxial forming press for evaluating forming limits at temperatures up to 600°C, developed at IUC Olofström

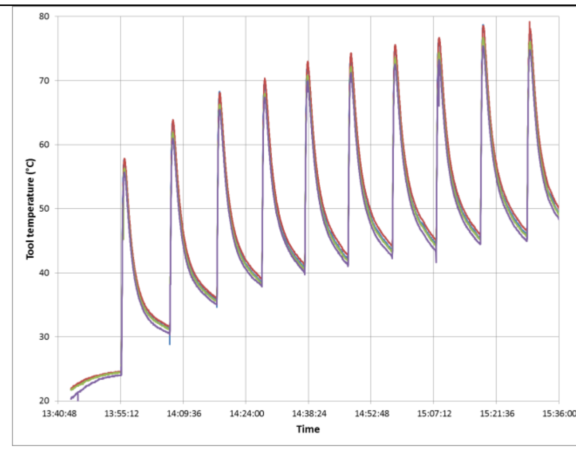
Figure 3: Equipment developed for measuring temperatures and estimated heat transfer coefficients during pilot plant press trials

(a) Instrumented press tool developed in the project for measuring the temperature of tool and blank during pilot plant hot pressing trials

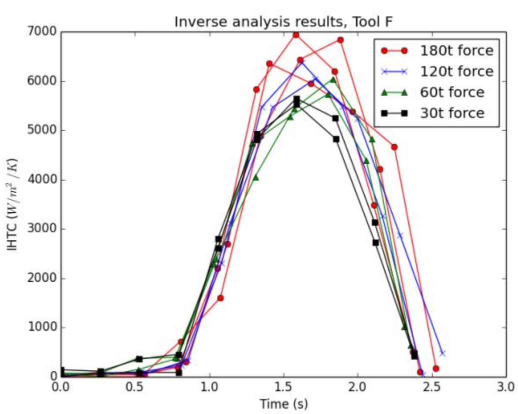
(b) Hot boron steel blank during pressing trials with an experimental tool at AP&T Blidsberg



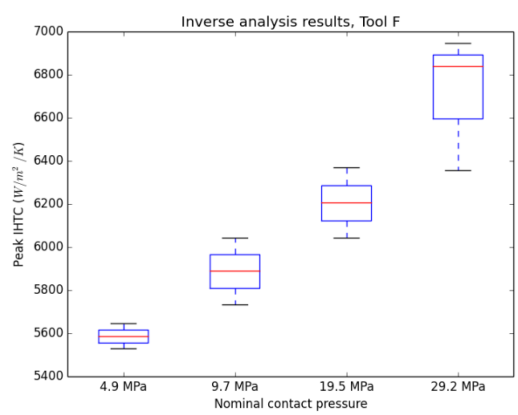
(c) Measured temperature and cooling rate of a blank during pressing



(d) Measure temperature of an experimental tool during a campaign of 10 blanks

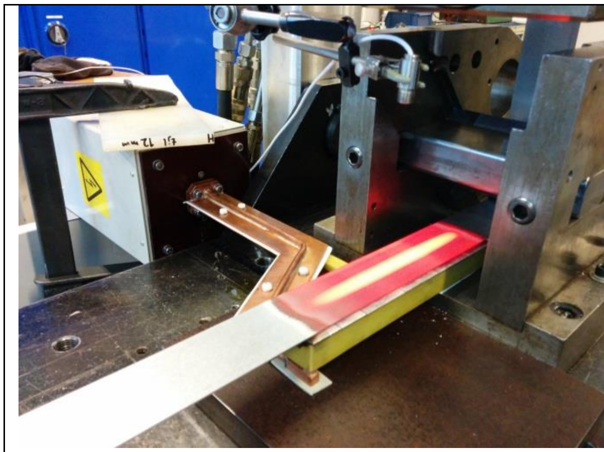


(e) Inverse analysis estimated heat transfer coefficient histories during pressing



(f) Correlation between press contact pressure and inverse estimated heat transfer coefficients

Figure 4: The hot bending-under-tension test method developed for evaluating friction during hot forming

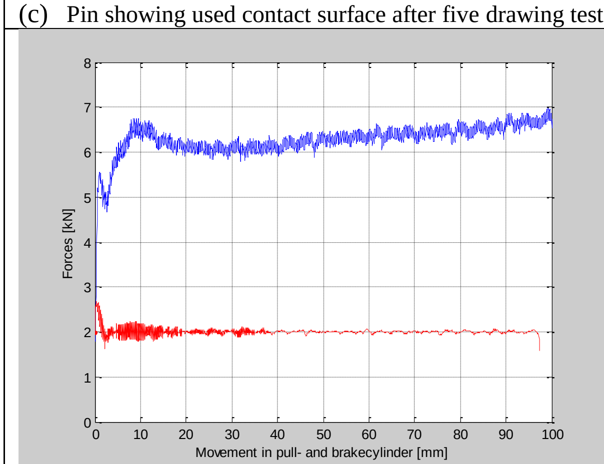


(a) Al-Si coated Boron steel during in-situ heating in the bending-under-tension machine at Swerea KIMAB

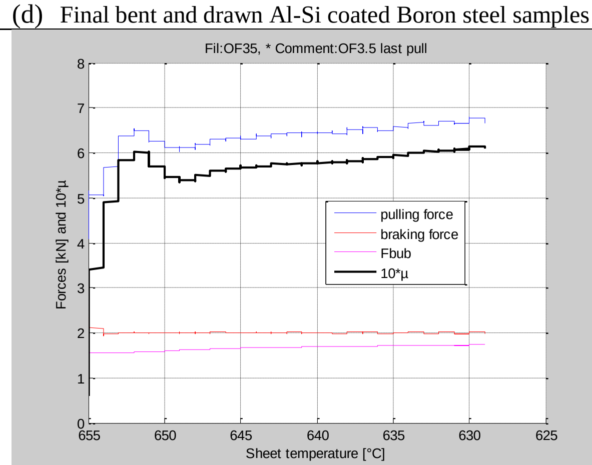
(b) PVD coated drawing pins manufactured by AP&T and Oerlikon using tool material supplied by Uddeholm.

(c) Pin showing used contact surface after five drawing tests

(d) Final bent and drawn Al-Si coated Boron steel samples



(e) Measured pulling and brake forces during a drawing simulation



(f) Computed friction coefficient after sheet bending and unbending forces have been removed

6. Dissemination and Publication

The first stage of dissemination plans will be compilation of all the results produced in the project into a detailed technical Annex and database for all the project partners. A seminar to discuss implementation needs and follow-up from the project is planned for 2015. Subject to resolution of intellectual property and secrecy discussions within the project consortium, it is planned to present selected results from the project at the FFI workshop on sheet metal forming in May 2015, and at the 3rd workshop on high temperature tribology, which will be held at Luleå Technical University in June 2015. Further dissemination activities on specific aspects of the results obtained in the project are expected in 2015, including a peer reviewed journal paper.

7. Conclusions and further research

The activities within this project have been able to produce a lot of high quality data relating to the thermal, metallurgical, tribological and mechanical features of the modern press hardening process with Al-Si metal coated steels. The data will make a positive contribution to advancing the state-of-the-art in simulation of the hot forming process.

However, one area which has proven to be very challenging is generating biaxial and plane strain deformation data at temperatures above 600°C, which is key to generating forming curves. KIMAB tested a gas based biaxial testing system in the project, but this proved not to be very robust. IUC Olofström developed a functional press based system and tensile testing methods in the project, but this approach is currently limited to a temperature of 600°C and cannot easily follow the thermal cycle of the blank in commercial press hardening press. Plane strain tensile tests conducted by KIMAB in a Gleeble thermomechanical simulator using convention grid and speckle pattern systems for optical strain measurements at 600-900°C also failed to yield good quality data. High temperature mechanical testing techniques for constructing forming limit diagrams remain a major challenge which will require further research.

8. Participating parties and Contacts

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