Benchmark 3 - springback of an Al-Mg alloy in warm forming conditions

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Benchmark 3 – Springback of an Al-Mg alloy in warm forming conditions

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Abstract. Accurate prediction of springback is a long-standing challenge in the field of warm forming of aluminium sheets. The objective of this benchmark is to predict the effect of temperature on the springback process through the use of the split-ring test [1] with an Al-Mg alloy. This test consists in determining the residual stress state by measuring the opening of a ring cut from the sidewall of a formed cylindrical cup. Cylindrical cups are drawn with a heated die and blank-holder at temperatures of 20, 150 and 240°C. The force-displacement response during the forming process, the thickness and the earing profiles of the cup as well as the ring opening and the temperature of the blank are used to evaluate numerical predictions submitted by the benchmark participants. Problem description, material properties, and simulation reports with experimental data are summarized.

Keywords: Deep drawing, warm conditions, Al-Mg alloy, springback

1. INTRODUCTION

Nowadays, aluminium alloys are increasingly used in the automotive industry, since they allow weight reduction in body-in-white. However, the large springback that occurs after aluminium alloy sheets have been formed at room temperature is one of the main reasons why this material has not been more widely used. In order to overcome this issue, good results on the stamping process are obtained for aluminium alloys when the temperature is elevated up to an intermediate temperature, below the recrystallisation temperature. This process is called warm forming, that promoted a great interest during the last few years, especially with the 5xxx series (Al–Mg alloys). The warm forming process has now become a widely used alternative to the classical forming processes performed at room temperature.

The aim of this benchmark is to investigate experimentally springback tests performed on an AA5086 alloy under warm forming conditions, such as to serve as a reference to compare the results obtained by numerical simulations. An experimental setup has been designed to perform the deep drawing of a cylindrical cup by heating the tools separately. Indeed, several authors have shown that the formability increases when selective localized heating strategies are applied to the forming tools, causing an inhomogeneous distribution of the temperature in the blank. Therefore, the aim is to confirm this improvement of the formability and to study the effects of warm forming conditions on residual stresses and springback. For that purpose, the springback is determined by measuring the opening of a ring cut from the sidewall of a drawn cylindrical cup (see Fig.1). This is the so-called split-ring test that was first presented by Demeri et al. [1]. It provides a simple and effective way of predicting the forming and springback properties of alloys based on experimental measurements.

Cylindrical cups are drawn with a heated die and blank-holder at temperatures of 20 (room temperature), 150 and 240°C. The force-displacement response during the forming process, the thickness and the earing profiles of the cup as well as the ring opening and the temperature of the blank are used to evaluate numerical predictions submitted by the benchmark participants.

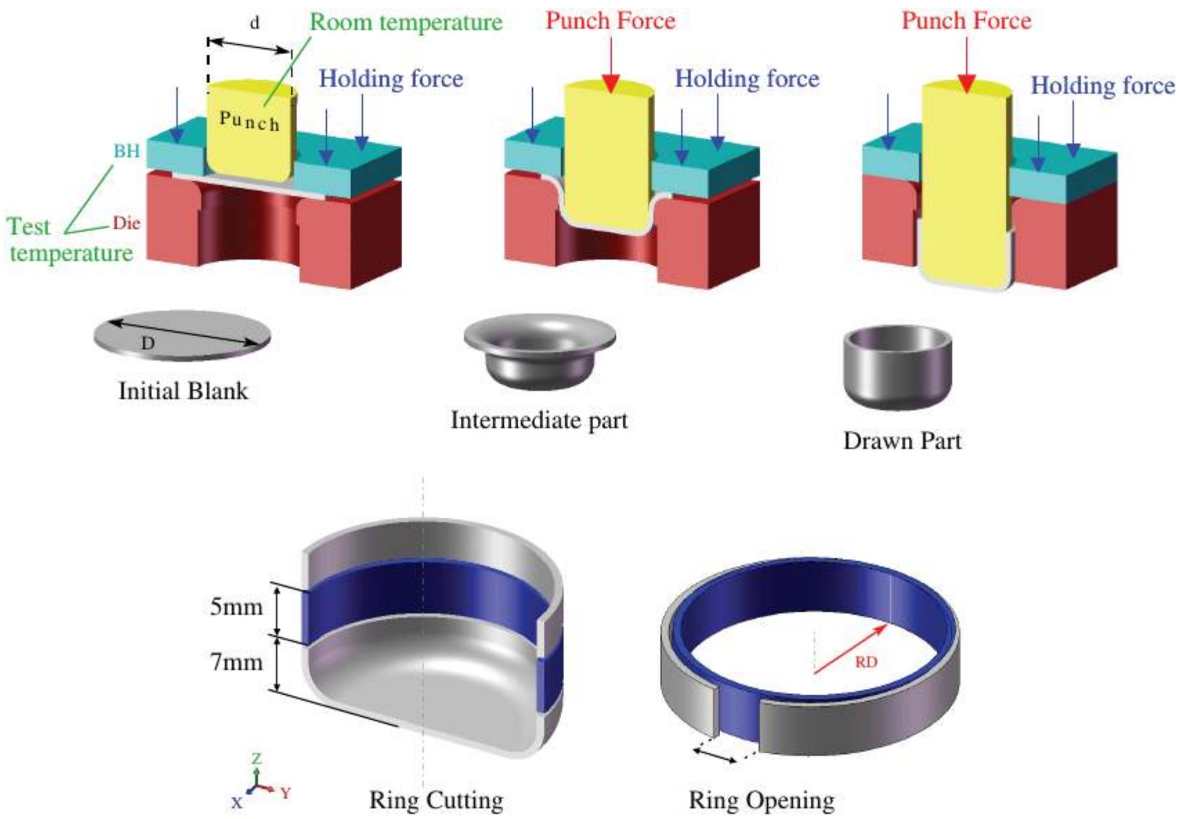


Figure 1: Main steps in the split-ring test

To simulate this process, a temperature-dependent anisotropic constitutive model is required for the material. The parameters of hardening models and strain rate dependency can be identified using data given in uniaxial tensile and shear tests at various temperatures and strain rates as well as biaxial expansion test, in order to account for temperature, viscous effects and anisotropy in a coupled thermo-mechanical constitutive law. Shell elements, solid elements, or solid-shell elements are recommended for this benchmark with careful control of the incremental punch stroke, with sufficient number of elements in the mesh to reproduce the curvature of the die and to capture plastic strain accurately. The analysis in this benchmark is highly non-linear, including thermal, viscosity and anisotropy. It is recommended to use a simple isotropic material model (such as von-Mises yield function) before attempting an advanced anisotropic material model.

This benchmark study has the main objective of predicting springback after warm forming, cutting and opening. Different challenging outputs will be required as a function of forming temperature:

i) Prediction of earing after the warm forming operation due to the plastic anisotropy of the material;
ii) Prediction of thickness profiles for several orientation to the rolling direction after the warm forming operation;
iii) Prediction of springback through ring opening;
iv) Prediction of punch force-punch stroke and temperature of the blank evolutions.

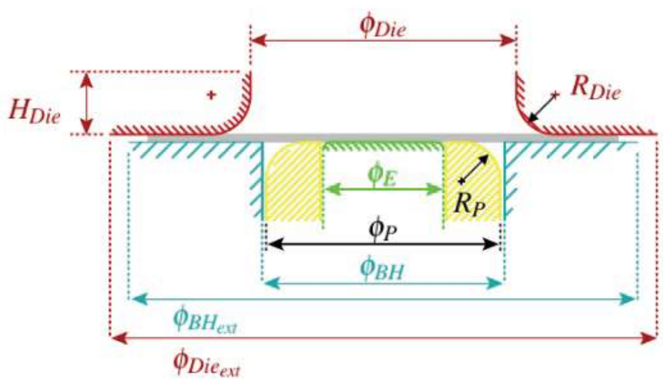
2. DESCRIPTION OF FORMING OPERATIONS

This section contains a description of the warm forming, cutting and opening operations for this benchmark.

2.1 Drawing operation

The benchmark is based on a paper presented in [2]. Cylindrical cup forming tests (Swift tests) are carried out on a Zwick/Roell Amsler BUP 200 sheet metal testing machine. A diagram of the deep-drawing procedure is presented in Fig.1. The blanks can be heated between the die and the blank-holder up to 240°C. Heating is obtained using electrical rods embedded both in the die and in the blank-holder. Axial water input and output channels are machined into the punch that allow controlling the temperature of the punch. An ejector located inside the punch is used to eject the cup from the punch at the end of the forming process. Type K thermocouples (TC) are used to control the temperature of the blank, the punch, the die and the blank-holder.

The geometry of the tools is given in Fig.2. The material is a rolled sheet of AA5086 aluminium alloy of 0.8 mm thick. The circular blank has an initial diameter of D=60 mm. At the beginning of the test, an oil lubricant (Jelt Oil) is applied manually on both sides of the blanks. To fully draw the cup, a punch displacement of 32.5 mm is imposed with a constant punch travel speed of 5 mm/s. The punch force, the punch stroke and the blank-holder force are recorded during the test.



Tool Dimensions [mm]

ϕ_{Die}	R_{Die}	H_{Die}	ϕ_P	R_P
35,25	5	8,75	33	5

ϕ_{BH}	$\phi_{BH_{ext}}$	$\phi_{Die_{ext}}$	ϕ_E
33,6	70	80	20

Figure 2: Dimensions of the tools used in the Swift-cupping test

All the tools are axisymmetric. The blank-holder force at the beginning of the deep drawing operation is set to 5 kN, and this force is maintained until the cup is fully drawn. Heating is applied using electrical heating rods as shown in Fig.3. The set of tools used includes:

i) A draw die composed of two inserts containing a resistance coil and a copper plate;
ii) A blank-holder machined with a suitable upper annular insert for placing the heating rods;
iii) The punch and the internal ejector;
iv) A base used to support previous parts, connected to the BUP 200 machine.

The positions of thermocouples used to control the temperature of the punch, the die and the blank-holder are shown in Fig. 3. In the die, the thermocouple (TC-Die) is located on a diameter $\phi_{TC\text{-}Die}$ = 38.4 mm, 1 mm from the contact surface. In the blank-holder, TC-BH is located on a diameter $\phi_{TC\text{-}BH}$ = 47.3 mm, 1 mm from the contact surface and for the punch, TC-Punch is located under the ejector, on a diameter $\phi_{TC\text{-}Punch}$ = 16 mm, 1.5 mm from the contact surface. The evolution of the temperature of the tools is supposed homogeneous around the circumference and as those of the thermocouples, and is given as a function of the punch stroke in the file **BM3_Process.xlsx** for each temperature. The resulting temperature of the blank is measured on the side in contact with the die, at a location of $\phi_{TC\text{-}Blank}$ = 11.5 mm for the orientation of 22.5° to the rolling direction.

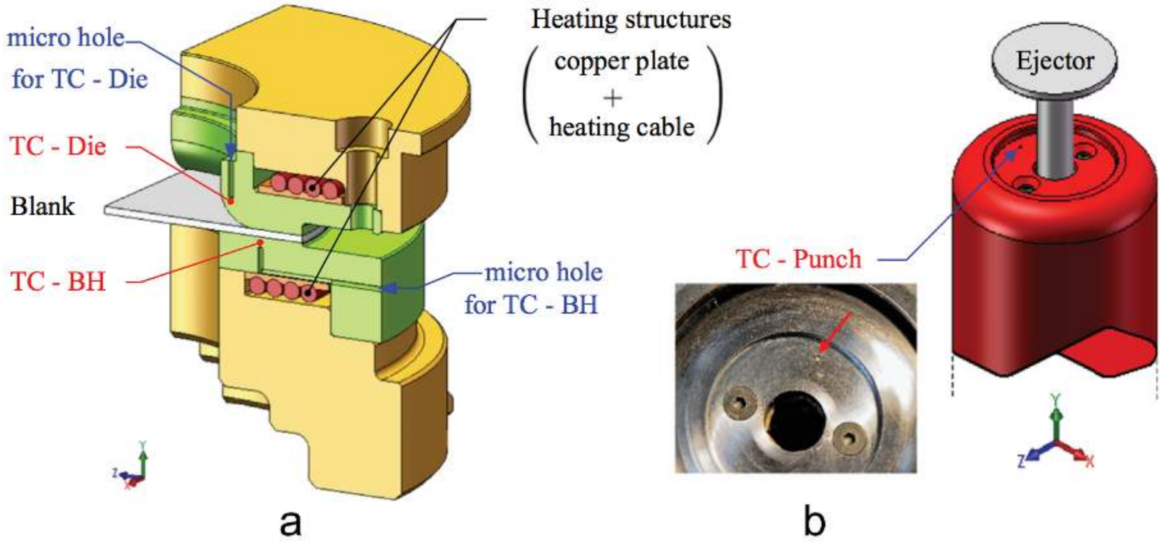


Figure 3: Heating parts in the tools and location of the thermocouples (TC)
(a) Die and BH, (b) Punch and ejector

2.2 Springback

Rings are cut from the sidewall of a formed cylindrical cup and split perpendicularly to the circle plane, in the rolling direction (RD). The cutting and splitting operations are carried out using a wire electro-erosion machine. Ring gap measurements are performed along the straight line connecting the two ends of the split rings (see Fig.1) in order to characterize residual stress state and to measure the springback effect.

2.3 Tool Materials

- Punch: XC38CrMoV5 Tool steel, 58-60 HRC, 2-4 Finish working surfaces
- Die: XC38CrMoV5 Tool steel, 58-60 HRC, 2-4 Finish working surfaces
- Blank-holder: XC38CrMoV5 Tool steel, 58-60 HRC, 2-4 Finish working surfaces

2.3 Experimental Measurements

The distributions of the thickness of the cup are measured in several directions (rolling direction RD, transverse direction TD, diagonal direction DD) from the center to the outer diameter every 1 mm in curvilinear distance, using a 3-D measuring machine. The curvilinear distance corresponds to the length of the average fiber of the cup. The earing profiles of the cups are also recorded and the cup height is plotted from the bottom of the cup as a function of the angular position (every 5°) to the RD. The punch force-displacement curves as well the temperature of the tools and the blank are recorded during the forming test. To help participants, the evolutions of temperatures of the tools as well as the temperature of the blank during the forming process are given in **BM3_Process.xlsx** file (see Fig.4). For example, these temperatures may be used to estimate the contact heat transfer coefficient. Thus, the participants can evaluate the relevance of their thermomechanical simulations on the temperature of the blank. Rings of 5 mm high are cut 7 mm from the bottom of the cups (see Fig.1), perpendicularly to the revolution axis of the cup. Ring gap measurements are performed along the straight line connecting the two ends of the split rings in order to evaluate the springback.

Time (s)	F - BH (kN)	Tc-Punch (°C)	Tc-BH (°C)	Tc-Blank (°C)	Tc-Die (°C)
0.000	5.258	23.860	23.563	23.662	23.364
0.005	5.265	23.860	23.563	23.662	23.265

Figure 4: Experimental data contained in the file **BM3_Process.xlsx**. For each temperature (RT, 150°C and 240°C), from columns left to right: time (s), blank-holder force (kN), Temperatures of the tools and the blank (Punch, Blank-holder, Blank and Die)

3. BLANK MATERIAL

The material used is sampled from a rolled sheet of 0.8 mm thick AA5086-H111 aluminium alloy. This material presents, at least at room temperature, the Portevin-Le Châtelier (PLC) effect. This effect is no more present for temperatures above 200°C. For the material parameters required in the constitutive models, the material is characterized under different conditions (temperature and strain rate) and strain paths (tensile, shear, bulge). Uniaxial tensile tests are performed under isothermal conditions at room temperature (20), 150 and 240°C. Tensile tests at room temperature are performed on a hydraulic Instron 8803 machine while the tests at 150 and 240°C are carried out with a Gleeble 3500 testing machine where the specimen is heated by Joule effect [3]. On this last machine, a constant crosshead velocity is difficult to achieve and the strain rate is thus non linear. For all the tensile tests, the participants can calculate the strain rate by fitting the time-strain signal. For the strain rate effects, a decade has been imposed between two consecutive tests, denoted by x1, x10 and x100.

Monotonous and reverse shear tests for several values of pre-strains are provided in order to evaluate Bauschinger effect and therefore kinematic hardening. Shear tests are performed with a tensile machine, using a specific shear device placed in a heating furnace [4]. But due to experimental considerations, it was not possible to reach temperatures higher than 150°C. Shear samples have been machined at dimensions: 60x15mm^2 and the shear width is constant equal to 3mm (see [4] for details). Finally, biaxial tests are carried out in a hydraulic bulge test setup only at room temperature. The material data necessary to identify the influence of temperature, anisotropy and strain rate is given in Section 5 and in the Excel file **AA5086-H111.xlsx**.

4. BENCHMARK REPORT

All results are expected to be reported using the benchmark report template **BM3_Report.xlsx**, which can be downloaded from the conference website, and when completed, uploaded to the website at a later date to submit the entry. The report file contains the following informations:

4.1 General description

1) Benchmark participant: name, affiliation, address, email and phone number
2) Simulation software: name of the FEM code, general aspects of the code, basic formulations, element/mesh technology, type of elements, number of elements, contact property model and friction formulation
3) Simulation hardware: CPU type, CPU clock speed, number of cores per CPU, main memory, operating system and total CPU time
4) Material model: Yield function/Plastic potential, Hardening rule and Stress-Strain Relation, and heat transfer model
5) Remarks

4.2 Simulation results

1) Earing profiles plotted through Cup height (h mm) after the warm forming operation for each temperature (RT, 150, 240°C), measured from the lower surface to the upper edge of the cup around the circumference starting from the rolling direction (0°) to 360°, reported every 5°
2) Plot of punch load (kN) vs punch stroke (mm) during the cup forming operation for each temperature (RT, 150, 240°C). The zero punch stroke is defined as the position when the punch makes initial contact with the blank with no interaction forces
3) Blank surface temperature as a function of punch stroke on the side in contact with the die, during the test for RT, 150 and 240°C. The temperatures of the tools should also be given for each test temperature
4) Thickness distribution (mm) vs curvilinear distance from the cup center after the forming operation, in the rolling direction (0°), transverse direction (90°) and diagonal direction (45°) for each temperature (RT, 150, 240°C). For the curvilinear distance, the medium thickness should be considered. The experimental values are the average between the four quarters of the cup
5) The ring opening (mm) for each temperature (RT, 150, 240°C) measured as the straight line connecting the two ends of the ring. As the ring may be slightly conical, the distance should be measured at the mid-height of the ring.

5. MATERIAL CHARACTERIZATION

Table 1. Elastic mechanical properties

Sample	Density	Young's modulus	Poisson's ratio
	g/cm3	GPa	
AA5086	2.70	71.7	0.31

Table 2. Uniaxial tension test data[1]

Test orientation	YS MPa	UTS MPa	% Elongation	r value
RD – 20°C	138.5	267.4	22.15	0.71
DD – 20°C	135.0	258.4	28.90	1.08
TD – 20°C	138.8	256.8	23.90	0.73
RD – 150°C	148.4	246.1	29.50	0.63
DD – 150°C	139.7	232.9	31.80	0.97
TD – 150°C	142.6	237.1	23.90	0.66
RD – 240°C	119.4	150.4	39.25	0.60
DD – 240°C	115.7	141.7	40.70	0.88
TD – 240°C	114.9	142.0	36.60	0.67

Table 3. Thermal properties of AA5086-H111

Material	AA5086-H111
Thermal expansion coefficient	2.2×10^{-5}
Specific heat (J/kg.°C)	900
Thermal conductivity (W/m.°C)	220
Inelastic heat fraction (%)	100

[1] Stress-strain curves are provided in the Excel file **AA5086-H111.xlsx** for several strain rates and temperatures. Equal Biaxial Tension Test Data and Reversed shear stress data are given directly in the Excel file.

Table 4. Mechanical and thermal properties of the tools

Tools	XC38CrMoV5
Density (kg/m^3)	8150
Young modulus (GPa)	215
Poisson's ratio	0.3
Thermal expansion coefficient	1.19×10^{-5}
Specific heat (J/kg.°C)	500
Thermal conductivity (W/m.°C)	25.
Contact heat transfer coefficient (W/m^2 °C)	To be estimated from the temperature of the tools
Die and BH temperature (°C)	20, 150, 240
Blank-Holder force (kN)	5
Punch speed (mm/s)	5
Friction coefficient (recommended)	0.09

6. REFERENCES

[1] M.Y. Demeri, M. Lou, M.J. Saran. A benchmark test for springback simulation in sheet metal forming, In Society of Automotive Engineers, Inc., Volume 01-2657 (2000)
[2] H. Laurent, J. Coër, P.Y. Manach, M.C. Oliveira, L.F. Menezes. Experimental and numerical studies on the warm deep drawing of an Al-Mg alloy, International Journal of Mechanical Sciences, 93 (2015) 59-72
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7. RESULTS

General description BM01

A. Benchmark participant	
Name	Bart Carleer, Alper Güner, Thomas Brenne
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B. Software/Hardware	
Name of the FEM code	AutoForm^plus R7
General aspect of the code	Static Implicit
Basic formulations	
Element/Mesh technology	
Number of elements	26000
Type of elements	Triangular elastic plastic shell, 11 integration points through thickness
Contact property model	Penalty method
Friction formulation	Coulomb friction
CPU type	
CPU clock speed	Intel Core i7-4910MQ - 2.90 GHz
Number of cores per CPU	8
Main memory	16 GB
Operating system	Windows 7 Professional
Total CPU time	Elapsed Time - RT: 08:49 , 150°C: 09:16, 240°C: 09:20 (minute:second)

C. Describe the material model	
Name of the material model	Barlat
Yield Function/Plastic Potential	Barlat89
Hardening Rule	Strain rate dependent isotropic hardening with temperature dependent r-values
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	

D. Remarks
Temperature of blankholder and die are modeled as constant. Punch and sheet temperature change is calculated through thermo-solver. Plotted punch temperatures are measured directly on the surface of the punch. So there is no delay due to depth of measurements or air gap.

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General description BM02

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B. Software/Hardware	
Name of the FEM code	AutoForm^plus R7
General aspect of the code	Static Implicit
Basic formulations	
Element/Mesh technology	
Number of elements	26000
Type of elements	Triangular elastic plastic shell, 11 integration points through thickness
Contact property model	Penalty method
Friction formulation	Coulomb friction
CPU type	
CPU clock speed	Intel Core i7-4910MQ - 2.90 GHz
Number of cores per CPU	8
Main memory	16 GB
Operating system	Windows 7 Professional
Total CPU time	Elapsed Time - RT: 08:14 , 150°C: 09:00 and 240°C: 08:56 (minute:second)

C. Describe the material model	
Name of the material model	BBC Model
Yield Function/Plastic Potential	Banabic 2005 (BBC 2005)
Hardening Rule	Strain rate dependent isotropic hardening with temperature dependent r-values
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	

D. Remarks
Temperature of blankholder and die are modeled as constant. Punch and sheet temperature change is calculated through thermo-solver. Plotted punch temperatures are measured directly on the surface of the punch. So there is no delay due to depth of measurements or air gap.

General description BM03

A. Benchmark participant	
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Fax number	0049 231 9742 322

B. Software/Hardware	
Name of the FEM code	AutoForm^plus R7
General aspect of the code	Static Implicit
Basic formulations	
Element/Mesh technology	
Number of elements	26000
Type of elements	Triangular elastic plastic shell, 11 integration points through thickness
Contact property model	Penalty method
Friction formulation	Coulomb friction
CPU type	
CPU clock speed	Intel Core i7-4910MQ - 2.90 GHz
Number of cores per CPU	8
Main memory	16 GB
Operating system	Windows 7 Professional
Total CPU time	Elapsed Time - RT: 08:36 , 150°C: 09:18 and 240°C: 08:41 (minute:second)

C. Describe the material model	
Name of the material model	BBC Model
Yield Function/Plastic Potential	Banabic 2005 (BBC 2005)
Hardening Rule	Strain rate dependent isotropic hardening with temperature dependent r-values and temperature dependent Young's Modulus
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	

D. Remarks
Temperature of blankholder and die are modeled as constant. Punch and sheet temperature change is calculated through thermo-solver. Plotted punch temperatures are measured directly on the surface of the punch. So there is no delay due to depth of measurements or air gap.

General description BM04

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B. Software/Hardware	
Name of the FEM code	PAM Stamp 2015.1
General aspect of the code	Dynamic explicit
Basic formulations	Updated Lagrangian formulation with associated flow rule
Element/Mesh technology	
Number of elements	6500
Type of elements	Belytschko-Tsay underintegrated shell element
Contact property model	Non-linear penalty contact
Friction formulation	Coulomb friction
CPU type	
CPU clock speed	Intel Xeon E5410 @ 2.33 GHz
Number of cores per CPU	8
Main memory	16 GB
Operating system	Linux
Total CPU time	3 hours

C. Describe the material model	
Name of the material model	Vegter-Lite
Yield Function/Plastic Potential	Hocket-Sherby
Hardening Rule	isotropic
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	

D. Remarks

General description BM05

A. Benchmark participant	
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B. Software/Hardware	
Name of the FEM code	AutoForm plus R6
General aspect of the code	Implicit; Iterative Solver
Basic formulations	3-node Shells
Element/Mesh technology	
Number of elements	Adaptive mesh refinement: 6514 initially; 5721 at the end.
Type of elements	elastic shell (gravity) ; EP shell (drawing, cutting & springback)
Contact property model	Penalty method with automatically selected penalty; Tool stiffness = 50
Friction formulation	Coulomb: mu=0.09
CPU type	
CPU clock speed	4 GHz
Number of cores per CPU	8
Main memory	16GB
Operating system	Windows 10 education
Total CPU time	RT: one minute and eleven seconds; 150°C: one minute and twenty four seconds; 240°C: one minute and twenty three seconds

C. Describe the material model	
Name of the material model	AA5086-H111-2016-02-25
Yield Function/Plastic Potential	von Mises/von Mises
Hardening Rule	Isotropic Hardening
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	HTC to tool equals to 5.000 mW/(mm²K)

D. Remarks
A negative strain rate sensitivity of the material AA5086 was observed, however, the software AutoForm doesn't allow flow curves with a negative strain rate sensitivity. As a compromise, the fitted flow stresses at room temperature at strain rate 0.001 and 0.1, as well as at 150°C at strain rate 0.001 and 0.01 were slightly modified compared to the given data, so that higher strain rates lead to higher stress values at the same temperature

General description BM06

A. Benchmark participant	
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B. Software/Hardware	
Name of the FEM code	JSTAMP (Solver: LS-DYNA)
General aspect of the code	Nonlinear Implicit(heat transfer & springback) / Explicit(mechanical forming) Coupling
Basic formulations	Thermo-Elasto-Viscoplastic Material, Planar Anisotropy, Kinematic Hardening
Element/Mesh technology	
Number of elements	Blank(4,638) for Thermo-mechanical / Tools(16,915) for Themal Analysis Only
Type of elements	Nonlinear Thermal 12node Shell Formulation (Fully Integrated)
Contact property model	Surface to Surface Contact / Penalty Method
Friction formulation	Coulomb's Law of Friction
CPU type	
CPU clock speed	3.2GHz
Number of cores per CPU	8 Cores
Main memory	16GB
Operating system	Windows 7 Professional (64bit)
Total CPU time	Drawing (2 hours 10 minutes) / Cooling (4 minutes) / Springback (1 minute)

C. Describe the material model	
Name of the material model	MAT_3-PARAMETER_BARLAT (MAT036) / MAT_KINEMATIC_HARDENING_BARLAT2000 (MAT242)
Yield Function/Plastic Potential	Barlat and Lian [1989] for Non-isothermal / Barlat et al. [2003] for Isothermal Analyses
Hardening Rule	Isotropic for Non-isothermal / Non-linear Kinematic (Yoshida-Uemori) for Isothermal Analyses
Flow rule (Associated/Non Associated)	Associated Elastic Viscoplastic Thermal (Stress-Strain-Strainrate-Temperature)
Heat transfer model	Transient Analysis by Diagonal Scaled Conjugate Gradient Iterative Method

D. Remarks

We add a special sheet (2.4) that shows an isothermal analysis result for room temperature case in the report (referred as BM06b). The isothermal analysis for room temperature case was conducted using Yoshida-Uemori hardening and Barlat 2000 2d yield function for more accurate springback result. Non-isothermal analyses were conducted using the planar anisotropic yield function, Barlat 89, for the room temperature, 150C, and 240C cases respectively.

General description BM07

A. Benchmark participant	
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B. Software/Hardware	
Name of the FEM code	DD3IMP
General aspect of the code	Static fully implicit
Basic formulations	Updated Lagrangian formulation with associated flow rule
Element/Mesh technology	
Number of elements	30237
Type of elements	Isoparametric 3D brick elements with selective reduced integration technique
Contact property model	Rigid tools modelled by 390 Nagata patches, Augmented lagrangian method
Friction formulation	Coulomb friction law
CPU type	
CPU clock speed	3.5 GHz
Number of cores per CPU	4 cores
Main memory	16 GB RAM
Operating system	Windows 8 Professional (64-bit)
Total CPU time	6 hours (RT); 8 hours (150ºC and 240ºC)

C. Describe the material model	
Name of the material model	Elastoplastic
Yield Function/Plastic Potential	Barlat 91 (RT); Hill'48 (150ºC and 240ºC)
Hardening Rule	Voce + Frederick and Armstrong (RT); Hockett-Sherby (150ºC and 240ºC)
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	Classical Fourier´s law for heat conduction

D. Remarks
For the thermal problem, a constant temperature was assumed for the rigid tools.

General description BM08

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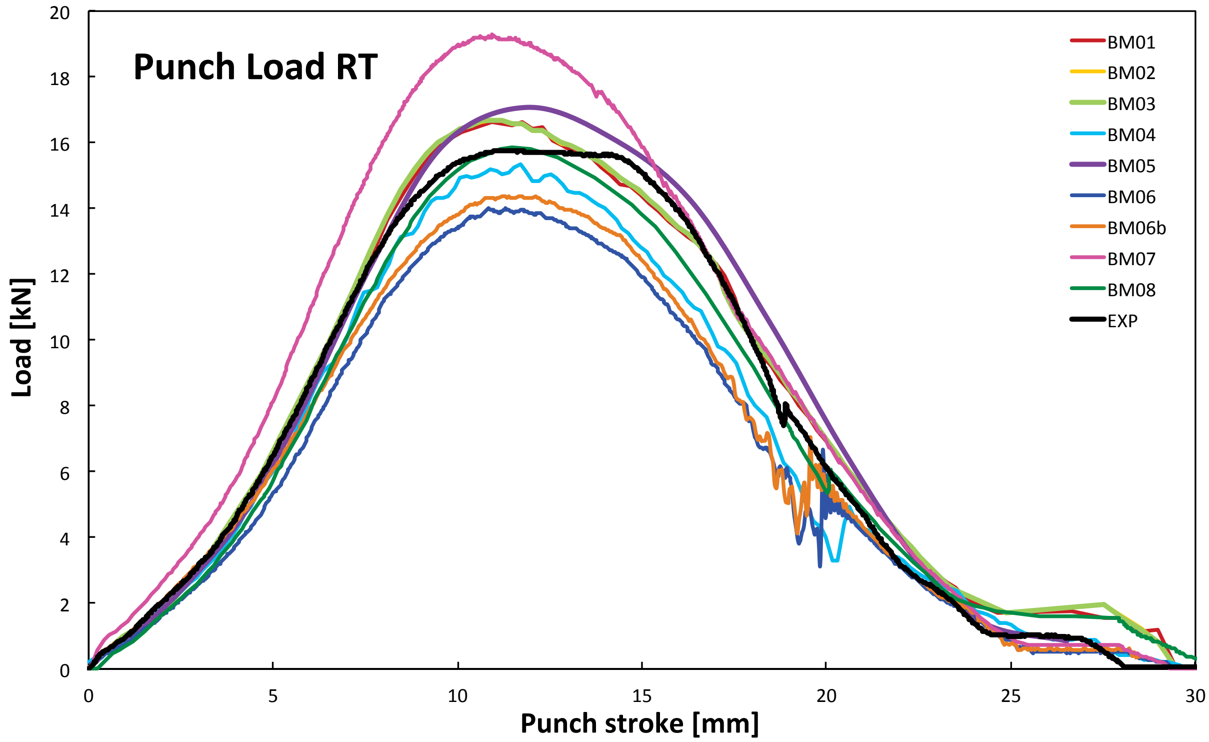
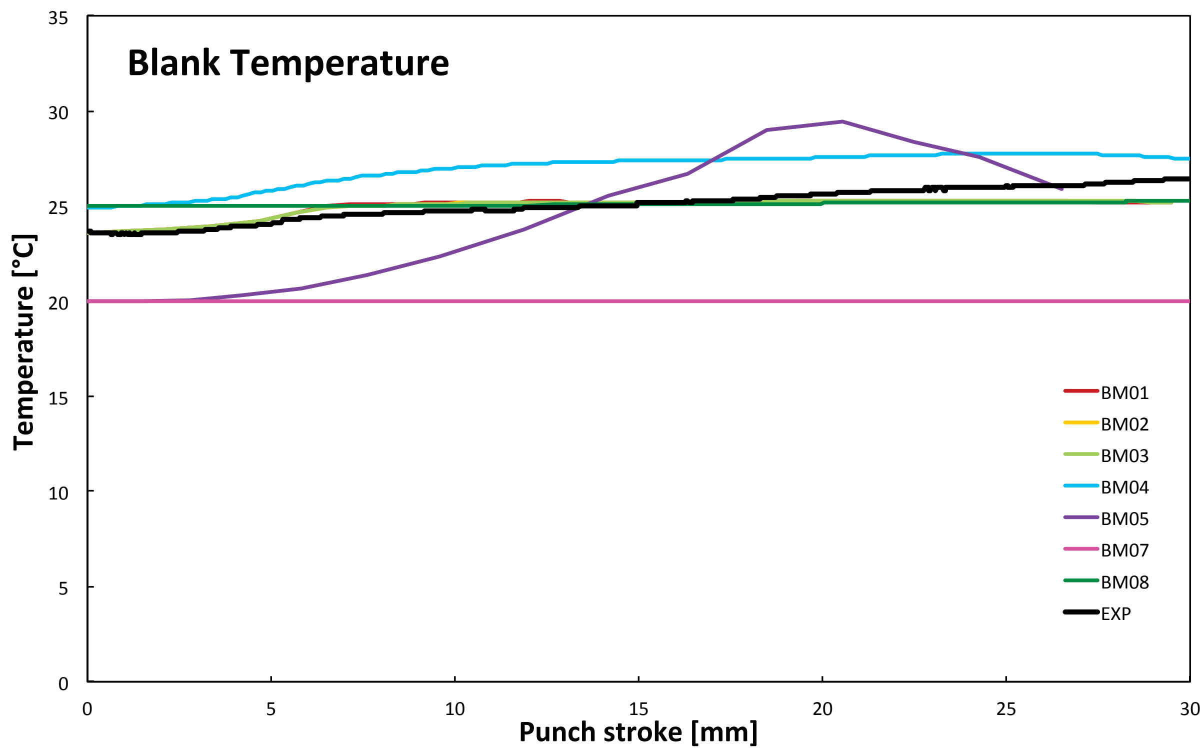
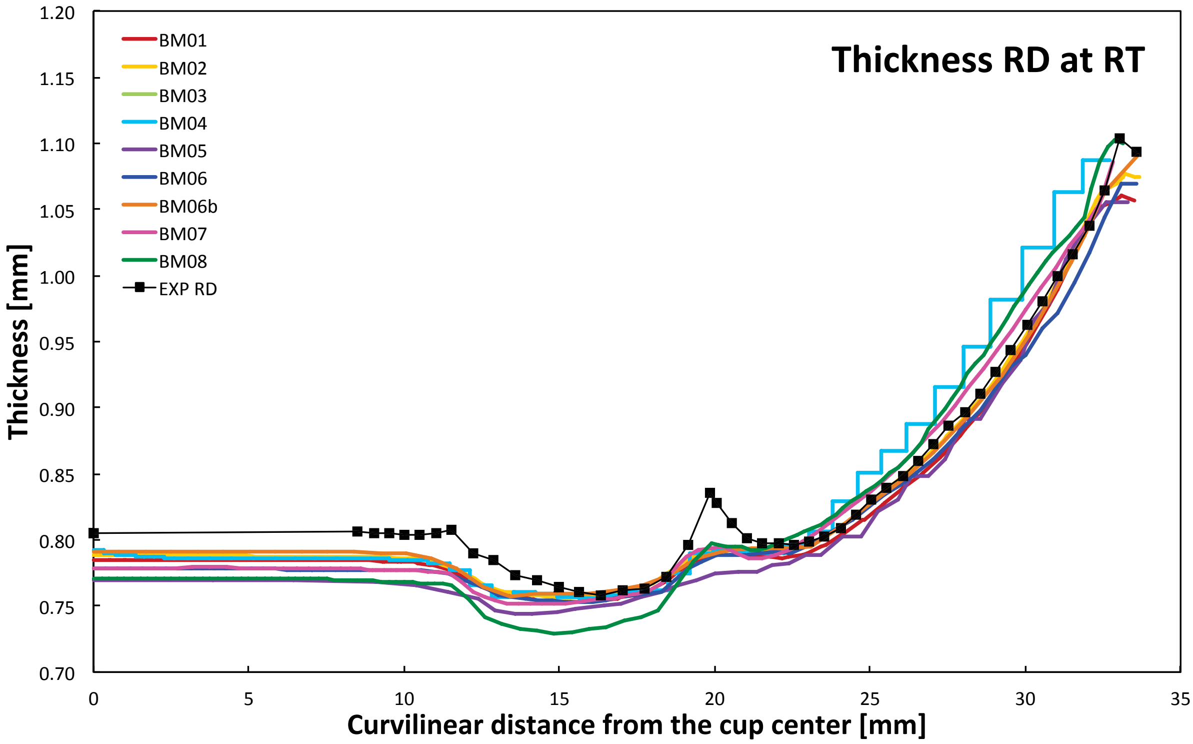
B. Software/Hardware	
Name of the FEM code	Abaqus-6.14
General aspect of the code	Standard Implicit
Basic formulations	Coupled Temperature-Displacement
Element/Mesh technology	
Number of elements	15936
Type of elements	C3D8RT
Contact property model	Surface to surface finite sliding
Friction formulation	Isotropic Coulomb friction coefficient 0.09
CPU type	
CPU clock speed	3.60 GHz
Number of cores per CPU	4
Main memory	16 GB
Operating system	3.16.0-4-amd64 GNU/Linux
Total CPU time	55227 s

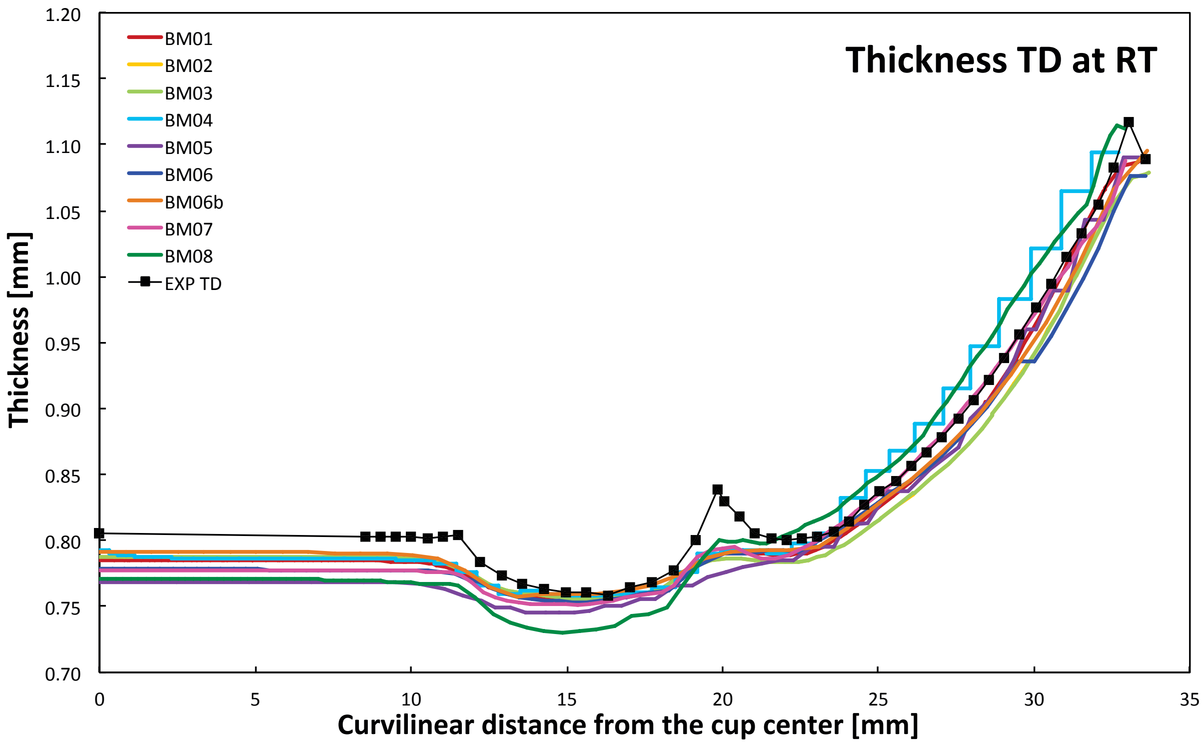
C. Describe the material model	
Name of the material model	H. Laurent et al. / International Journal of Mechanical Sciences 93 (2015) 59–72
Yield Function/Plastic Potential	Hill 1948
Hardening Rule	Hockett–Sherby hardening model and a power law strain rate dependency
Flow rule (Associated/Non Associated)	Associated
Heat transfer model	Fully transient coupled thermal-stress analysis

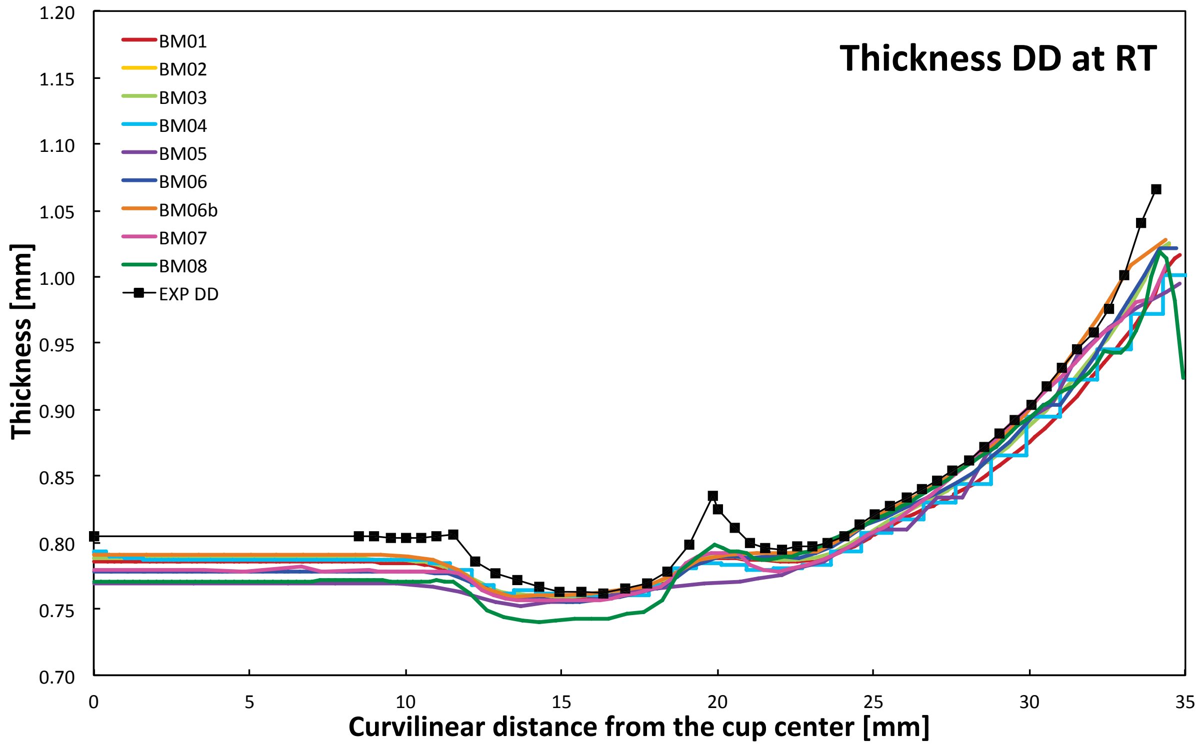
D. Remarks
The ring opening is perfomed as in the reference: H. Laurent et al., International Journal of Mechanical Sciences 93 (2015) 59–72, with a ring of 7mm height instead of 5mm, located at 8mm from the cup bottom instead of 7mm

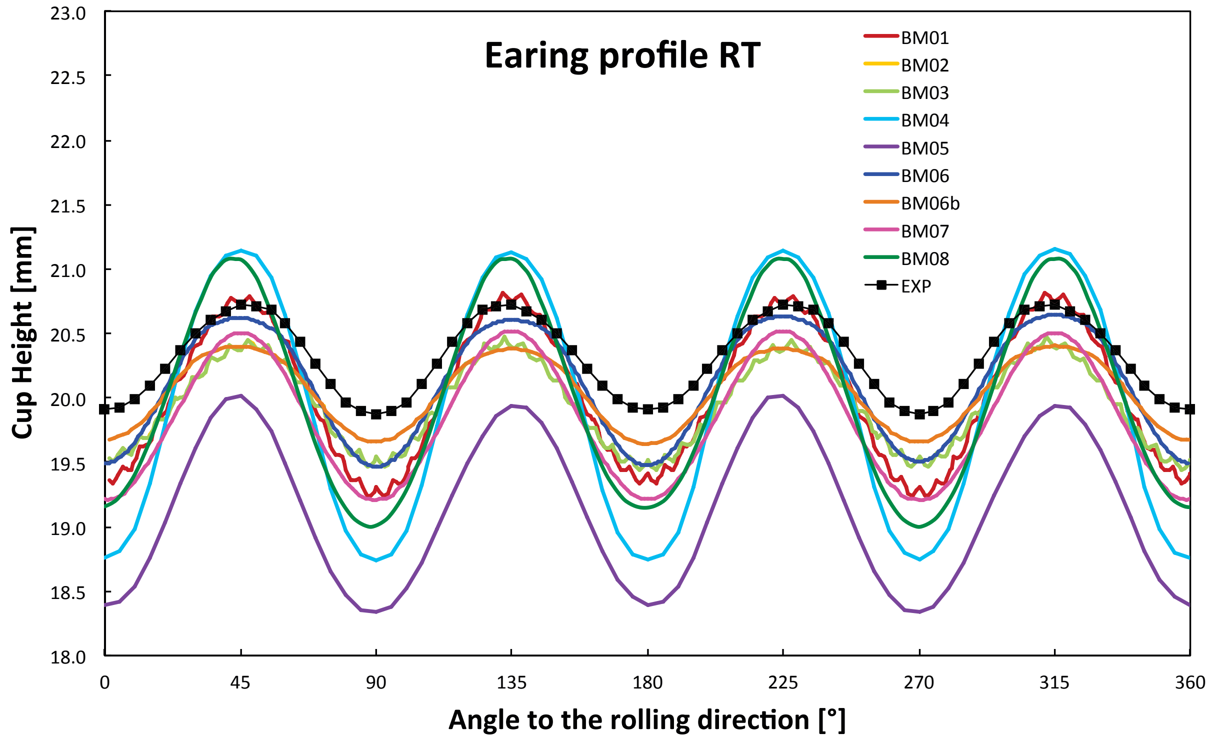

Punch Load RT
Load [kN]
Punch stroke [mm]
BM01
BM02
BM03
BM04
BM05
BM06
BM06b
BM07
BM08
EXP

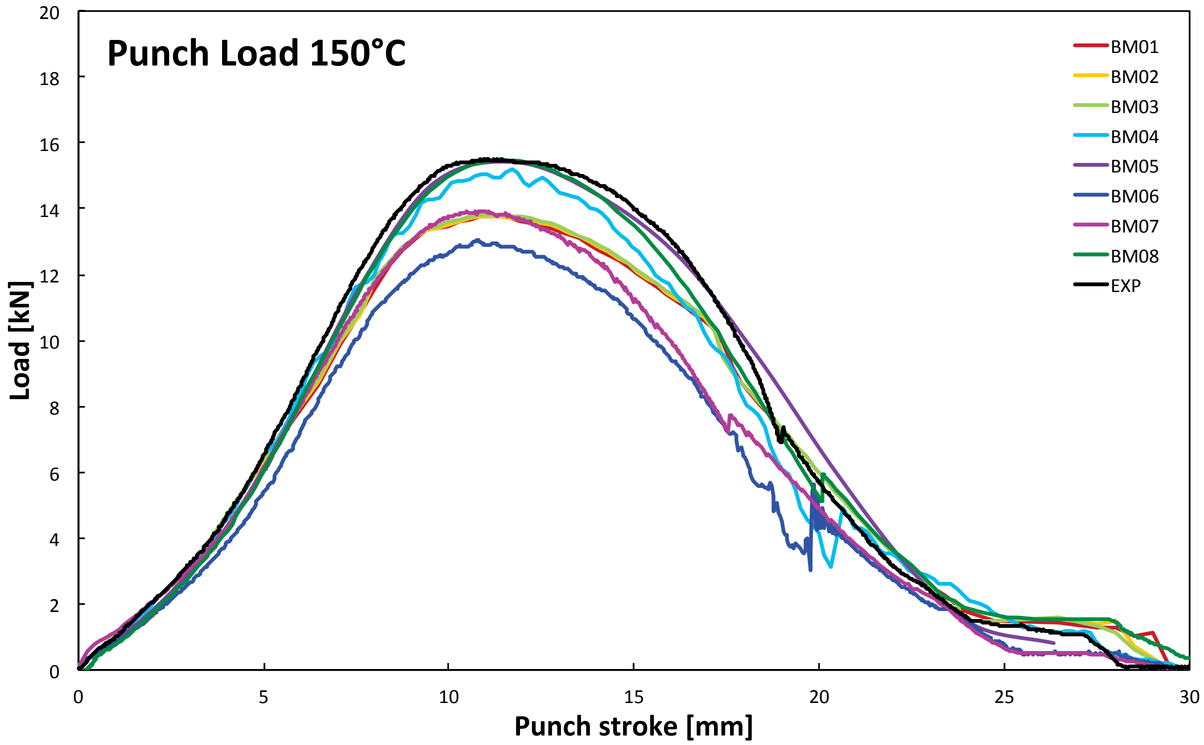

Blank Temperature
Temperature [°C]
Punch stroke [mm]
BM01
BM02
BM03
BM04
BM05
BM07
BM08
EXP

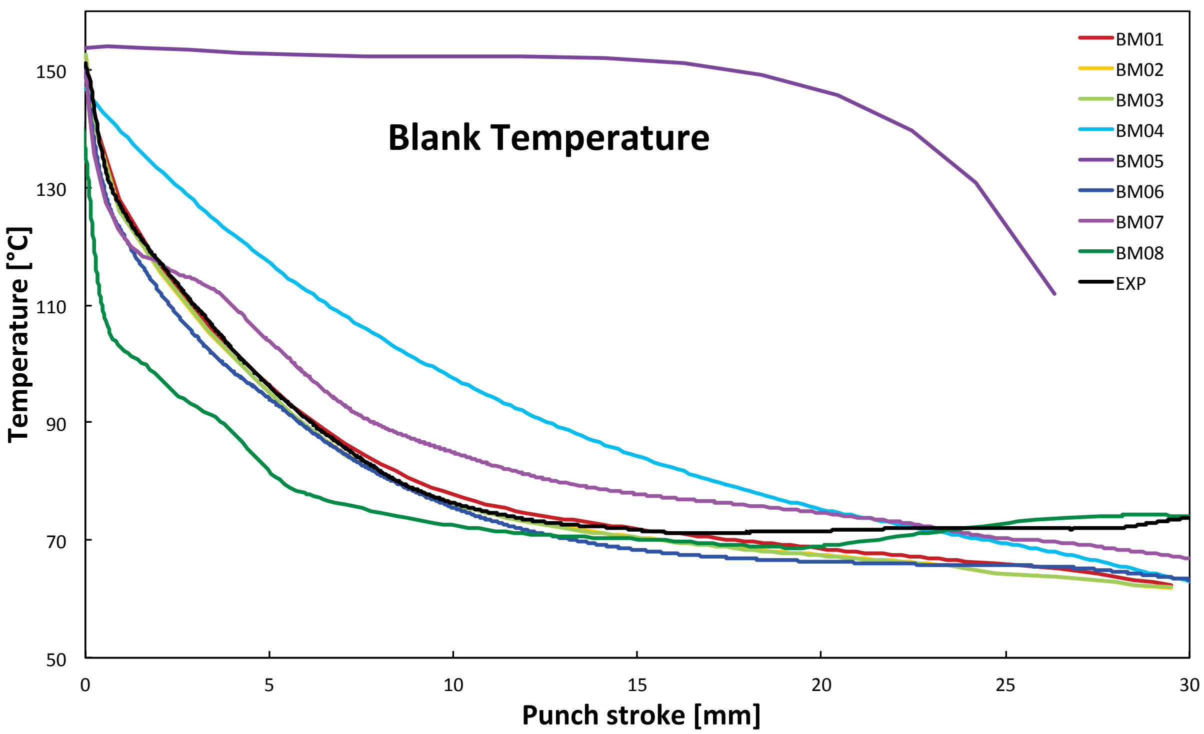

Thickness RD at RT
BM01
BM02
BM03
BM04
BM05
BM06
BM06b
BM07
BM08
EXP RD
Thickness [mm]
Curvilinear distance from the cup center [mm]

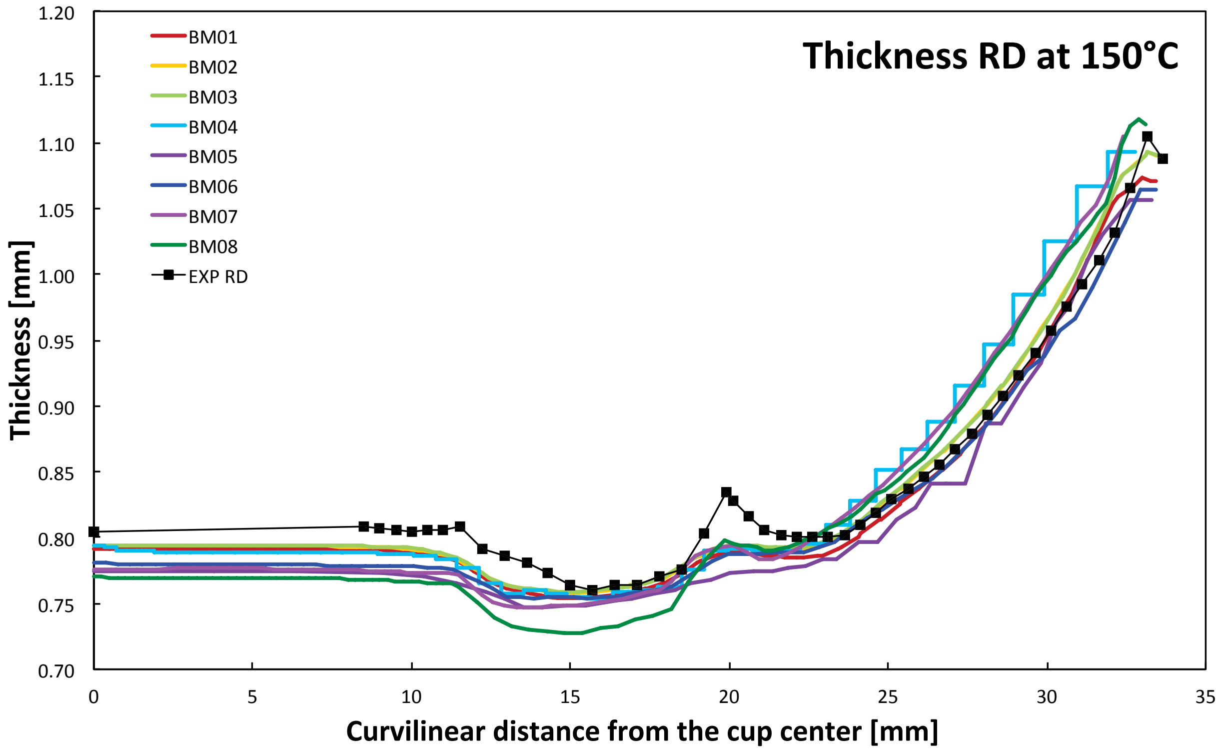

Thickness TD at RT
BM01
BM02
BM03
BM04
BM05
BM06
BM06b
BM07
BM08
EXP TD
Thickness [mm]
Curvilinear distance from the cup center [mm]

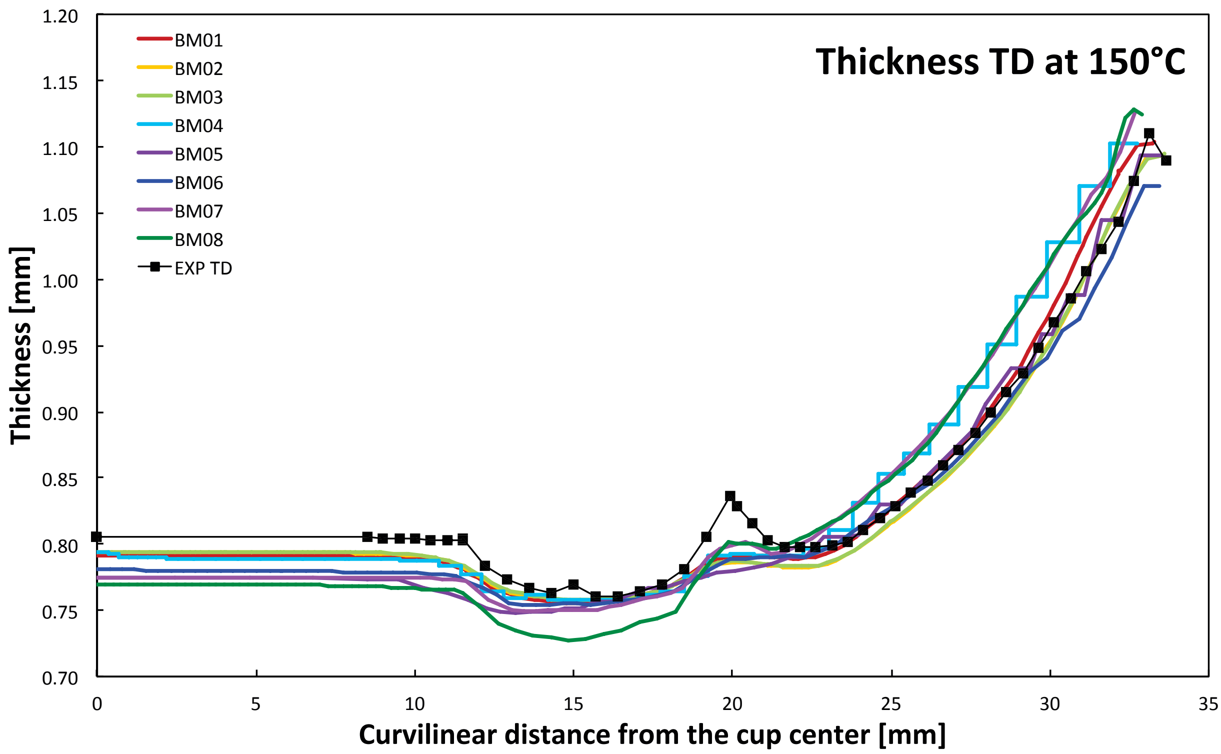

Thickness DD at RT
BM01
BM02
BM03
BM04
BM05
BM06
BM06b
BM07
BM08
EXP DD
Thickness [mm]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
5
10
15
20
25
30
35
Curvilinear distance from the cup center [mm]

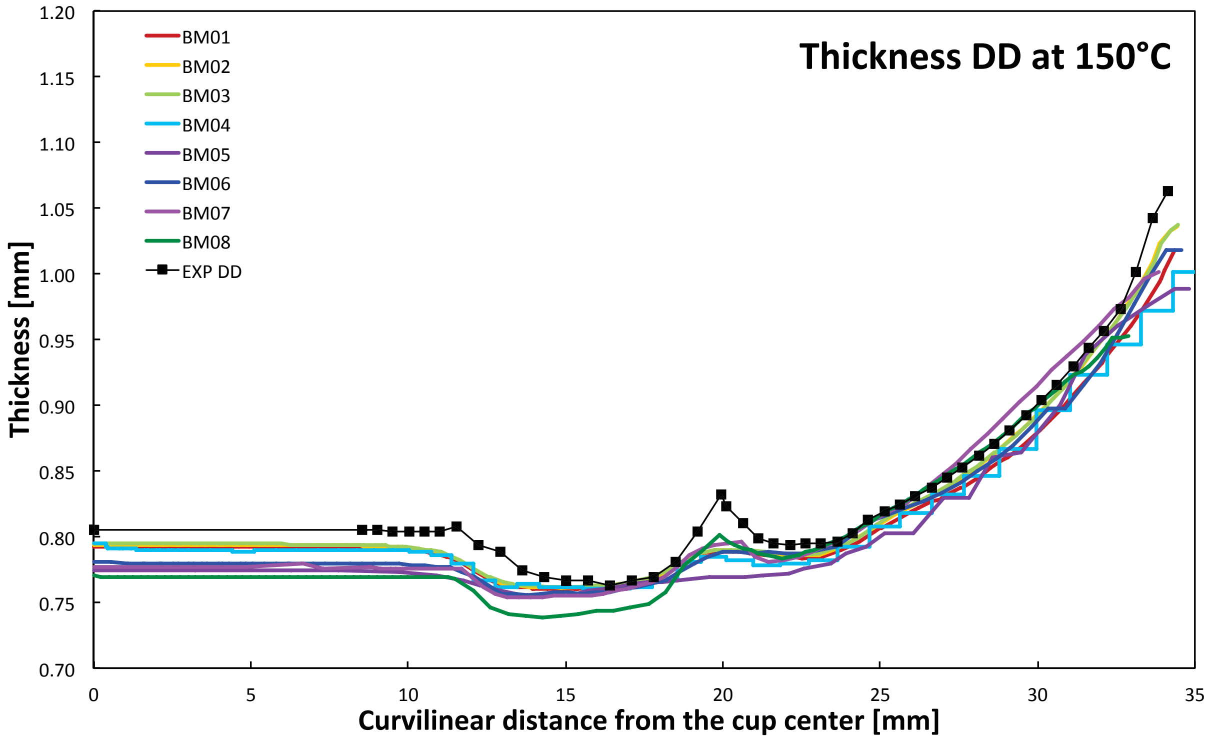

Earing profile RT
BM01
BM02
BM03
BM04
BM05
BM06
BM06b
BM07
BM08
EXP
Cup Height [mm]
23.0
22.5
22.0
21.5
21.0
20.5
20.0
19.5
19.0
18.5
18.0
0
45
90
135
180
225
270
315
360
Angle to the rolling direction [°]

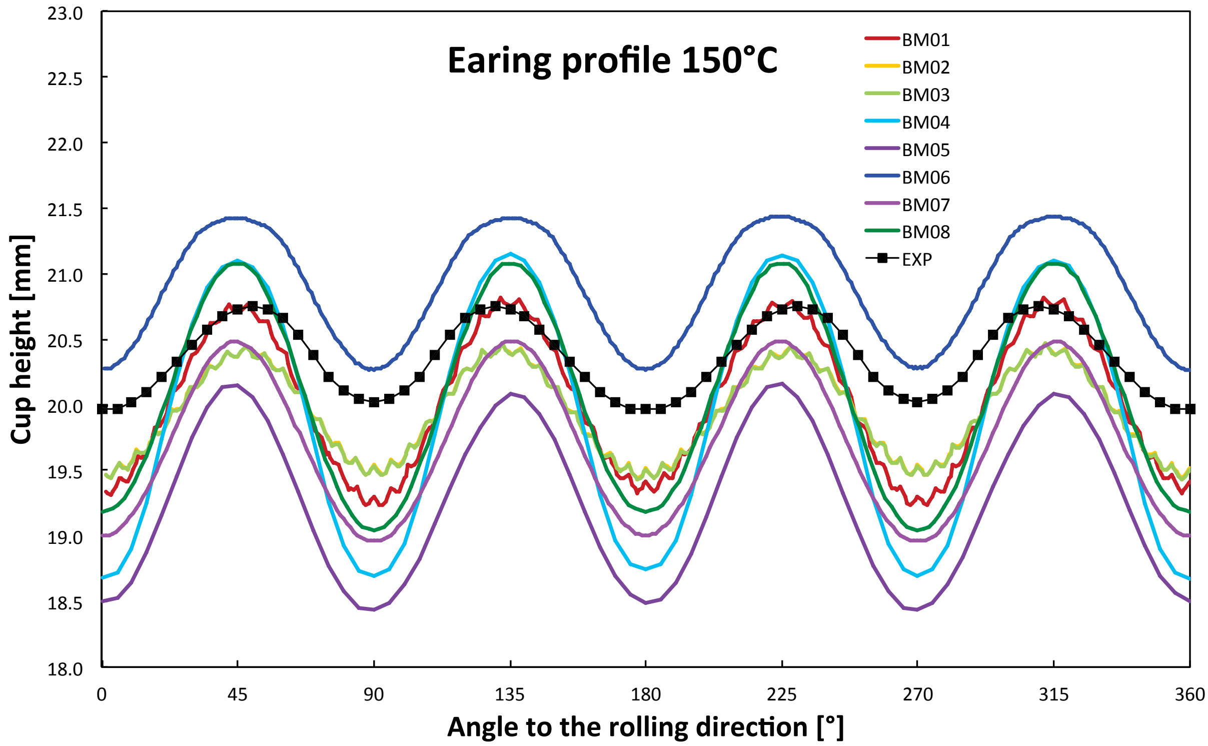

Punch Load 150°C
Load [kN]
Punch stroke [mm]
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
30

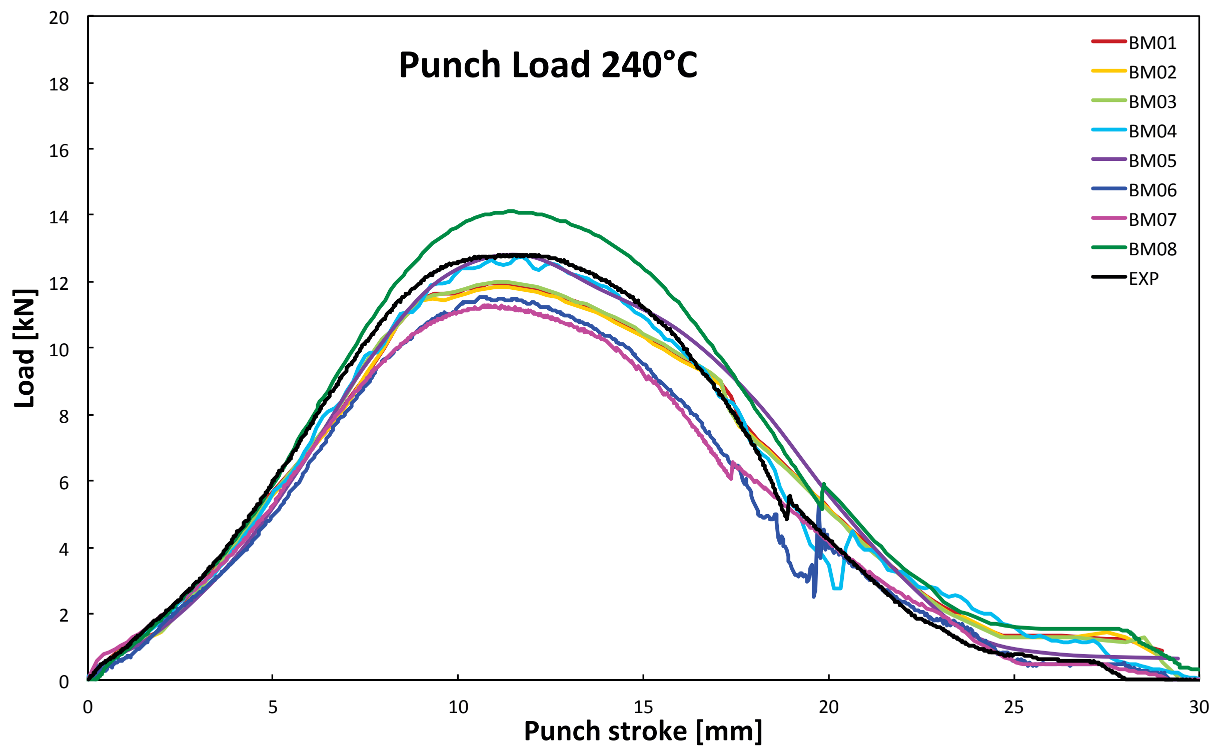

Blank Temperature
Temperature [°C]
Punch stroke [mm]
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP
50
70
90
110
130
150
0
5
10
15
20
25
30

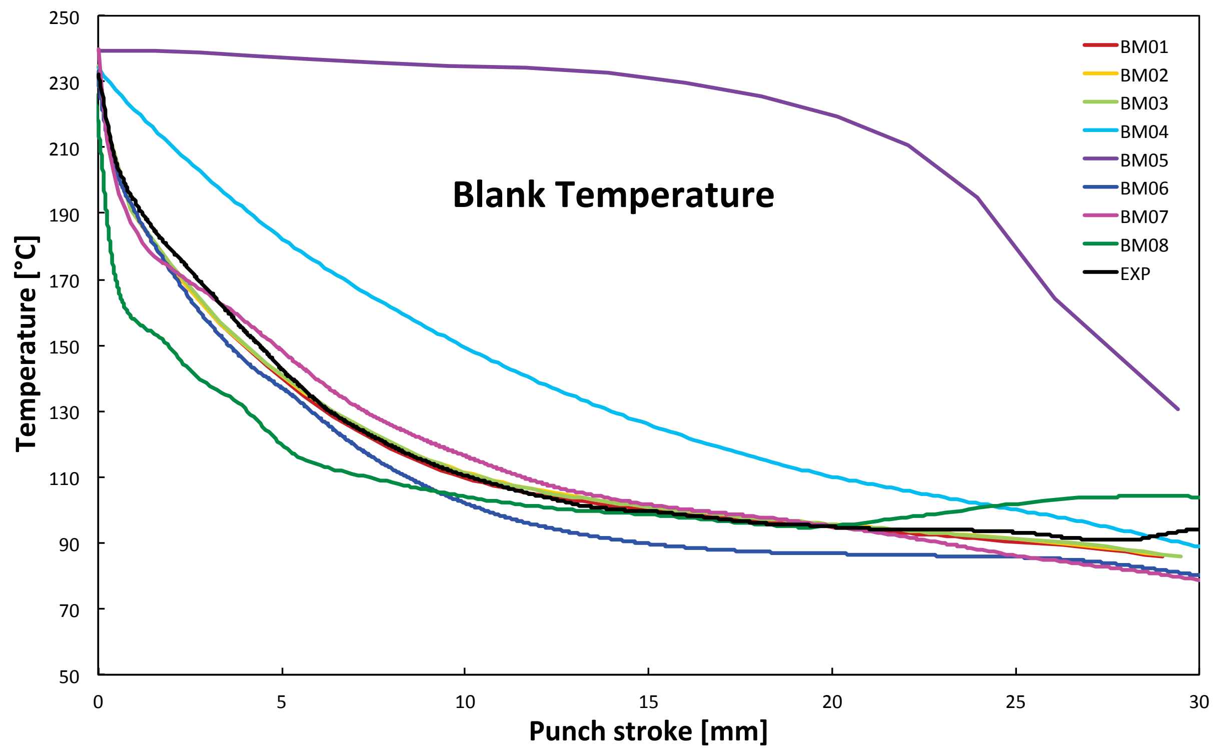

Thickness RD at 150°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP RD
Thickness [mm]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
5
10
15
20
25
30
35
Curvilinear distance from the cup center [mm]

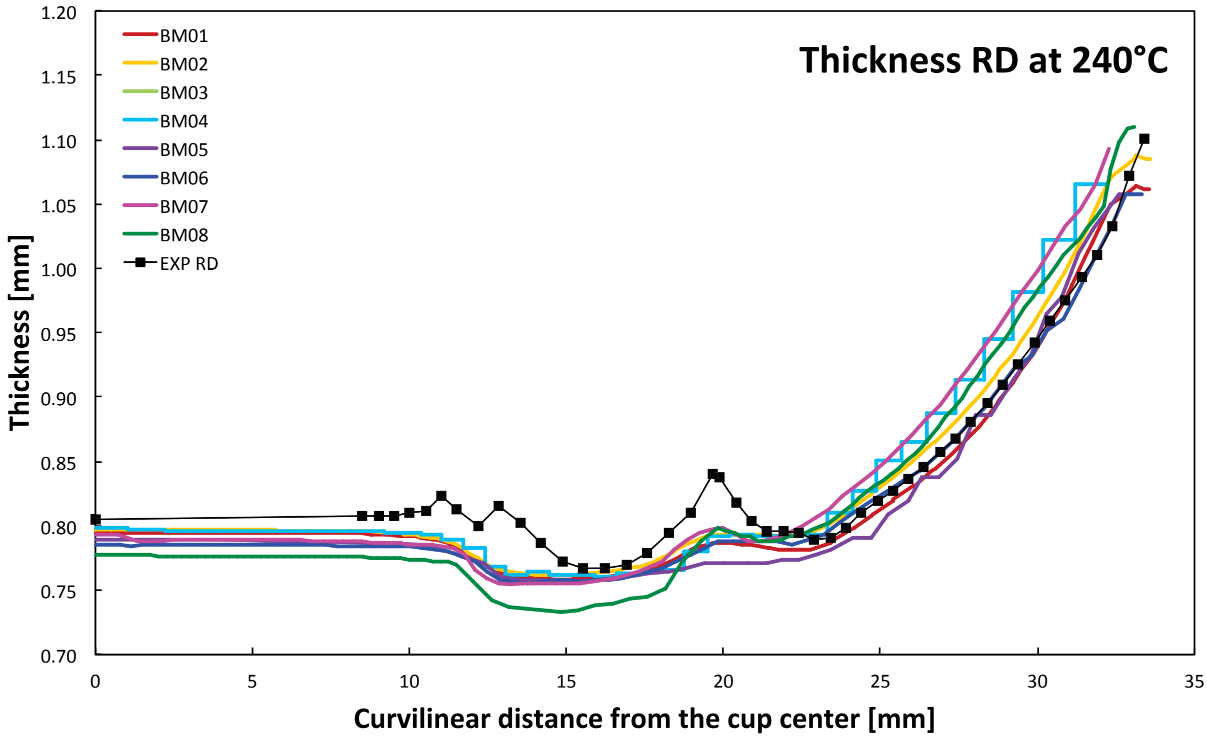

Thickness TD at 150°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP TD
Thickness [mm]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
5
10
15
20
25
30
35
Curvilinear distance from the cup center [mm]

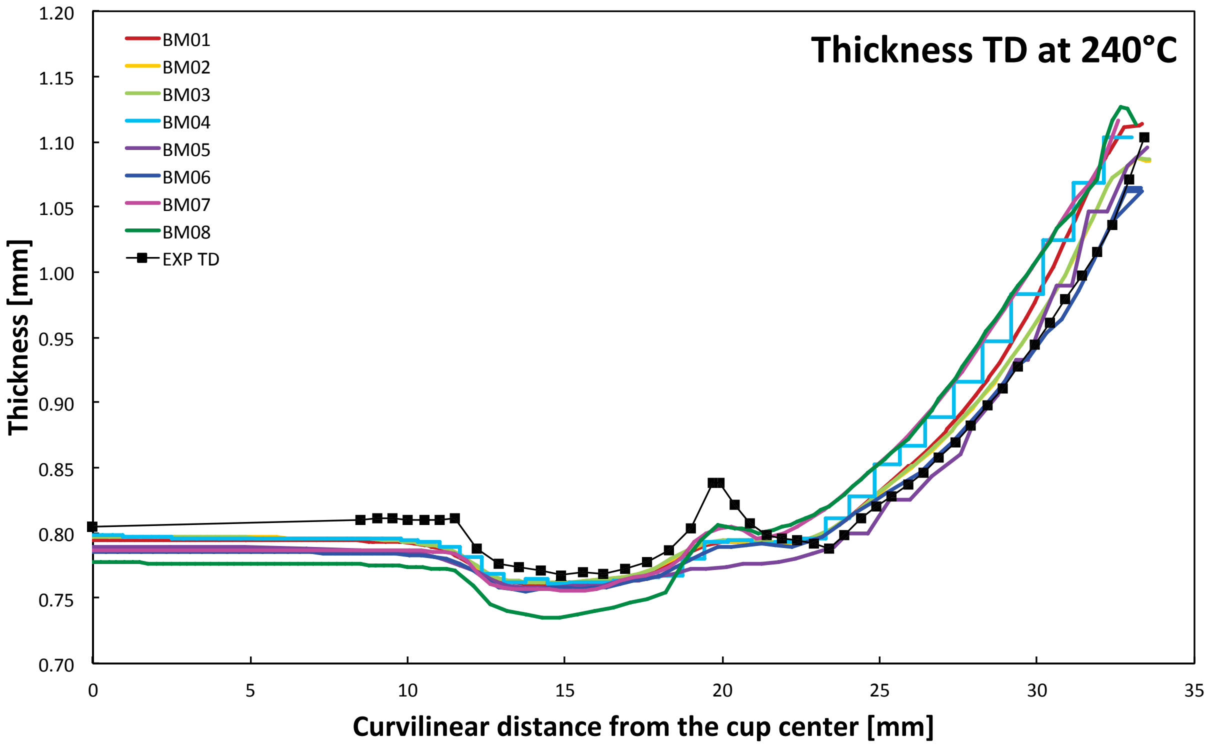

Thickness DD at 150°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP DD
Thickness [mm]
Curvilinear distance from the cup center [mm]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
5
10
15
20
25
30
35

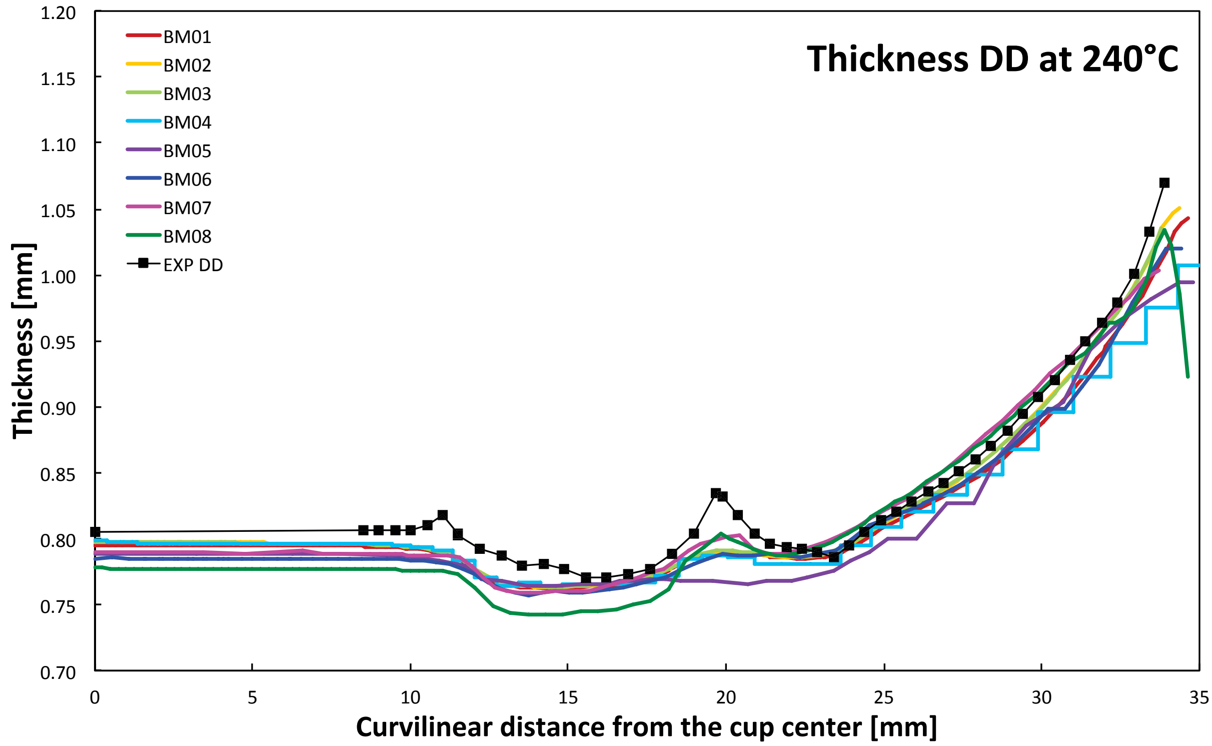

Earing profile 150°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP
Cup height [mm]
Angle to the rolling direction [°]
23.0
22.5
22.0
21.5
21.0
20.5
20.0
19.5
19.0
18.5
18.0
0
45
90
135
180
225
270
315
360

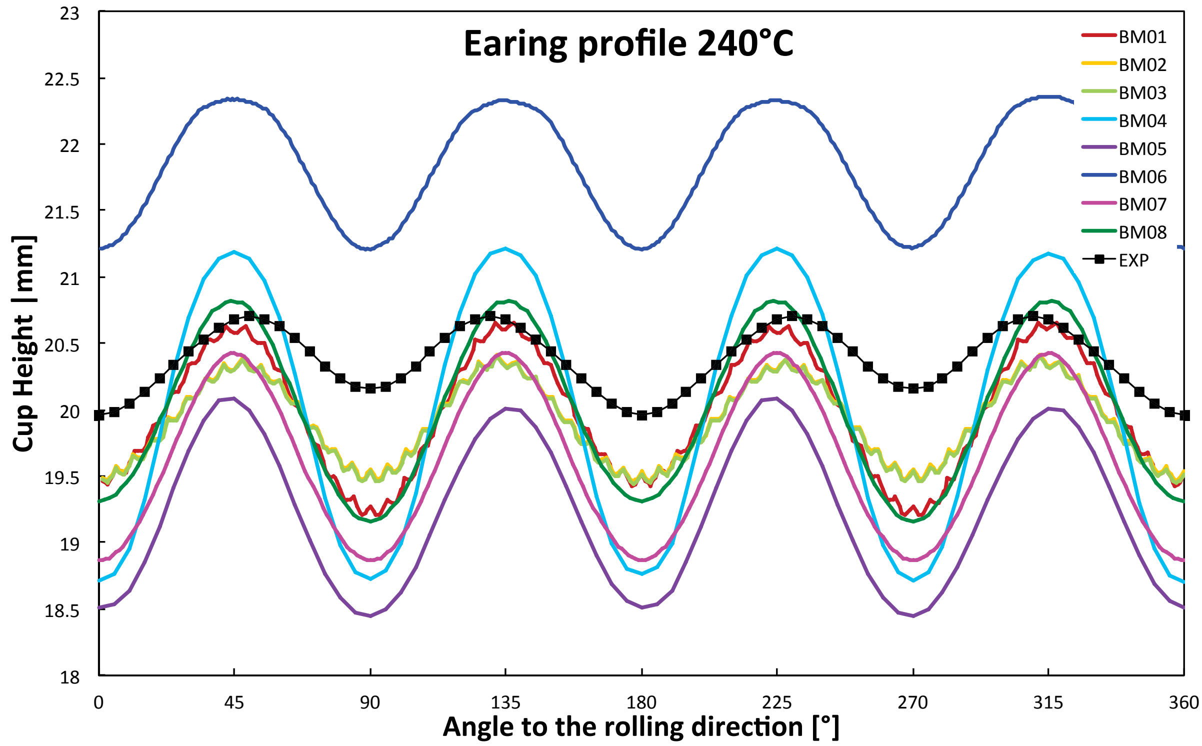

Punch Load 240°C
Load [kN]
Punch stroke [mm]
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
30

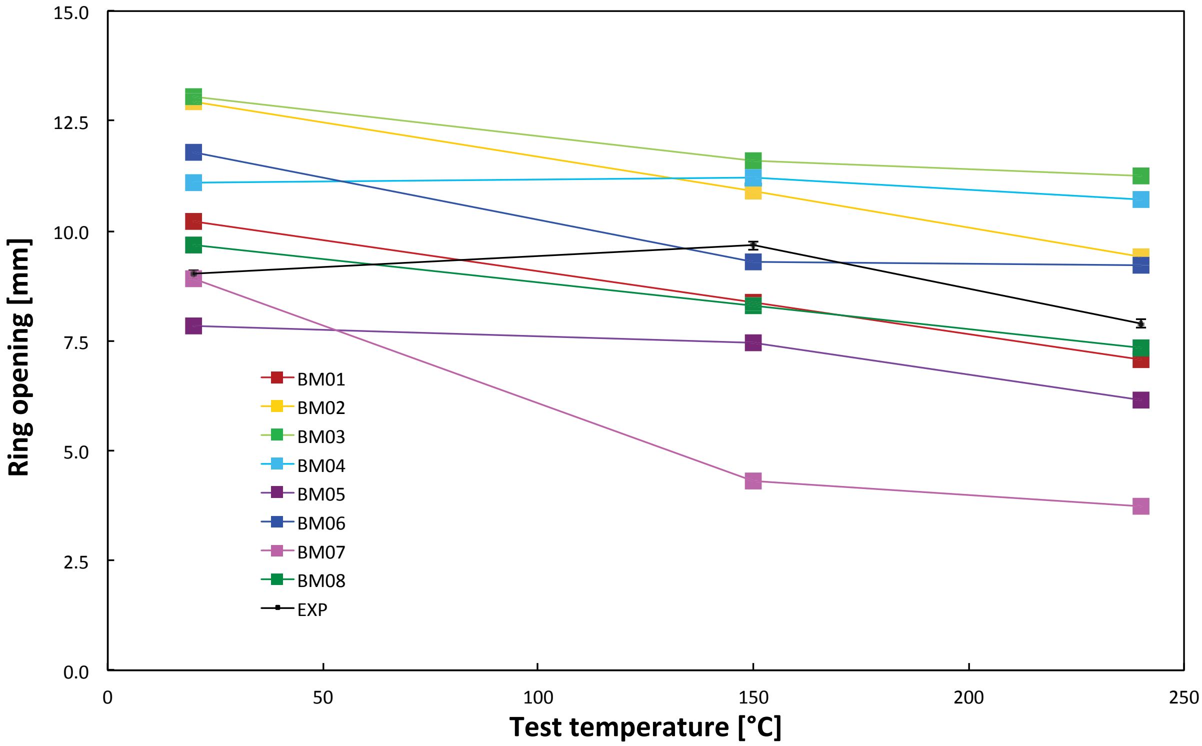

Blank Temperature
Temperature [°C]
Punch stroke [mm]
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP
50
70
90
110
130
150
170
190
210
230
250
0
5
10
15
20
25
30


Thickness RD at 240°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP RD
Thickness [mm]
Curvilinear distance from the cup center [mm]


Thickness TD at 240°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP TD
Thickness [mm]
Curvilinear distance from the cup center [mm]


Thickness DD at 240°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP DD
Thickness [mm]
Curvilinear distance from the cup center [mm]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
5
10
15
20
25
30
35


Earing profile 240°C
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP
Cup Height [mm]
Angle to the rolling direction [°]
23
22.5
22
21.5
21
20.5
20
19.5
19
18.5
18
0
45
90
135
180
225
270
315
360


15.0
12.5
10.0
7.5
5.0
2.5
0.0
Ring opening [mm]
0
50
100
150
200
250
Test temperature [°C]
BM01
BM02
BM03
BM04
BM05
BM06
BM07
BM08
EXP