Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Benchmark 2 – Springback of a Jaguar Land Rover Aluminium

To cite this article: Martin Allen *et al* 2016 *J. Phys.: Conf. Ser.* **734** 022002

Benchmark 2 – Springback of a Jaguar Land Rover Aluminium Panel

Part A: Benchmark Description

Martin Allen[a], Marta Oliveira[b], Sumit Hazra[c], Oluwamayokun Adetoro[d], Abhishek Das[c] and Rui Cardoso[e]

[a] *Jaguar Land Rover, Coventry CV3 4LF, UK*
[b] *University of Coimbra, Coimbra 3030-790, Portugal*
[c] *University of Warwick, Coventry CV4 7AL, UK*
[d] *University of the West of England, Bristol BS16 1QY, UK*
[e] *Brunel University London, Uxbridge, UB8 3PH, UK*

Abstract. The aim of this benchmark is the numerical prediction of the springback of an aluminium panel used in the production of a Jaguar car. The numerical simulation of springback has been very important for the reduction of die try outs through the design of the tools with die compensation, thereby allowing for the production of dimensionally accurate complex parts at a reduced cost. The forming stage of this benchmark includes one single forming operation followed by a trimming operation. Cross-sectional profiles should be reported at specific (provided) sections in the part before and after springback. Problem description, tool geometries, material properties, and the required simulation reports are summarized in this benchmark briefing.

Keywords: Forming, Trimming, Springback, Plastic Anisotropy

1 INTRODUCTION

Springback is one of the most important problems for the sheet metal forming industry due to the strong geometrical deviations which occurs through elastic recovery after forming. These deviations can lead to many manufacturing difficulties such as joining parts together into a more complex assembly. Springback is influenced by the forming operations and the degree of constraints imposed by the geometry of the part but it is also strongly dependent on the material properties of the blank sheet. For aluminum, springback behaviour is more complex because of its strong plastic anisotropy and low Young's modulus. Consequently, inaccurate material models can lead to major or unexpected deviations in the prediction of springback.

The main objective of this benchmark is to predict the springback of a single stage formed panel, assess the influence of material models and quantify the influence of different numerical modelling techniques that affect springback prediction. Numerical techniques includes the finite elements used, integration rules, implicit or explicit code analysis, contact and friction models and the use of emerging techniques such as isogeometric analysis and meshless methods.

The kinematic hardening effect of bending and unbending deformation through the different die radius and curvatures of the tools can significantly influence the nature and prediction of panel's springback. The springback prediction of different loading/unloading forming operations requires the use of appropriate kinematic and/or combined kinematic/isotropic hardening models, together with sophisticated flow rules and yield functions. Cyclical shear tests for different levels of pre-strains were therefore performed for the material characterisation of the kinematic/isotropic hardening (the Bauschinger effect) for this benchmark study and the measured shear strain-stress curves are summarised in the attached excel file "Cyclical_Shear.xls".

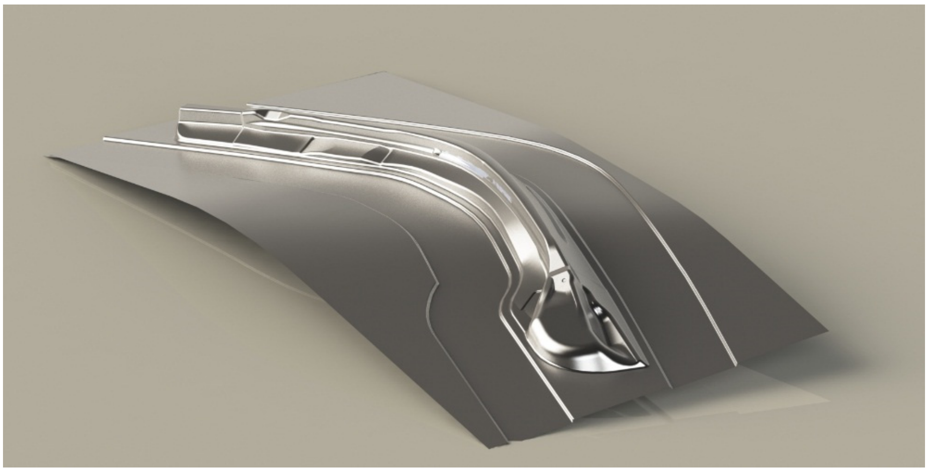


Figure 1. Die face.

2 BLANK MATERIAL

The blank material to be used in this benchmark is the aluminium alloy (AA6451-T4) with thickness t = 3.0 mm. The elastic mechanical properties are given in Table 1.

Table 1. Elastic mechanical properties

Sample	Density, ρ ($g.cm^{-3}$)	Young's modulus, E (GPa)	Poisson's ratio, ν
AA6451-T4	2.7	70.0 GPa	0.3

The uniaxial tensile yield stress and r-values are given in Table 2.

Table 2. Uniaxial Tension Test Data

Test Direction	YS, σ_{yld} (MPa)	r-value
0º	151.28	0.62
45º	171.2	0.33
90º	163.6	0.8

The equal biaxial tensile yield stress and the biaxial r-value are given in Table 3.

Table 3. Equal Biaxial Tension Test Data

σ_b (MPa)	r-value, r_b
153.6	0.55

The material constants for the hardening curve at 0 degrees from the rolling direction (RD) are described in Table 4 for the Voce hardening law.

Table 4. Hardening curve

Voce		
A, (MPa)	B, (MPa)	C
359.093260	196.310139	9.374256

The Voce hardening curve gives a better fitting to the experimental results at 0 degrees from RD. The material constants for Barlat's Yld2000-2d yield function are provided in Table 5 with the eight anisotropy coefficients and the material constants for Barlat's Yld89 yield function are provided in Table 6.

Table 5. Material Constants for Yield Function **Yld2000-2d** (a = 8.0)

Sample	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
AA6451-T4	1.065173	0.841891	0.960059	0.958652	1.034037	1.027112	0.838988	0.877033

Table 6. Material Constants for Yield Function **Yld89** (m = 8.0)

Sample	a	c	h	p
AA6451-T4	1.3033	0.9556	0.9247	0.8465

Cyclical shear mechanical tests were conducted (with the specimen at 0 degrees from RD) for different pre-strains so that a full characterization of the kinematic and/or combined kinematic/isotropic hardening can be conducted effectively for the numerical simulation of the springback of the aluminium panel. The plots for the shear stress vs shear strain for the different pre-strain levels are shown in Figure 2. The excel file "Cyclical_Shear.xls" with the full data for the cyclical shear tests is available on the website of the conference.

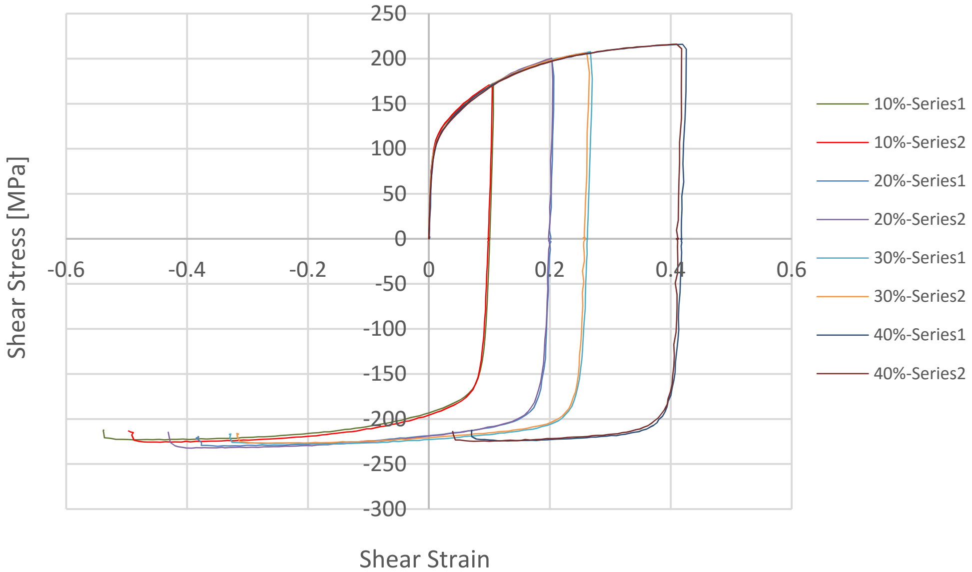


Figure 2. Experimental results for the cyclical shear tests on the AA6451-T4 aluminium alloy.

The rolling direction is specified schematically in Figure 3, with the rolling direction making an angle of 87^0 with the global x-axis.

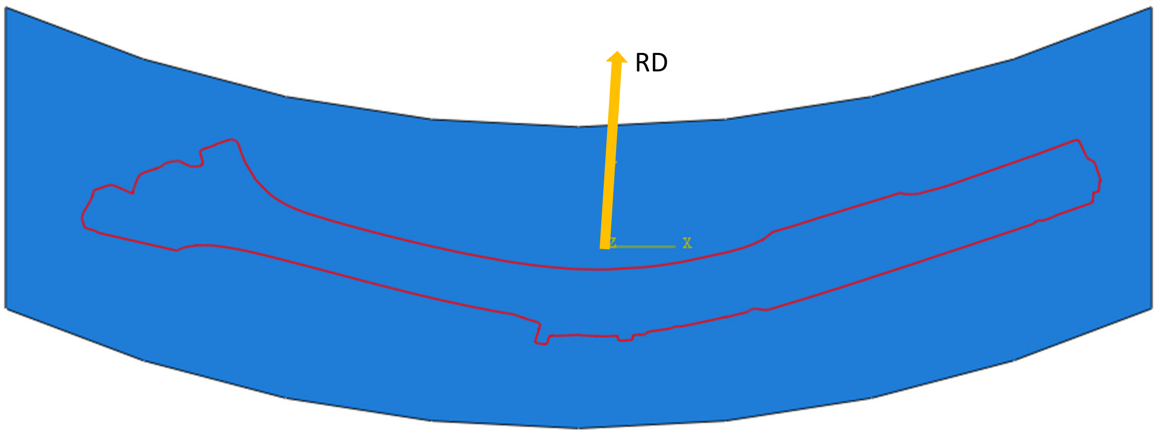


Figure 3. Rolling direction.

3 SIMULATING THE FORMING OPERATION

The simulation involves three operations: forming, trimming and springback. The drawing occurs continuously in a single action process during which the die moves at 100 $mm.s^{-1}$. The CAD geometries for the blank, the lower punch, the upper die and the binder, as well as a mesh for the punch, die and blank holder are provided. The parts/tools are provided in their corresponding orientation and position in the global axis and the forming direction is aligned to the global *z*-axis, whilst no symmetry plane exists as shown in Figure 4. Participants should not move the tool position in the *x-y* plane.
The indicative values for the coefficient of friction to be used in the forming operations are: i) 0.08 for Pam-Stamp and LS-DYNA; ii) 0.14 for AutoForm.
The lower punch, binder and upper die are illustrated in Figure 4. Only one blank material (3 *mm* thick) is investigated in this benchmark, properties of which are given in the previous section. The required simulation boundary conditions are given in Table 7.

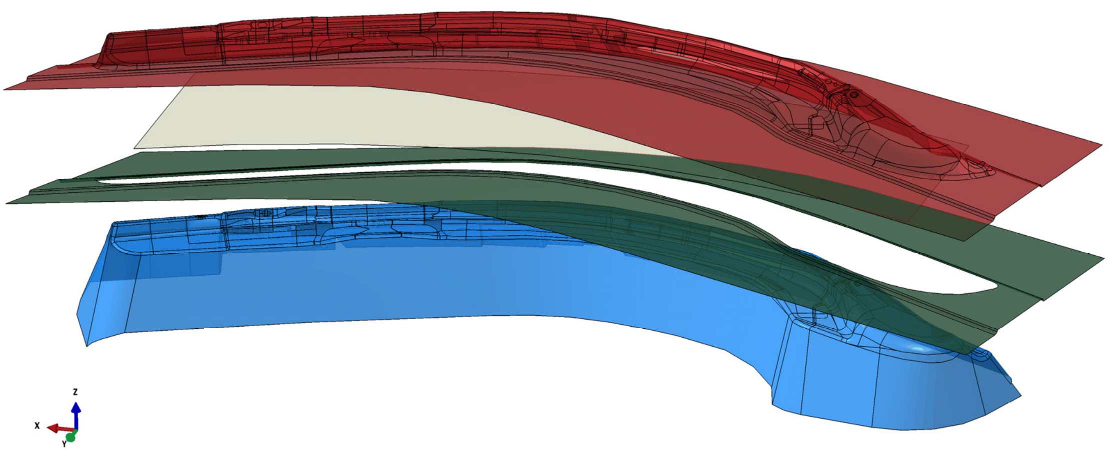


Figure 4. Forming Tool Setup.

Table 7. Boundary Conditions

Part	Operation			
	Binder Closure	**Forming**	**Trimming**	**Springback**
Die	Z-Disp: –300 *mm*	Z-Disp: –200 *mm*	Clamped	Refer to Section 4.3 (SB Analysis)
Binder	Clamped	BHF: 1900 *kN*	Clamped	
Blank	Free	Free	Free	
Punch	Clamped	Clamped	Clamped	

4 FORMING ANALYSIS

4.1 Tool moving directions and force:

4.1.1 Binder Closure

Lower Punch: stationary
Upper Die: moving (z-direction), see Table 7
Binder: stationary

4.1.2 Forming

Lower Punch: stationary
Upper Die: moving (z-direction), see Table 7
Binder: loading (z-direction), see Table 7

4.1.3 Blank holding force

The blank holding force is defined in table 7. It should be applied after the binder has been moved into position.

4.2 Trimming

The trim line is illustrated in Figure 5 (the red line/edge) and it is provided in the attached IGES file.

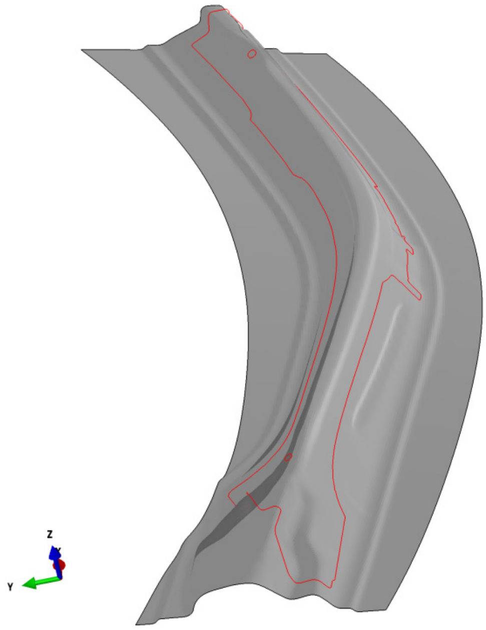
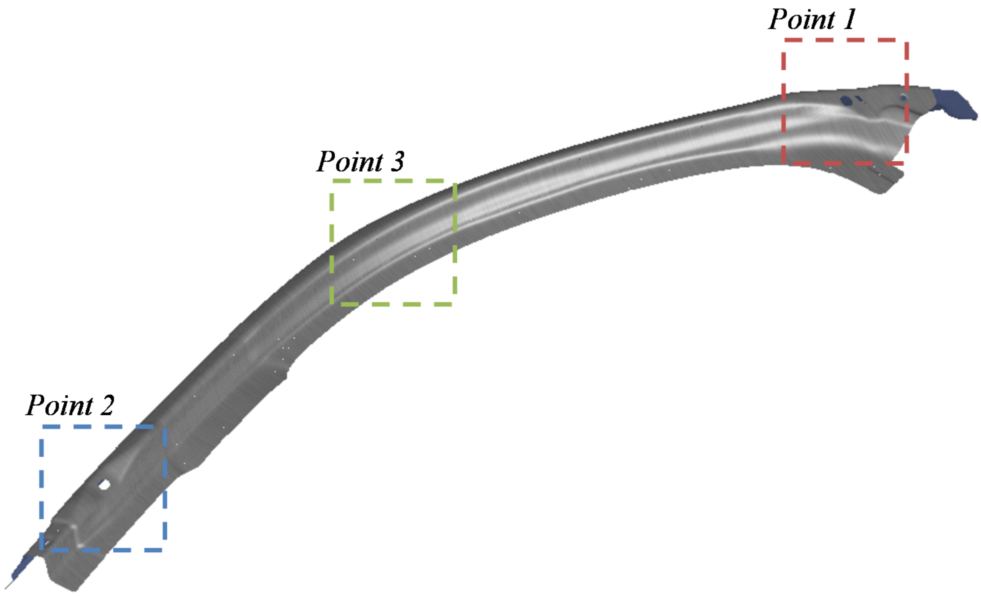
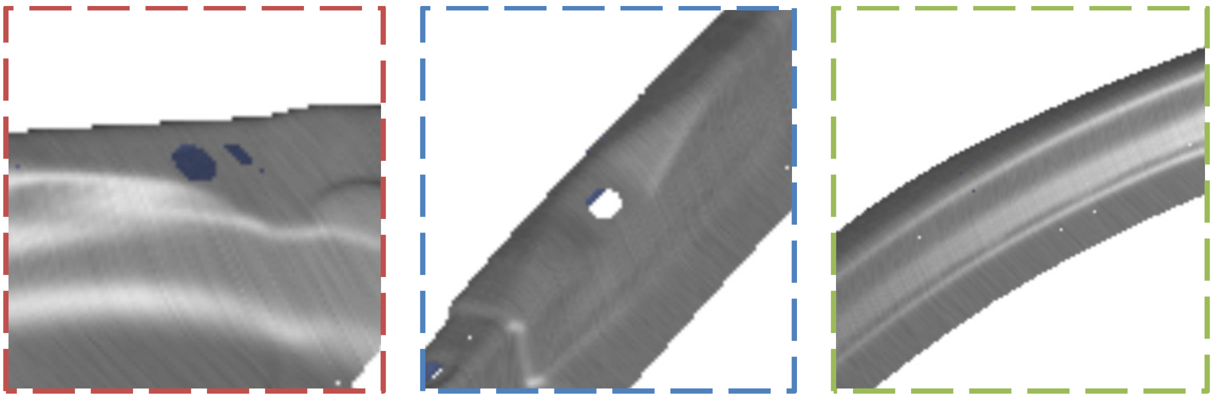


Figure 5. Trim line on the formed part.



(a) Location of boundary conditions for springback analysis



(b) Point 1 – Pin BC (c) Point 2 – Slot BC (d) Point 3 – Simply Supported

Figure 6. Springback BC locations.

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

4.3 Springback Analysis

The locations of the boundary conditions (BCs) to be defined for springback analysis simulation are depicted in Figure 6. A 3-2-1 locating configuration will be used for part measurement. Points 1 and Point 2 correspond to the centre of the holes shown in Figures 5 and 6.

4.3.1.1 Point 1 – Pin BC (all dimensions in mm)

The blank is restrained in all global translation directions, *X*, *Y*, *Z* at Point 1 with the coordinates, (-749.3, 75.5, 206.2).

4.3.1.2 Point 2 – Slot (all dimensions in mm)

A local coordinate system is to be defined and restrained in translation directions, *y'*, *z'*. The coordinates of the origin (Point 2) of the local coordinate system is (711.0, 83.8, 220.0) and the vector defining the free *x'* local axis is (30.0, 10.0, 0.1).

4.3.1.3 Point 3 – Simply Supported (all dimensions in mm)

The blank is restrained in global translation direction, *Z* at Point 3 with the coordinates, (-68.7, -46.5, 193.4).

4.4 Simulation Files

CAD geometry (IGES) files are provided for the die face, binder, blank, punch and the trim line. The trim lines are indicated by lines in the IGES file.

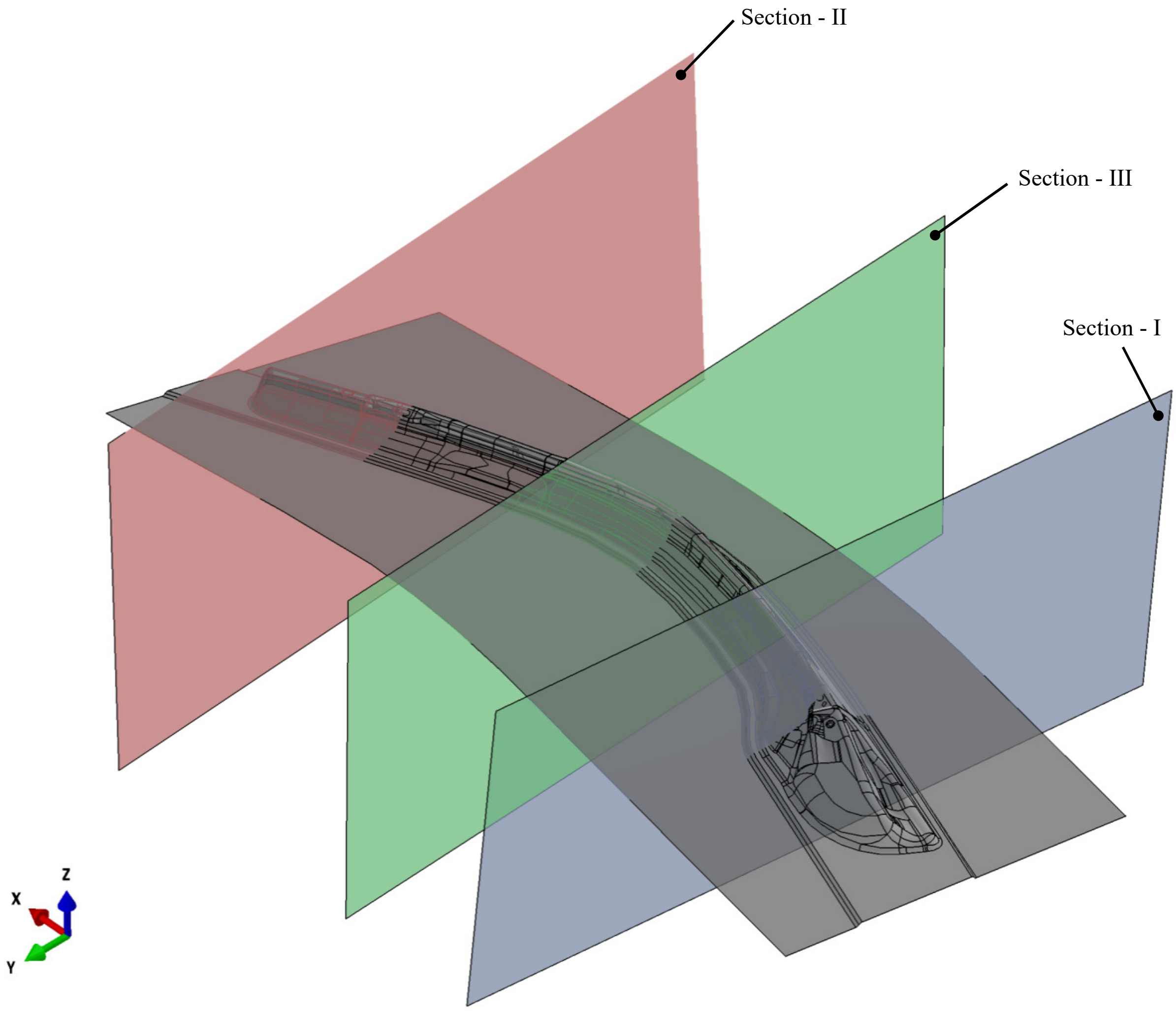


Figure 7. Sections for springback measurement.

5 BENCHMARK REPORT

The due date for benchmark submission is listed on the website. All results are to be reported using the benchmark report template which can be downloaded from the conference website.

5.1 General Description

- Benchmark participant: name, affiliation, address, email and phone number.
- 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.
- Simulation hardware: CPU type, CPU clock speed, number of cores per CPU, main memory, operating system, a breakdown of CPU time for the three stages and analysis methods adopted (e.g. explicit or implicit) for each operation.
- Material model: Yield function/Plastic potential, Hardening rule and Stress-Strain Relation, strain-based.
- Delegate's remarks on the results template.

Table 8. Section normal vectors

Plane	*x*	*y*	*z*
Section I	- 0.985572	0.100936	- 0.135870
Section II	- 0.997984	- 0.062806	0.009108
Section III	-0.998390	-0.044252	-0.035492

5.2 Simulation Results Required

The following information are requested from your simulation:

- Die stroke (*mm*) vs. total punch force (*kN*) from the simulation during forming, reported for at least every 5 *mm* of die movement.
- Blank thickness after forming at Sections I, II and III (as shown in Figure 7). The sections are provided as IGES files and the normal vectors of these sections are provided in Table 8, whilst the origin points coincide with the points defined in sections 4.3.1.1, 4.3.1.2 and 4.3.1.3, respectively. Local in-plane axes are defined for each section as described in figures 8, 9 and 10 and Table 9 and, together with the normal vectors from Table 8, they form a right-handed local coordinate system that should be used for the report of the blank thickness after forming.
- Profiles of the formed sheet at Sections I, II and III, taken of the punch-side surface for two different instants: (i) end of the forming operation and (ii) after trimming and springback. The profiles should be plotted in graphs with local coordinate system defined by local axes described schematically in figures 8, 9 and 10 and Table 9 and the normal vectors from Table 8. The origin of these coordinate systems are the BC points defined in section 4.3.1.1, 4.3.1.2 and 4.3.1.3., respectively.
- As an option, the part after springback can be reported in the form of a geometric (*.stl) file. The committee will report the springback results from correlation with the real part after springback. This will be carried out by aligning the springback result to the measured data by using the same three BC points from section 4.3 – Springback Analysis.

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

Table 9. Local axes for the plot of springback profiles

Local axis	*x*	*y*	*z*
$\vec{X}_I$	-0.099951436	-0.994896865	-0.013781841
$\vec{Y}_I$	-0.136593212	0.0	0.990627223
$\vec{X}_{II}$	0.062801814	-0.998026018	0.0
$\vec{Y}_{II}$	0.00908191	0.000571486	0.999958595
$\vec{X}_{III}$	0.04432748	-0.999017054	0.0
$\vec{Y}_{III}$	-0.035464739	-0.001573602	0.999369689

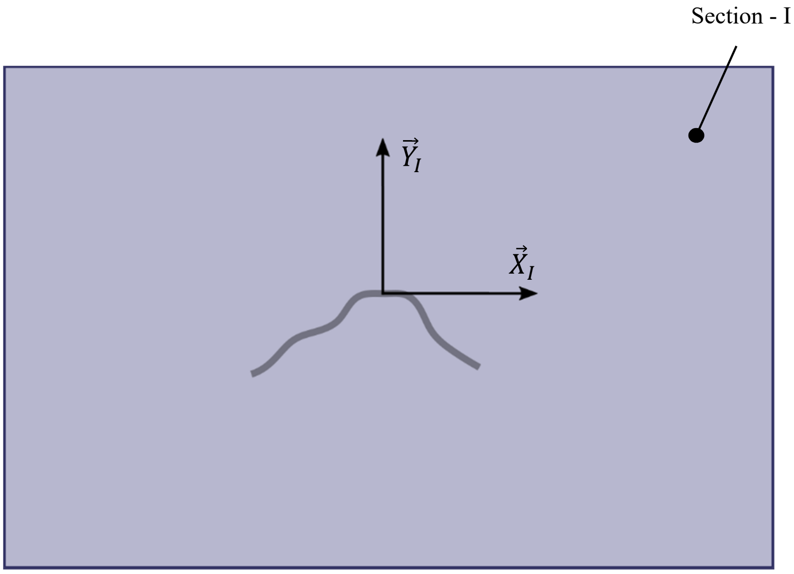


Figure 8. Local coordinate system $\vec{X}_I$ - $\vec{Y}_I$ for the report of springback profile at section I.

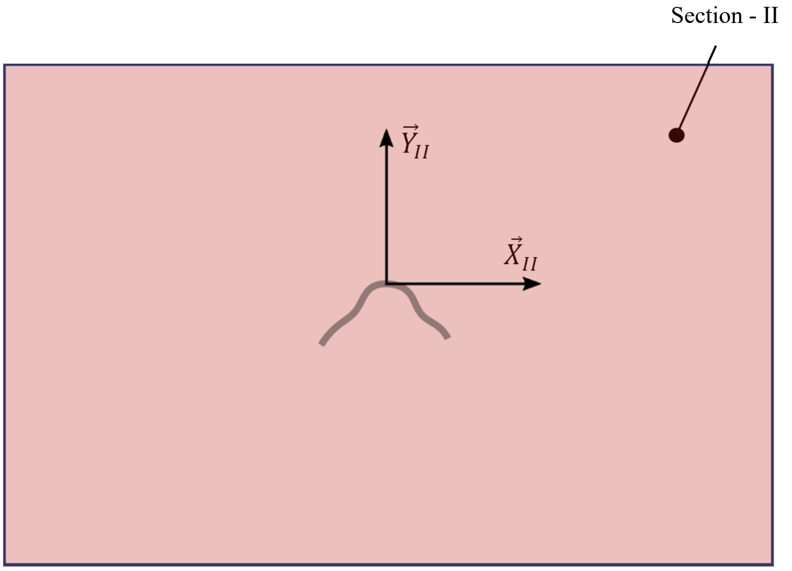


Figure 9. Local coordinate system $\vec{X}_{II}$ - $\vec{Y}_{II}$ for the report of springback profile at section II.

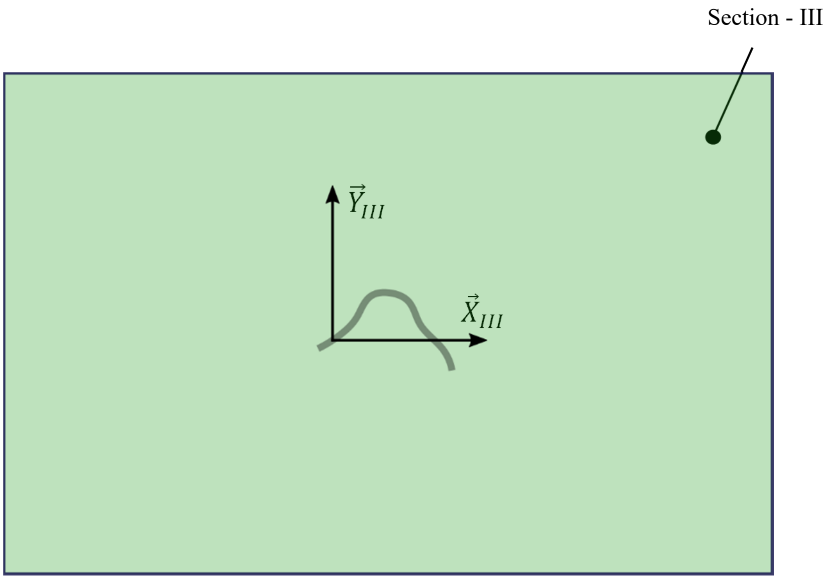


Figure 10. Local coordinate system $\vec{X}_{III}$ - $\vec{Y}_{III}$ for the report of springback profile at section III.

Benchmark 2 – Springback of a Jaguar Land Rover Aluminium Panel

Part B: Responses

Martin Allen[a], Marta Oliveira[b], Sumit Hazra[c], Oluwamayokun Adetoro[d], Abhishek Das[c] and Rui Cardoso[e]

BM2-00

1. Benchmark Participant	
Name	**Martin Allen, Marta Oliveira, Sumit Hazra, Oluwamayokun Adetoro, Abhishek Das, Rui Cardoso**
Prepared by	Benchmark-2 Committee

BM2-01

1. Benchmark Participant	
Name	**Jan NOVY, Takayuki OGAWA**
Affiliation	ESI Group (MECAS ESI, ESI Japan)
Address	Brojova 16 33201 Plzen, Czech Republic; 6-14-1 Nishi-Shinjuku, Shinjyuku-ku, Tokyo 1600-0023, Japan
Email	jno@esi-group.com, tog@esi-group.com
Phone number	+420724269068; +81-3-6381-8494
Fax number	+420 377 432 930; +81-3-6381-8494

2. Simulation Software	
Name of the FEM code	Pam-Stamp
General aspect of the code	Dynamic explicit(forming), Static implicit (gravity, springback)
Basic formulations	Updated Lagrangian formulation with associated flow rule, Barlat2000 yield function, Yoshida kinematic hardening
Element/Mesh technology	
Number of elements	175,582 (After stamping), 75,084 (after trimming)
Type of elements	explicit solution:Belytschko-Tsay shell , implicit solution: Batoz Q4 gamma shell
Contact property model	explicit solution: non-linear penalty contact, implicit solution: contact 54
Friction formulation	Standard Coulomb friction

3. Simulation Hardware	
CPU Type	Intel Xeon CPU E5645 approach 1, Xeon e5-2650 approach 2
CPU clock speed	2.40GHz approach 1, 2.6GHz approach 2
Number of cores per CPU	12 approach 1, 8 approach 2
Main memory	48 GB approach 1, 64 GB approach 2
Operating system	Linux
Total CPU time	17 hours approach 1, 27 hours approach 2

4. Describe the material model used for each material	
Material	AA6451-T4
Yield Function/ Plastic Potential	**Yld2000-2D - the parameters for Yld2000-2D used as provided**
Hardening Rule (e.g. Isotropic, kinematic)	**Kinematic hardening**
Stress-Strain Relation (e.g. Swift, Voce)	**Yoshida-Uemori (Y-U): Cyclic shear data "Cyclical.xls" were transered into stress-strain curves. And then, Y-U parameters are evaluated from them by**

5. Remarks

There were used 2 approaches of computation:
Approach 1:
Gravity - Holding - Stamping - Trimming&springback using locked nodes of model

Approach 2:
OP20 (Gravity-Holding-Stamping-Springback) - OP30 (Holding-Trimming-Springback)-Fixure(Clamping)
Since trimming dies and fixtures are not provided by organizer, those shapes are estimated from the specifications and provided CAD data.
For more please check video:Fixture.avi
There are submitted two result only in STL

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-02

1. Benchmark Participant	
Name	**HARSH R AGRAWAL**
Affiliation	M.Tech Student (First Year) (Branch - Steel Technology), Department of Metallurgical Engineering & Materials Science, IIT Bombay, Powai , Mumbai (India)
Address	Hostel No. 4, Room No. 332, Indian Institute of Technology Bombay, Powai, Mumbai (Maharashtra, India) (PIN - 400076)
Email	harshagrawal1993@gmail.com
Phone number	9770892835
Fax number	+91 22 2572 6975

2. Simulation Software	
Name of the FEM code	PAM-STAMP 2012.2
General aspect of the code	Dynamic Explicit (for Holding/Stamping), Static Implicit (springback after trimming)
Basic formulations	Updated Lagrangian formulation with associated flow rule, Barlat 2000 (Yld 2000-2D), Isotropic Hardening, Tabulated data for hardening curve following Voce Equation
Element/Mesh technology	
Number of elements	Number of blank elements = 4856 (initial mesh), 188528 (after mesh refinements at the end of stamping stage)
Type of elements	Type of blank elements = 4-node Belytschko-Tsay shell, reduced integration, hour glass control, 5 integration points through thickness.
Contact property model	Accurate Contact
Friction formulation	Standard Coulomb friction, value is 0.08 which is constant at all blank-tool interface

3. Simulation Hardware	
CPU Type	Intel® Core™ i7-3770 CPU @ 3.40 GHz
CPU clock speed	3.4 GHz
Number of cores per CPU	1 Core
Main memory	16 GB
Operating system	64-bit Operating System
Total CPU time	Total time = 25 hours [Binder closure (explicit) = 3.25 hours, Forming (Explicit) = 21.5 hours, Trimming-Springback (Implicit) = 0.25 Hours]

4. Describe the material model used for each material	
Material	AA6451-T4
Yield Function/ Plastic Potential	**Barlat 2000 or Yld 2000-2D**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic Hardening**
Stress-Strain Relation (e.g. Swift, Voce)	**Tabulated data following Voce Equation**

5. Remarks
Not Applicable In this Case.

BM2-03

1. Benchmark Participant	
Name	T.F. Neves, D.M. Neto, M.C. Oliveira, J.L Alves and L.F. Menezes
Affiliation	Departament of Mechanical Engineering, University of Coimbra
Address	Polo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
Email	diogo.neto@dem.uc.pt
Phone number	+351 239 790 700
Fax number	+351 239 790 701

2. Simulation Software	
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	141476
Type of elements	Isoparametric 3D brick elements with selective reduced integration technique
Contact property model	Rigid tools modelled by 132719 Nagata patches, Augmented lagrangian method
Friction formulation	Coulomb friction law

3. Simulation Hardware	
CPU Type	Intel® Core™ i7-5930K
CPU clock speed	3.5 GHz
Number of cores per CPU	6 cores
Main memory	64 GB RAM
Operating system	Windows 10 Professional (64-bit)
Total CPU time	284 hours (forming) 11 hours (trimming)

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Barlat 91**
Hardening Rule (e.g. Isotropic, kinematic)	**Armstrong–Frederick kinematic hardening**
Stress-Strain Relation (e.g. Swift, Voce)	**Voce law**

5. Remarks

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-04

1. Benchmark Participant	
Name	**Jun Hu, Fadi Abu-Farha**
Affiliation	Clemson University
Address	4 Research Drive, Greenville, SC 29607
Email	junh@g.clemson.edu | fadi@clemson.edu
Phone number	1-859-489-2926
Fax number	1-864-283-7225

2. Simulation Software	
Name of the FEM code	LS-DYNA
General aspect of the code	Forming: dynamic explicit; springback: static implicit
Basic formulations	Updated Lagrangian formulation with associated flow rule
Element/Mesh technology	
Number of elements	80657
Type of elements	Fully integrated shell element (ELFORM=16)
Contact property model	Surface to surface contact
Friction formulation	Coulomb friction

3. Simulation Hardware	
CPU Type	Intel Xeon64
CPU clock speed	
Number of cores per CPU	8 SMP double-precision
Main memory	16GB
Operating system	Scientific Linux 6
Total CPU time	12 hours 22 minutes

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Hill1948-3R, associated flow rule**
Hardening Rule (e.g. Isotropic, kinematic)	**Yoshida-Uemori model (isotropic + nonlinear kinematic hardening rule)**
Stress-Strain Relation (e.g. Swift, Voce)	**Voce**

5. Remarks

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-05

1. Benchmark Participant	
Name	**Kaiping Li, Yang Hu**
Affiliation	FCA US LLC
Address	800 Chrysler Dr, Auburn Hills, MI48326, USA
Email	Kaiping.li@fcagroup.com, yang.hu@fcagroup.com
Phone number	(1)2485766176, (1)2487015302
Fax number	(1)2485767190

2. Simulation Software	
Name of the FEM code	AutoForm R6
General aspect of the code	
Basic formulations	
Element/Mesh technology	
Number of elements	117081
Type of elements	Shell element
Contact property model	N/A
Friction formulation	constant (0.14 as Instructed)

3. Simulation Hardware	
CPU Type	Working Station with 8 Cpus
CPU clock speed	N/A
Number of cores per CPU	48
Main memory	32 GB
Operating system	LINUX
Total CPU time	Forming: 2 hours & Springback: 1min

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Barlat**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic**
Stress-Strain Relation (e.g. Swift, Voce)	**Combined Swift/Hockett-Sherby**

5. Remarks

BM2-06

1. Benchmark Participant	
Name	**Kaiping Li, Yang Hu**
Affiliation	FCA US LLC
Address	800 Chrysler Dr, Auburn Hills, MI48326, USA
Email	Kaiping.li@fcagroup.com, yang.hu@fcagroup.com
Phone number	(1)2485766176, (1)2487015302
Fax number	(1)2485767190

2. Simulation Software	
Name of the FEM code	LS-DYNA
General aspect of the code	
Basic formulations	
Element/Mesh technology	
Number of elements	560000
Type of elements	Fully integrated shell element
Contact property model	FORMING_ONE_WAY_SURFACE_TO_SURFACE + Penalty
Friction formulation	constant (0.08 as instructed)

3. Simulation Hardware	
CPU Type	HPC
CPU clock speed	N/A
Number of cores per CPU	48
Main memory	N/A
Operating system	LINUX
Total CPU time	Forming: 23 hours & Springback: 17mins

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**M36: Barlat89**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic**
Stress-Strain Relation (e.g. Swift, Voce)	**Swift**

5. Remarks

BM2-08

1. Benchmark Participant	
Name	1Rongfeng Liu , 2Ninshu Ma
Affiliation	1 2JSOL Corporation
Address	117F KS Bulding 2-18-25, Marunouchi Naka-ku, Nagoya 460-0002, Japan 2Tosabori Daibiru Building, 2-2-4, Tosabori Nishi-ku, Osaka 550-0001, Japan
Email	rongfeng.liu@jsol.co.jp, ma.ninshu@jsol.co.jp
Phone number	+81-52-202-8181
Fax number	+81-52-202-8172

2. Simulation Software	
Name of the FEM code	JSTAMP/NV
General aspect of the code	Integrated sheet metal forming simulation system
Basic formulations	Forming: Dynamic Explicit(LS-DYNA); Spribingback : Static implicit(LS-DYNA)
Element/Mesh technology	
Number of elements	Solid Blank: 1398855 / Die shell: 150884 /Holder shell:87704/Punch shell:97480
Type of elements	Constant stress solid element with 8 nodes
Contact property model	Penalty Mehtod, Node to Surface
Friction formulation	Coluomb's friction law, fricition coefficient m=0.08

3. Simulation Hardware	
CPU Type	Xeon E5-2670
CPU clock speed	2.60GHz
Number of cores per CPU	16 Core
Main memory	64G
Operating system	CentOS5.8
Total CPU time	37533 seconds(10 hours 25 min. 33 sec.) for 1420998 cycles

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Hill48**
Hardening Rule (e.g. Isotropic, kinematic)	**Yoshida-Uemori Kinematic hardending model**
Stress-Strain Relation (e.g. Swift, Voce)	**Swift**

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-09

1. Benchmark Participant	
Name	Jan NOVY, Takayuki OGAWA
Affiliation	ESI Group (MECAS ESI, ESI Japan)
Address	Brojova 16 33201 Plzen, Czech Republic; 6-14-1 Nishi-Shinjuku, Shinjyuku-ku, Tokyo 1600-0023, Japan
Email	jno@esi-group.com, tog@esi-group.com
Phone number	+420724269068; +81-3-6381-8494
Fax number	+420 377 432 930; +81-3-6381-8494

2. Simulation Software	
Name of the FEM code	Pam-Stamp
General aspect of the code	Dynamic explicit(forming), Static implicit (gravity, springback)
Basic formulations	Updated Lagrangian formulation with associated flow rule, Barlat2000 yield function, Yoshida kinematic hardening
Element/Mesh technology	
Number of elements	175,582 (After stamping), 75,084 (after trimming)
Type of elements	explicit solution:Belytschko-Tsay shell , implicit solution: Batoz Q4 gamma shell
Contact property model	explicit solution: non-linear penalty contact, implicit solution: contact 54
Friction formulation	Standard Coulomb friction

3. Simulation Hardware	
CPU Type	Intel Xeon CPU E5645 approach 1, Xeon e5-2650 approach 2
CPU clock speed	2.40GHz approach 1, 2.6GHz approach 2
Number of cores per CPU	12 approach 1, 8 approach 2
Main memory	48 GB approach 1, 64 GB approach 2
Operating system	Linux
Total CPU time	17 hours approach 1, 27 hours approach 2

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Yld2000-2D - the parameters for Yld2000-2D used as provided**
Hardening Rule (e.g. Isotropic, kinematic)	**Kinematic hardening**
Stress-Strain Relation (e.g. Swift, Voce)	**Yoshida-Uemori (Y-U): Cyclic shear data "Cyclical.xls" were transered into stress-strain curves. And then, Y-U parameters are evaluated from them by**

5. Remarks

There were used 2 approaches of computation:
Approach 1:
Gravity - Holding - Stamping - Trimming&springback using locked nodes of model

Approach 2:
OP20 (Gravity-Holding-Stamping-Springback) - OP30 (Holding-Trimming-Springback)-Fixure(Clamping)
Since trimming dies and fixtures are not provided by organizer, those shapes are estimated from the specifications and provided CAD data.
For more please check video:Fixture.avi
There are submitted two result only in STL

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-10

1. Benchmark Participant	
Name	**Albert Forgas**
Affiliation	Quantech ATZ
Address	C/Gran Capità 2/4 08034 Barcelona, Spain
Email	aforgas@stampack.com
Phone number	+342047083
Fax number	

2. Simulation Software	
Name of the FEM code	Stampack V7.1.2
General aspect of the code	Finite Element Method
Basic formulations	Explicit Formability, Implicit Springback
Element/Mesh technology	
Number of elements	93099
Type of elements	Hexahedra Special Integration
Contact property model	Penalty Method
Friction formulation	Coluomb

3. Simulation Hardware	
CPU Type	Intel Core i7-3770
CPU clock speed	3,40 GHz
Number of cores per CPU	8 threads
Main memory	16 GB
Operating system	Win 7 64 Bit
Total CPU time	3 Hour 35 Min 20 Sec

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Yoshida Uemori**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic**
Stress-Strain Relation (e.g. Swift, Voce)	**Voce**

5. Remarks
Variable young modulus

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-11

1. Benchmark Participant	
Name	Albert Forgas
Affiliation	Quantech ATZ
Address	C/Gran Capità 2/4 08034 Barcelona, Spain
Email	aforgas@stampack.com
Phone number	+342047083
Fax number	

2. Simulation Software	
Name of the FEM code	Stampack V7.1.2
General aspect of the code	Finite Element Method
Basic formulations	Explicit Formability, Implicit Springback
Element/Mesh technology	
Number of elements	59638
Type of elements	Basic Shell Triangle
Contact property model	Penalty Method
Friction formulation	Coluomb

3. Simulation Hardware	
CPU Type	Intel Core i7-3770
CPU clock speed	3,40 GHz
Number of cores per CPU	8 threads
Main memory	16 GB
Operating system	Win 7 64 Bit
Total CPU time	0 Hour 40 Min 10 Sec

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Yoshida Uemori**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic**
Stress-Strain Relation (e.g. Swift, Voce)	**Voce**

5. Remarks
Variable young modulus

Journal of Physics: Conference Series **734** (2016) 022002 doi:10.1088/1742-6596/734/2/022002

BM2-12

1. Benchmark Participant	
Name	SARIN BABU THOKALA
Affiliation	STADCO LTD
Address	Queens way, Hortonwood, Telford - TF1 7LL, UK
Email	S.Thokala@stadco.co.uk
Phone number	0044 (0) 787 554 6247 or 0044 (0) 772 481 6535
Fax number	0044 (0) 1952 222050

2. Simulation Software	
Name of the FEM code	AutoForm^plus R6
General aspect of the code	Stamping Simulation
Basic formulations	Static Implicit
Element/Mesh technology	
Number of elements	Form - 205000, After Trim -88000
Type of elements	Triangular elastic plastic shell, 11 Integration points through thickness
Contact property model	
Friction formulation	Coulomb friction (0.14)

3. Simulation Hardware	
CPU Type	Intel®Core™i7-2760QM CPU @ 2.40GHz
CPU clock speed	2.40GHz
Number of cores per CPU	4
Main memory	32.0GB
Operating system	Windows 7 Professional
Total CPU time	01Hour:20Mins:32Sec

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Barlat -1989**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic hardening**
Stress-Strain Relation (e.g. Swift, Voce)	**Aproximation (Combined Swift - Hockett-Sherby formulation)**

5. Remarks

BM2-13

1. Benchmark Participant	
Name	Jan Slota, Marek Siser
Affiliation	Technical University of Kosice
Address	Masiarska 74, 040 01 Kosice, Slovakia
Email	jan.slota@tuke.sk, marek siser@tuke.sk
Phone number	
Fax number	

2. Simulation Software	
Name of the FEM code	PAM-Stamp 2015.1
General aspect of the code	Explicit
Basic formulations	
Element/Mesh technology	
Number of elements	82000
Type of elements	Quadrilateral
Contact property model	Accurate
Friction formulation	0.08

3. Simulation Hardware	
CPU Type	Intel Xeon CPU E5 2670
CPU clock speed	2,6 GHz
Number of cores per CPU	6, total 12 cores
Main memory	16 GB
Operating system	Win 8.1 64 bit
Total CPU time	14:30 hod.

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Barlat2000**
Hardening Rule (e.g. Isotropic, kinematic)	**Isotropic**
Stress-Strain Relation (e.g. Swift, Voce)	**Krupkowski/Swift**

5. Remarks

BM2-14

1. Benchmark Participant	
Name	**Hariharasudhan Palaniswamy, Subir Roy**
Affiliation	Altair Engineering
Address	1820 E Big Beaver road, Troy, MI, 48085, USA
Email	hpalaniswamy@altair.com, subir@altair.com
Phone number	248-614-2400
Fax number	248-614-2411

2. Simulation Software	
Name of the FEM code	HyperForm - RADIOSS
General aspect of the code	Commercial nonlinear finite element software
Basic formulations	Forming (Explicit), Springback(Implicit)
Element/Mesh technology	
Number of elements	810934
Type of elements	Shell element - QEPH formulation
Contact property model	Penaltly based contact formulations
Friction formulation	Coulomb's Law

3. Simulation Hardware	
CPU Type	HPC Cluster
CPU clock speed	2.50GHz
Number of cores per CPU	13 Node, 24 cores per node. 24 cpu's used for the simulation
Main memory	128 GB of RAM per core
Operating system	Linux
Total CPU time	Forming: 16118 Secs, Trimming: 0 Sec, springback : 390 Secs

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	**Barlat 3 parameter model**
Hardening Rule (e.g. Isotropic, kinematic)	**Combined hardening rule**
Stress-Strain Relation (e.g. Swift, Voce)	**Voce hardening law**

5. Remarks

BM2-15

1. Benchmark Participant	
Name	[1]Yasuyoshi Umezu , [1]Toshiro Amaishi, [2]Wan-Jin Chung
Affiliation	[1] JSOL Corporation , [2] Seoul National Univerisity of Science & Technology
Address	[1]Tosabori Daibiru Building, 2-2-4, Tosabori Nishi-ku, Osaka 550-0001, Japan [2]232 Gongneung-ro, Nowon-gu, Seoul, 01811, korea
Email	umezu.yasu@jsol.co.jp, amaishi.toshirou@jsol.co.jp, wjchung@seoultech.ac.kr
Phone number	+81-6-4803-5820
Fax number	+81-6-6225-3517

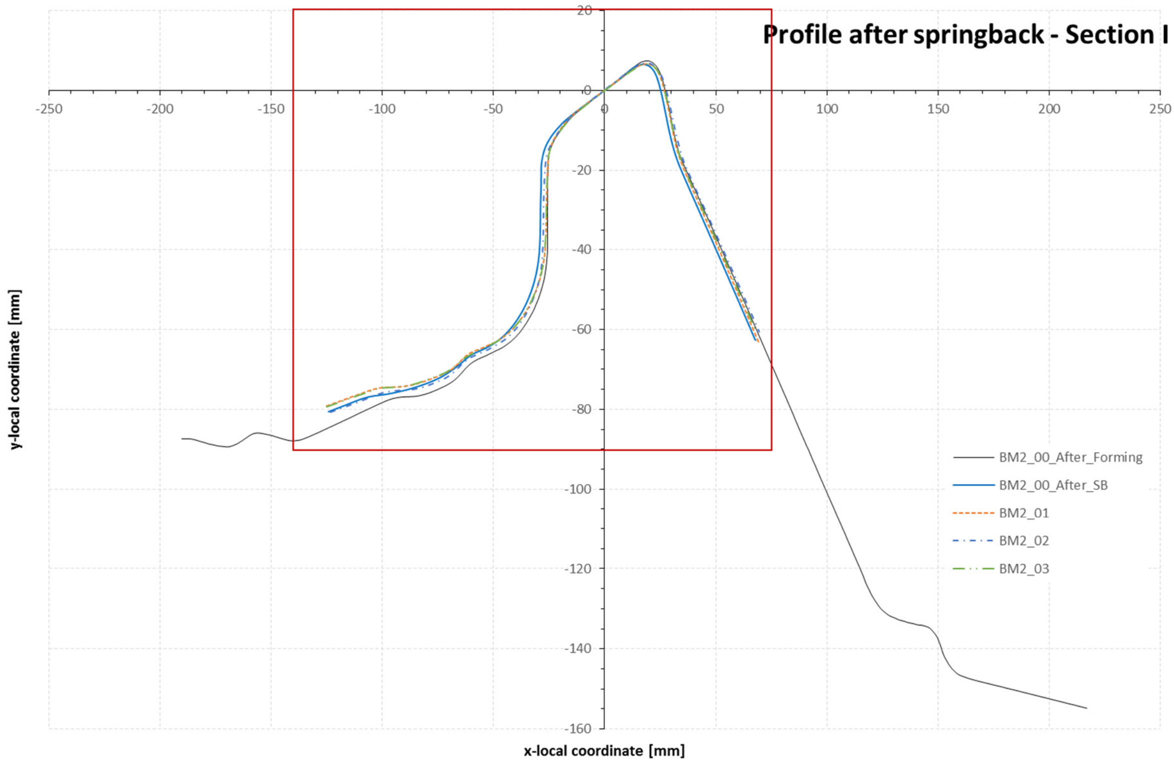
2. Simulation Software	
Name of the FEM code	ASTAMP(for Forming), JOH/NIKE(for Spring back)
General aspect of the code	Press Simulation Softrware Optimized for GPGPU
Basic formulations	Forming:Dynamic Explicit, Spring back:Static Implicit
Element/Mesh technology	
Number of elements	466544 (for Blank)
Type of elements	Quadrilateral Belytschko-Tsay and C0 Triangular
Contact property model	Penalty Method, Node to Surface
Friction formulation	Coulomb's friction law

3. Simulation Hardware	
CPU Type	GPGPU(TESLA-K20)
CPU clock speed	706MHz (TESLA-K20)
Number of cores per CPU	2496 cores (TESLA-K20)
Main memory	5Gb (TESLA-K20)
Operating system	Windows 7 Professional
Total CPU time	15226 sec (4 hours 14 min 46sec) for 194124 Binder&Forming steps, 551 sec for Springback

4. Describe the material model used for each material	
Material	AA6451-T4
Yield Function/ Plastic Potential	Hill 48
Hardening Rule (e.g. Isotropic, kinematic)	Isotropic Hardening
Stress-Strain Relation (e.g. Swift, Voce)	Voce

5. Remarks

Binder Closure and Forming steps are not separated in this calculation, 60% of computation times was required for Binder Closure and 40% for Forming.



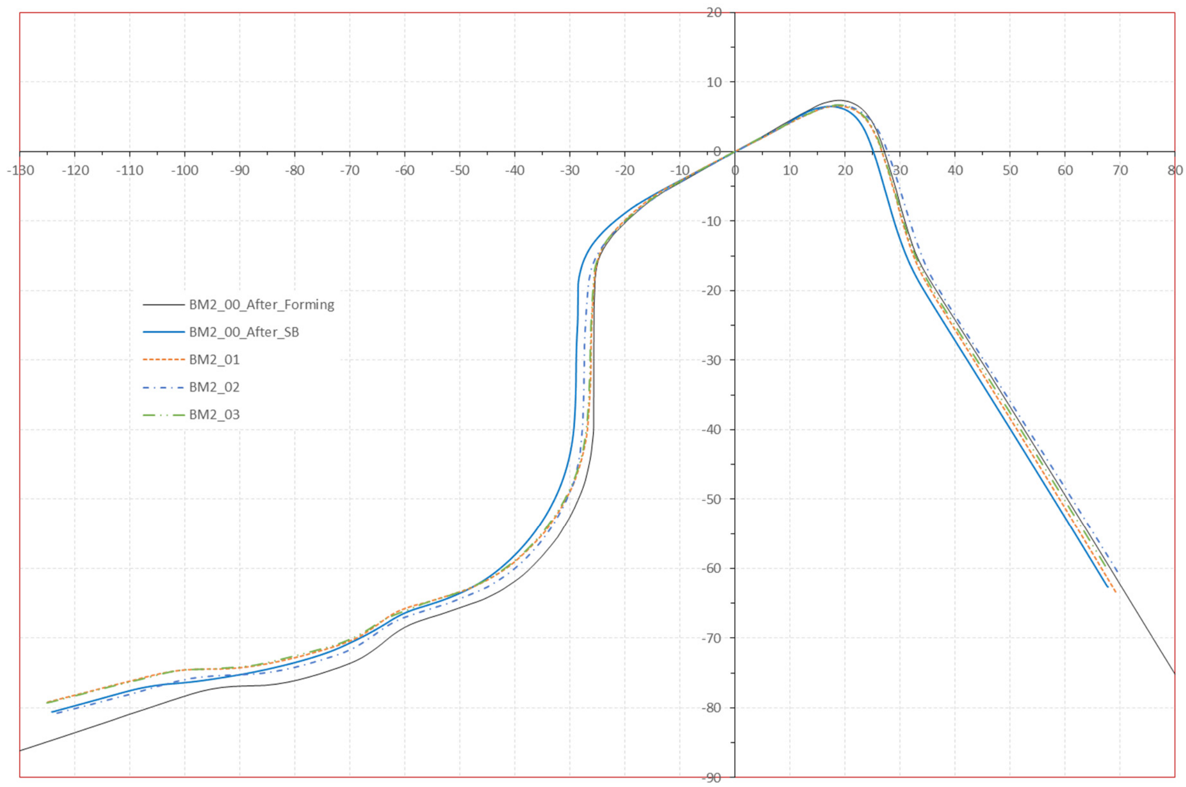
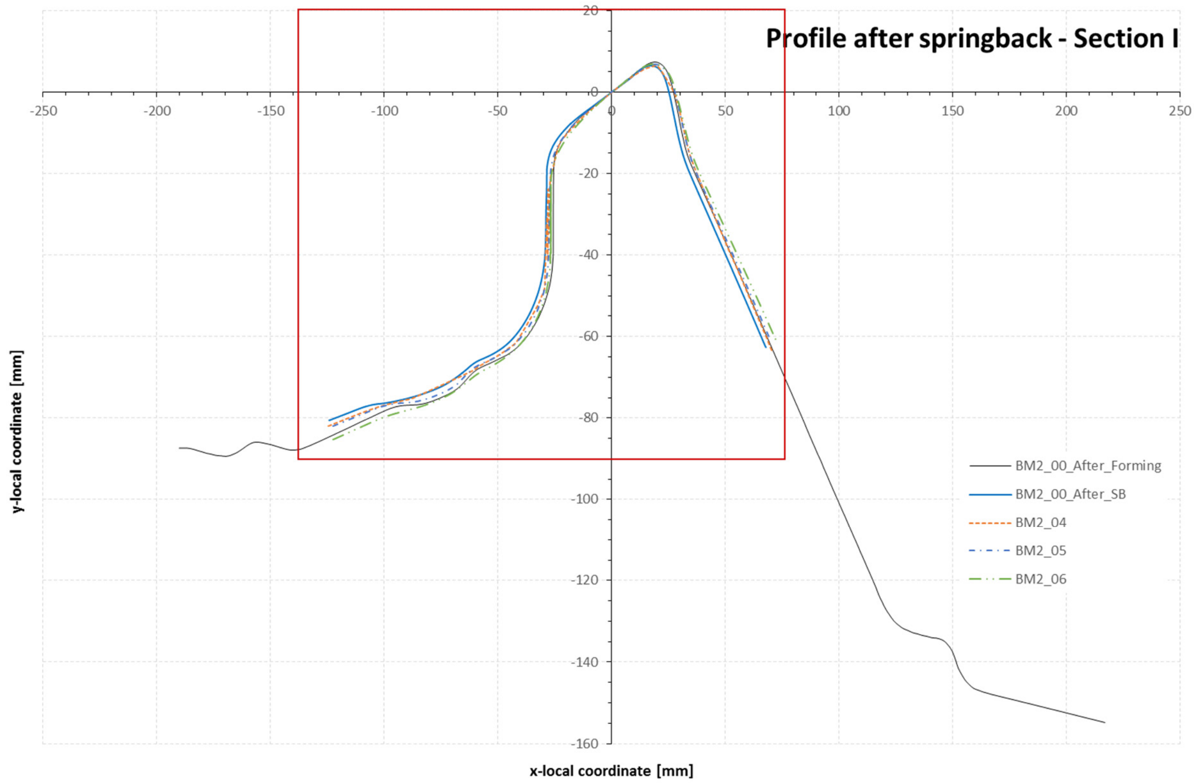


Figure 6.1. Profile after springback for Section I: BM2_01, BM2_02, BM2_03.



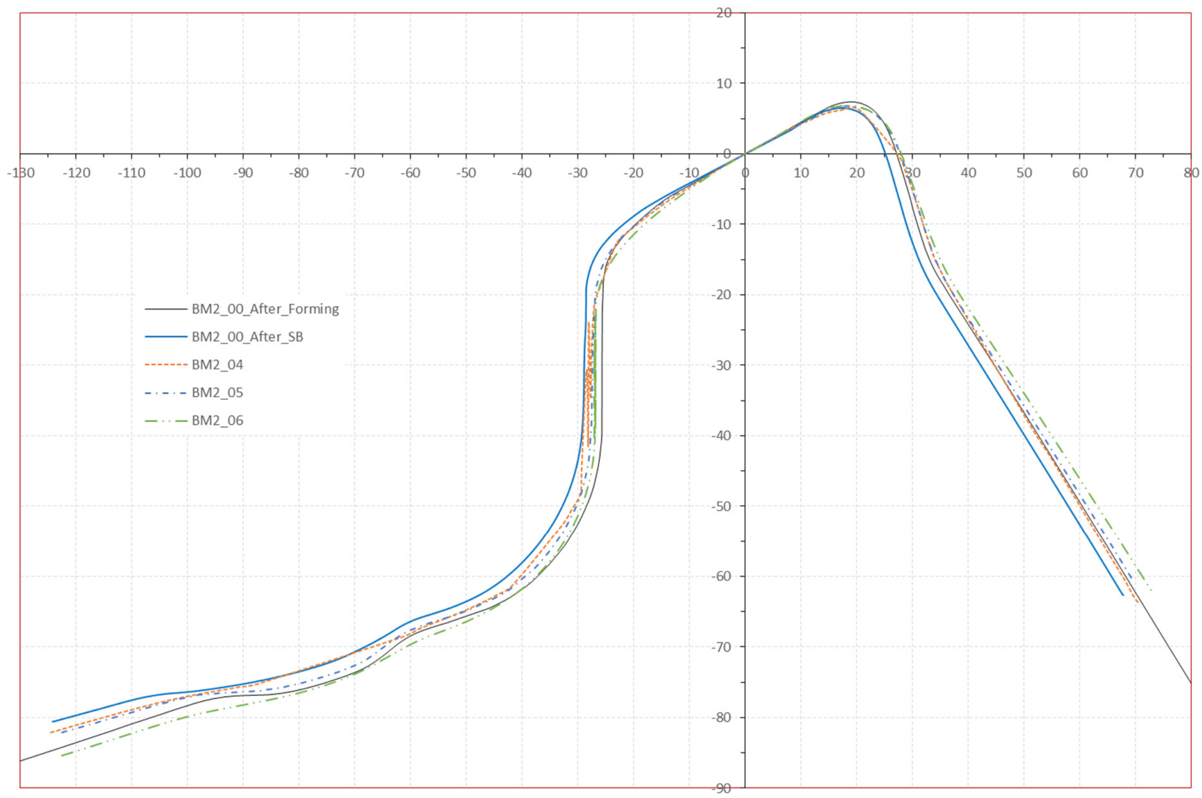
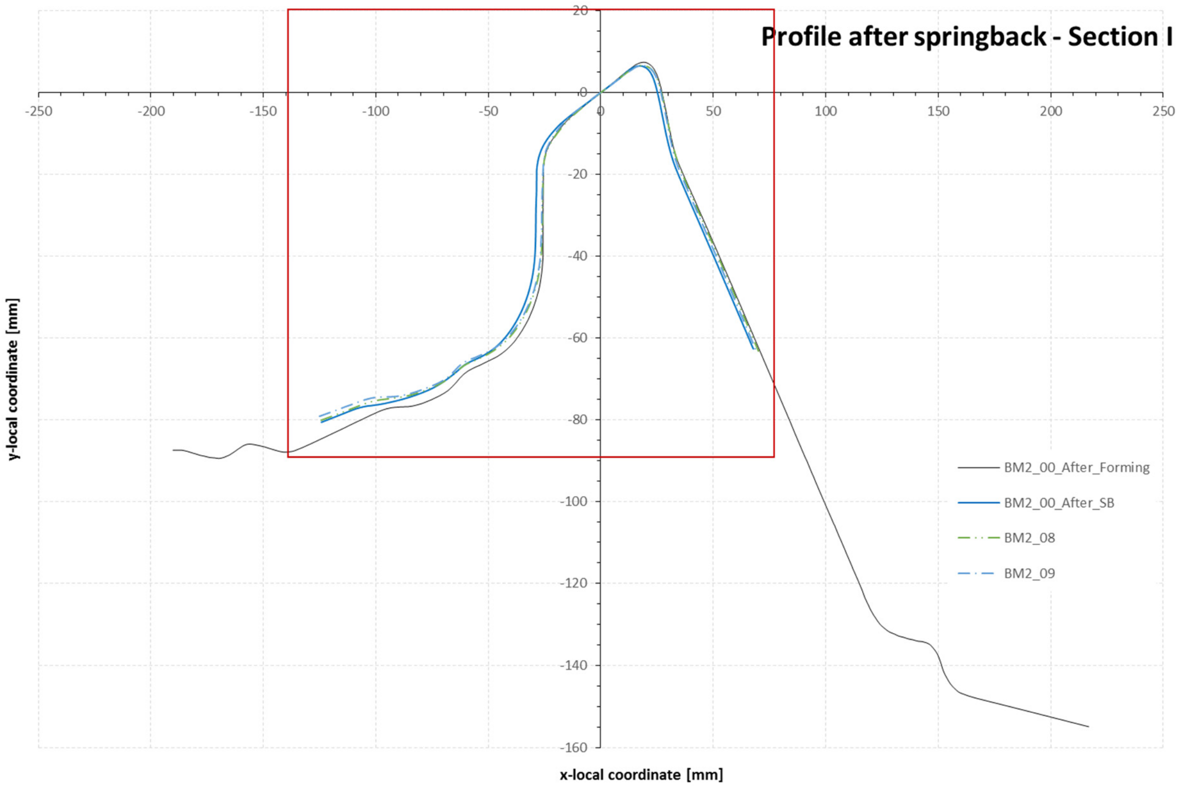


Figure 6.2. Profile after springback for Section I: BM2_04, BM2_05, BM2_06.



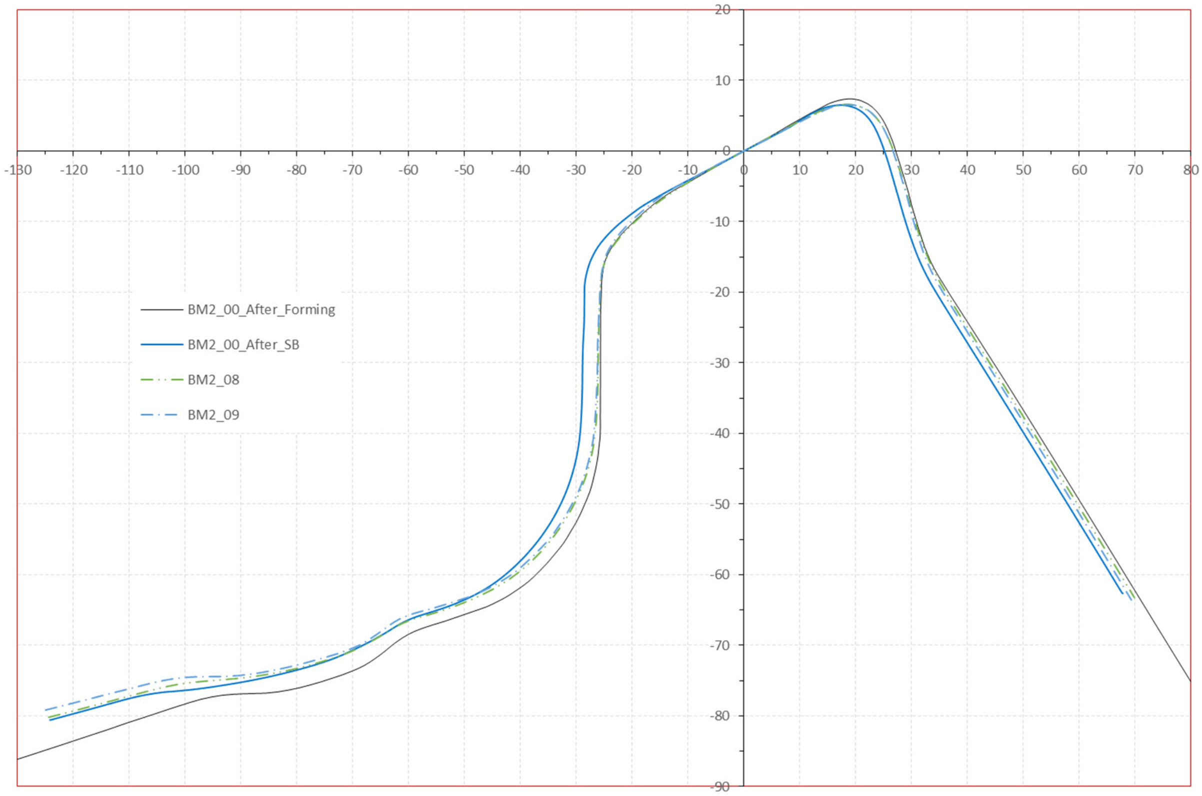


Figure 6.3. Profile after springback for Section I: BM2_08, BM2_09.

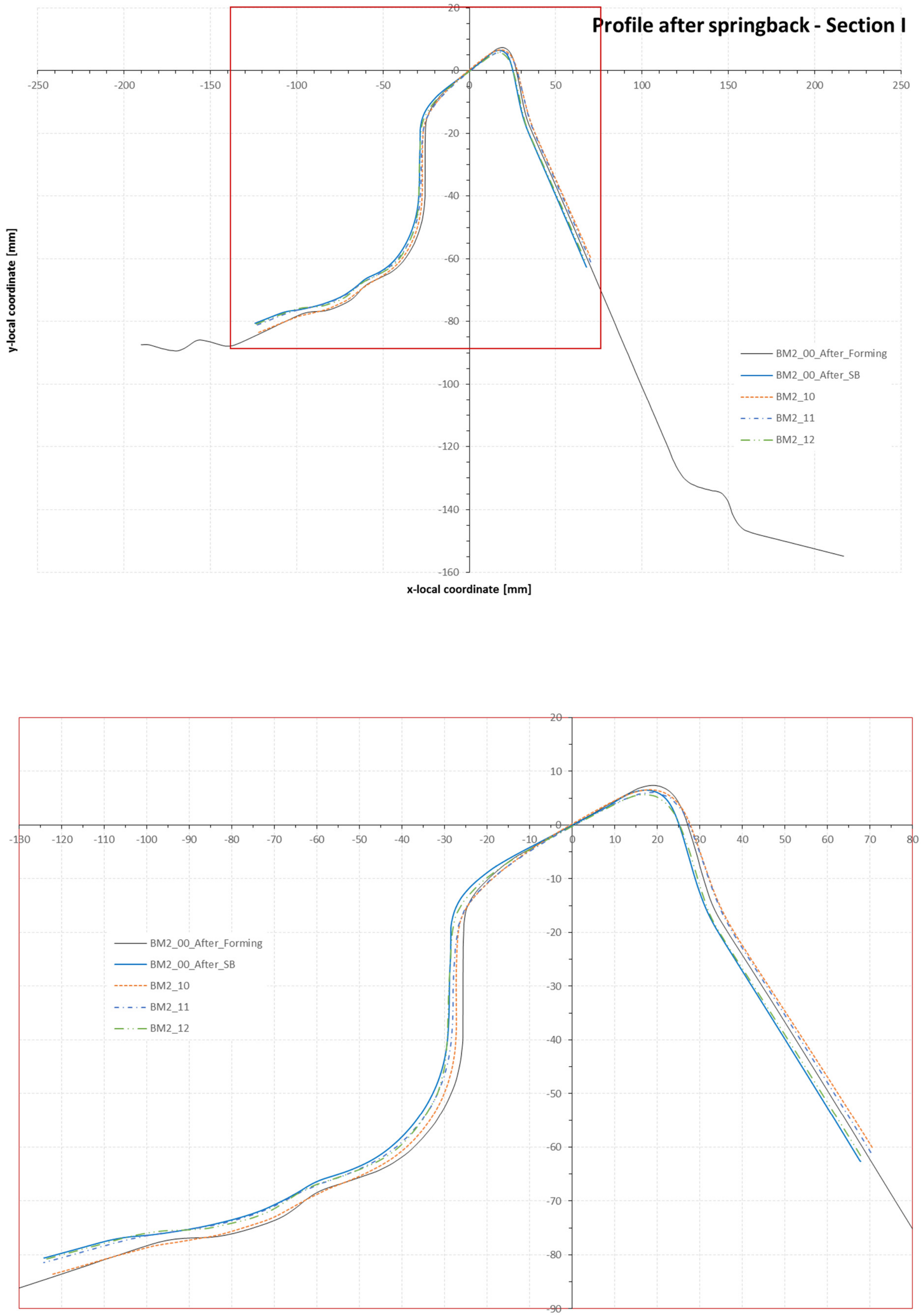
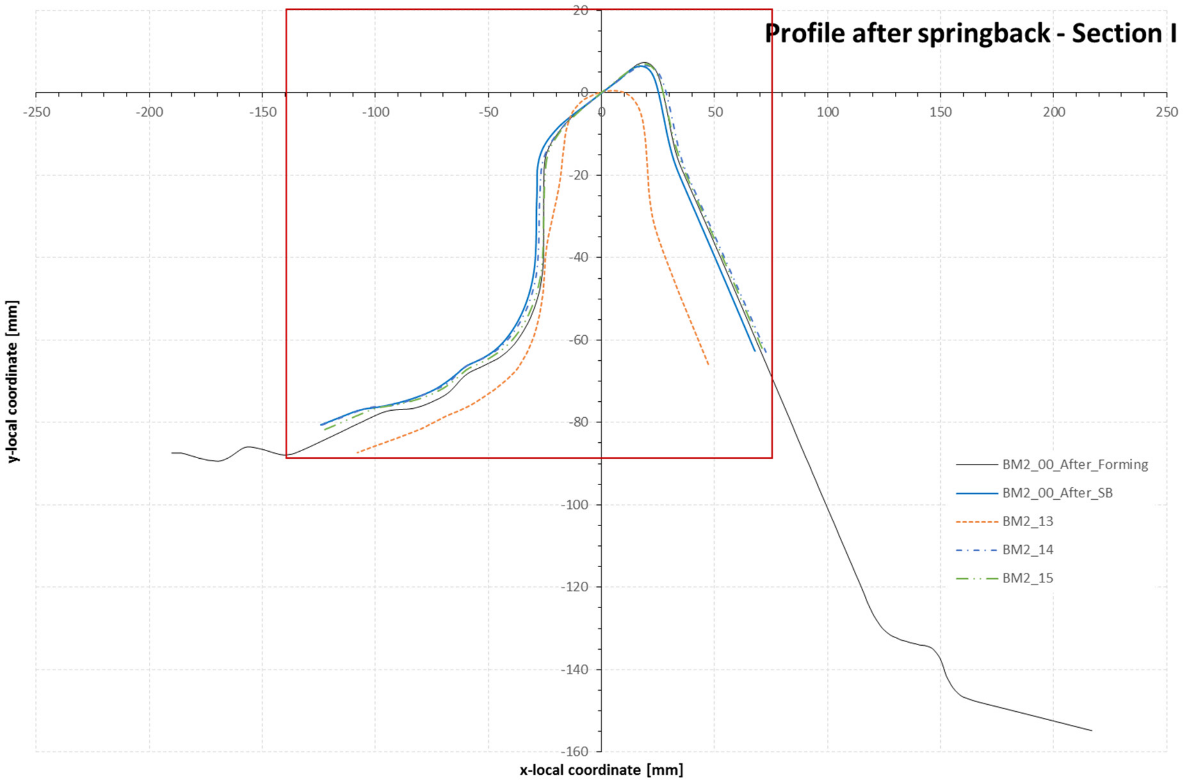


Figure 6.4. Profile after springback for Section I: BM2_10, BM2_11, BM2_12.



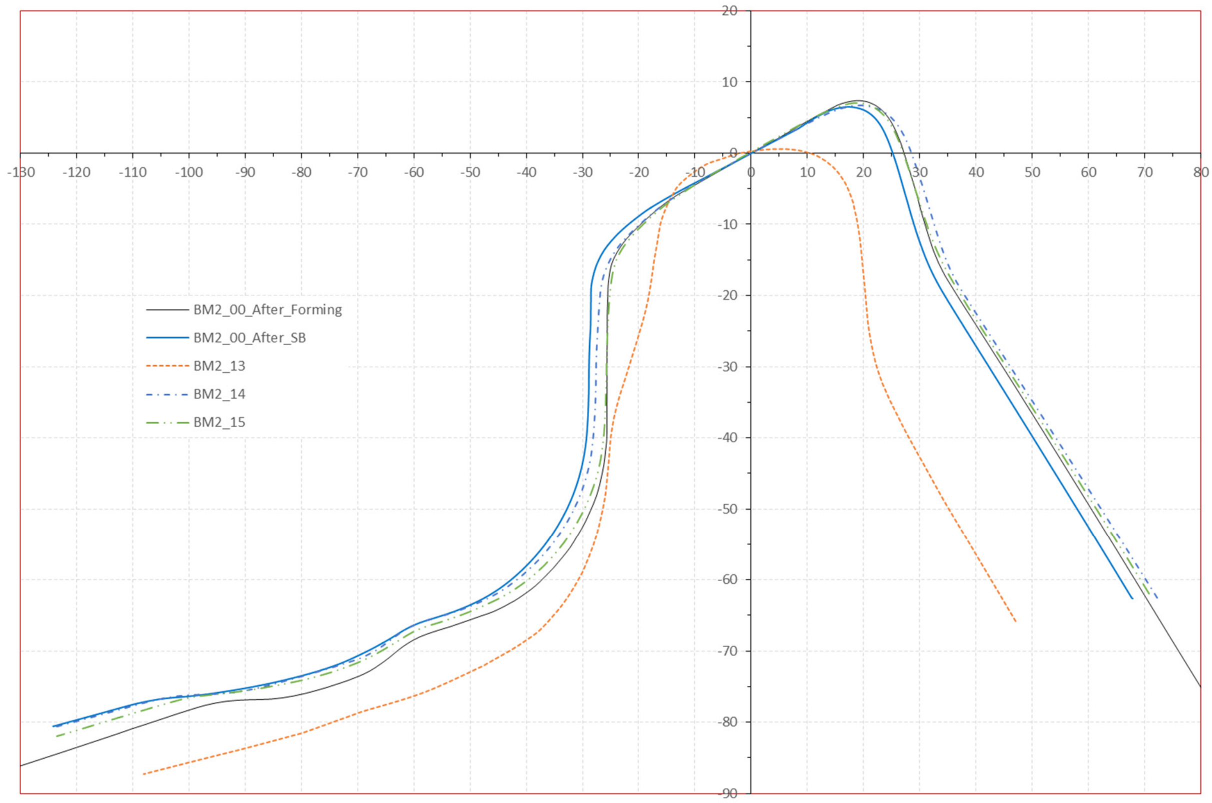
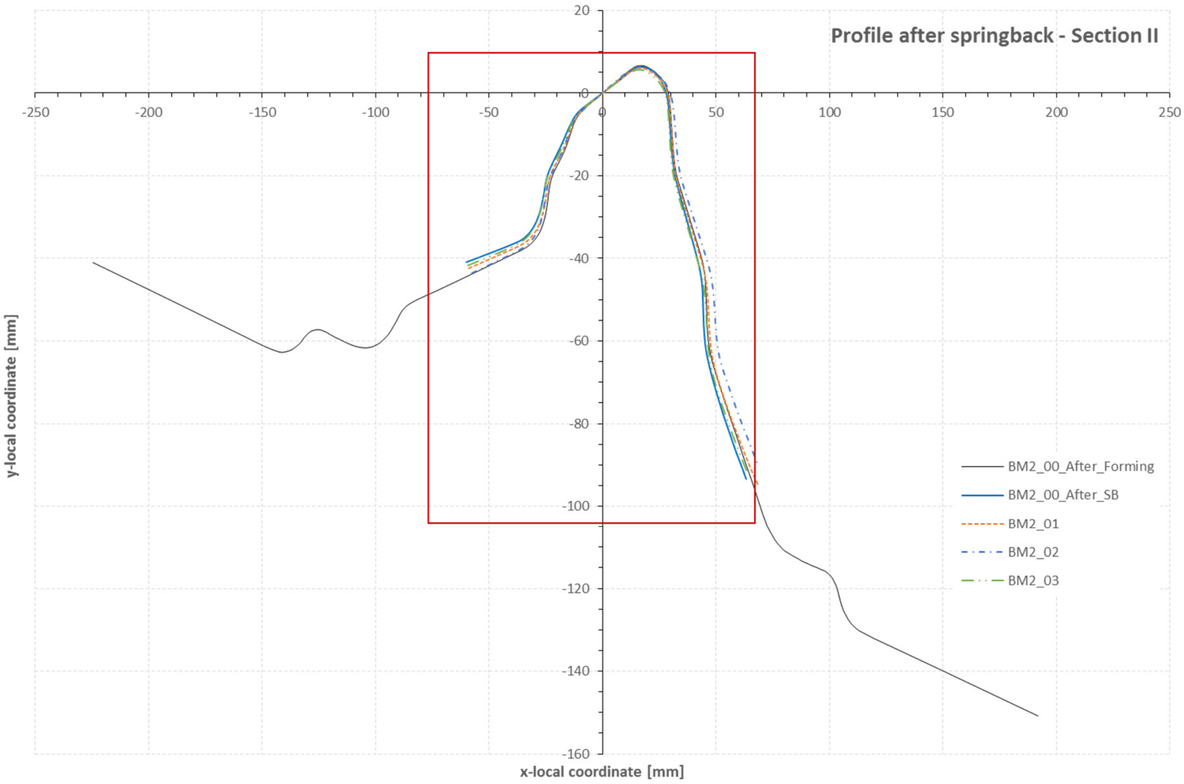


Figure 6.5. Profile after springback for Section I: BM2_13, BM2_14, BM2_15.



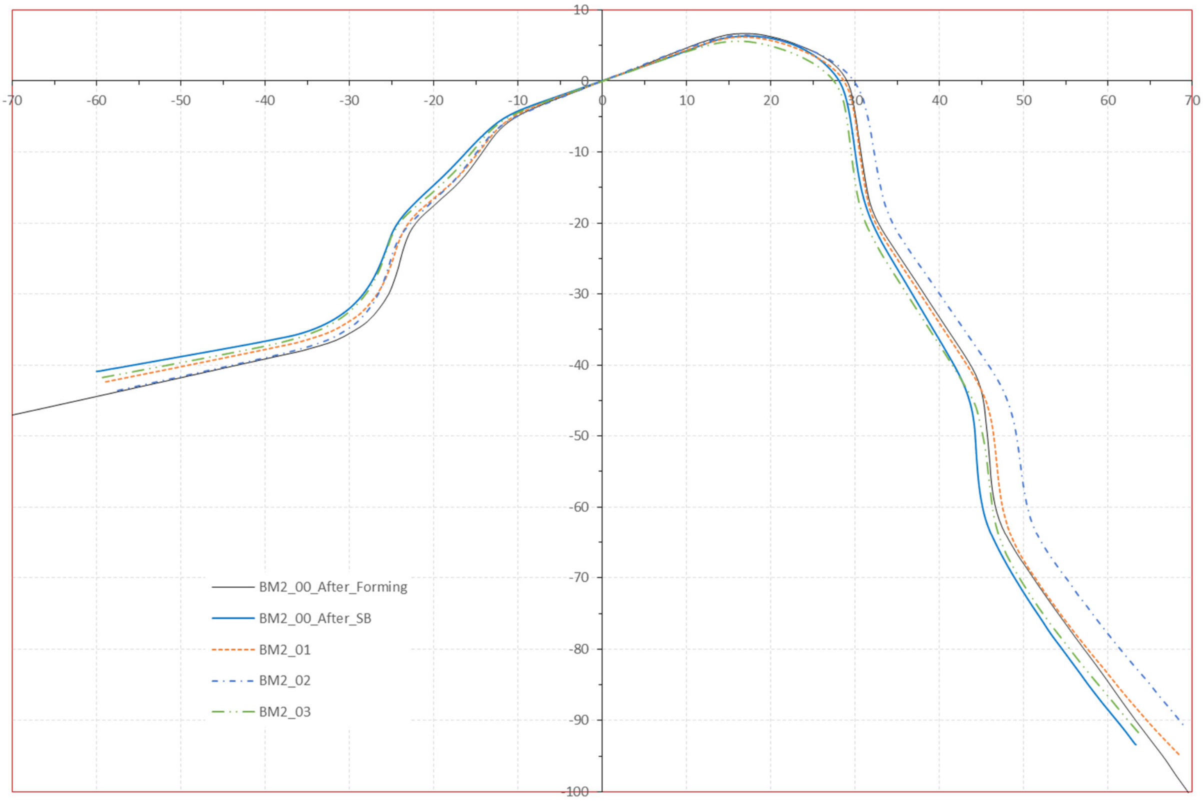
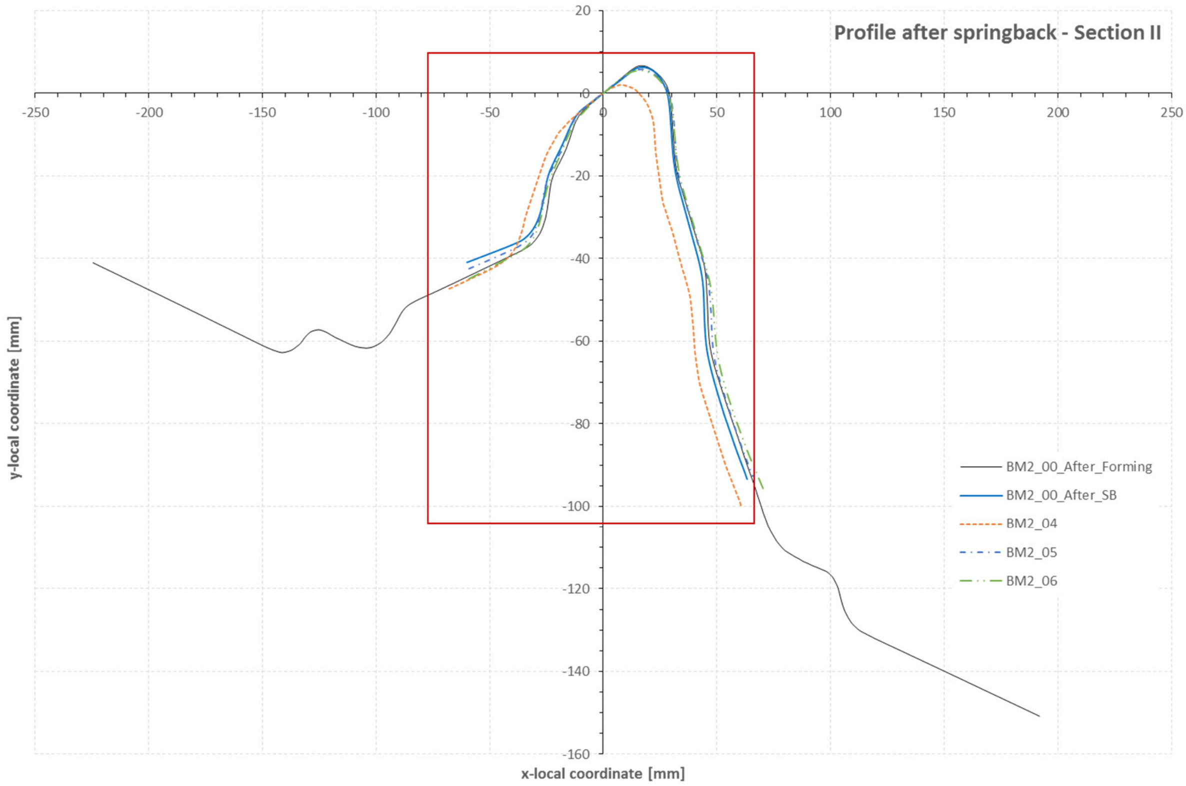


Figure 6.6. Profile after springback for Section II: BM2_01, BM2_02, BM2_03.



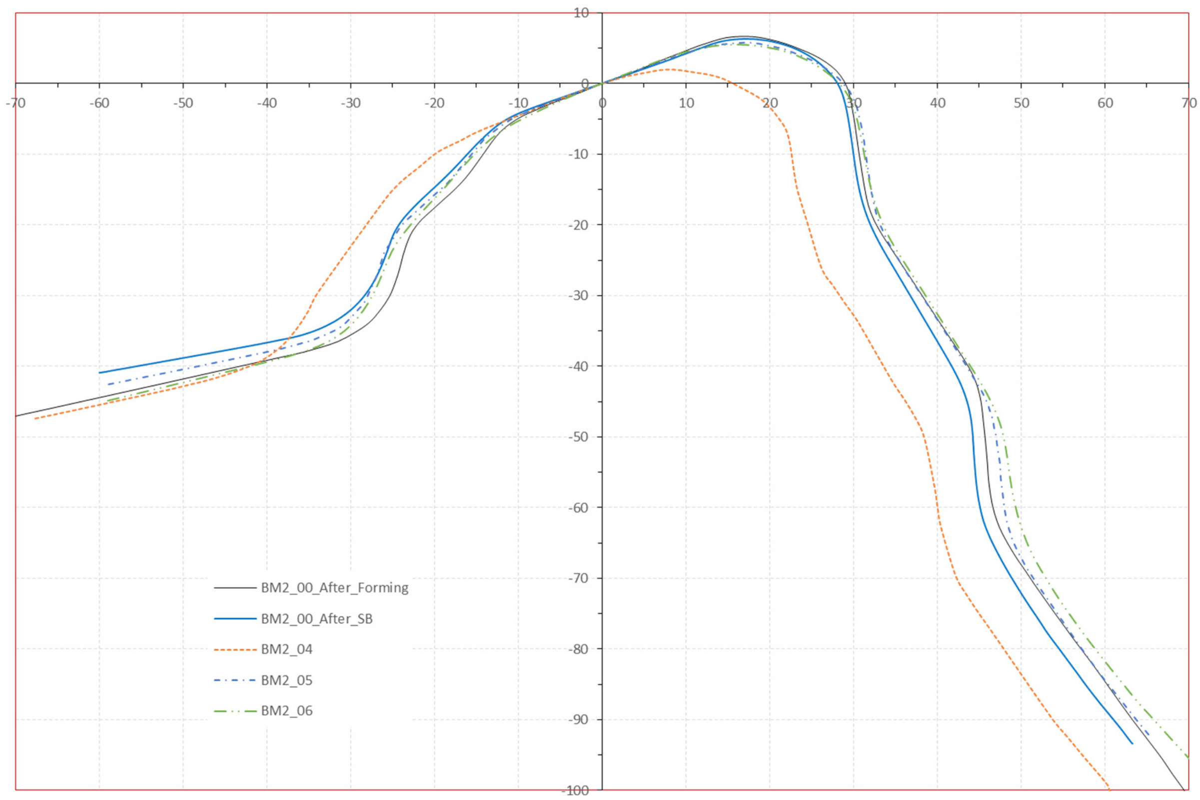
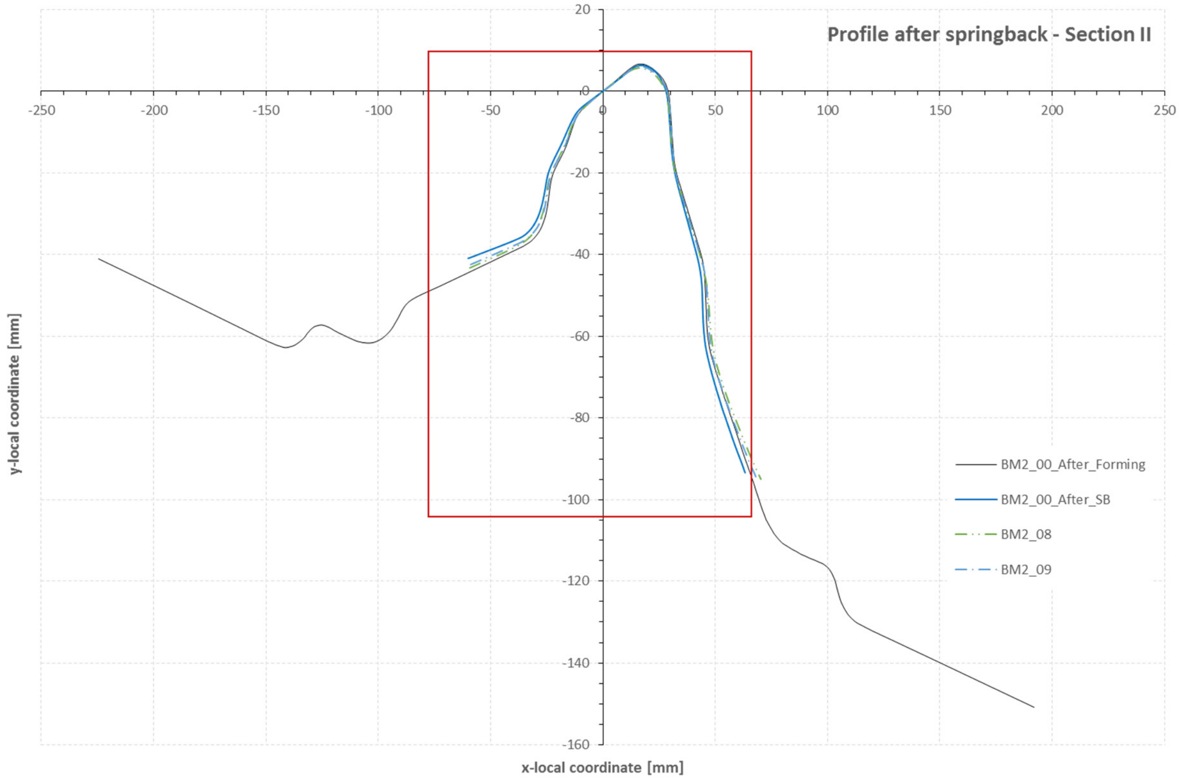


Figure 6.7. Profile after springback for Section II: BM2_04, BM2_05, BM2_06.



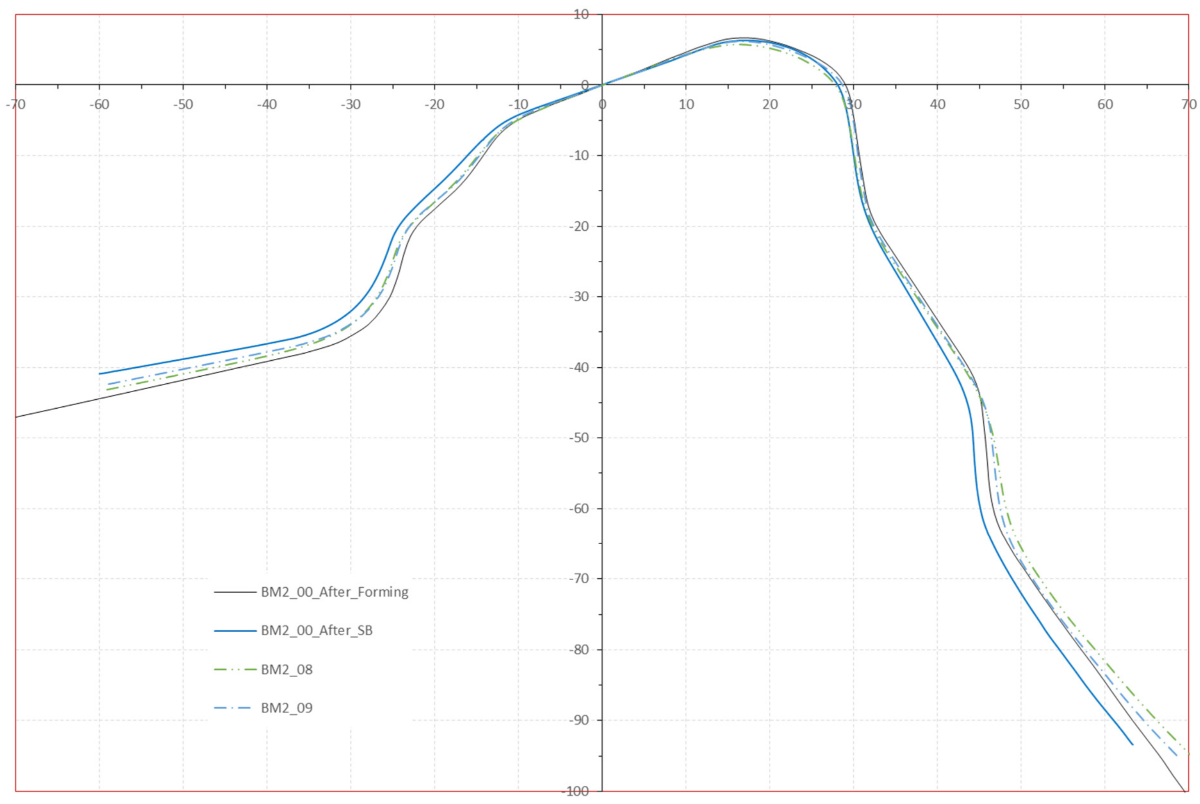
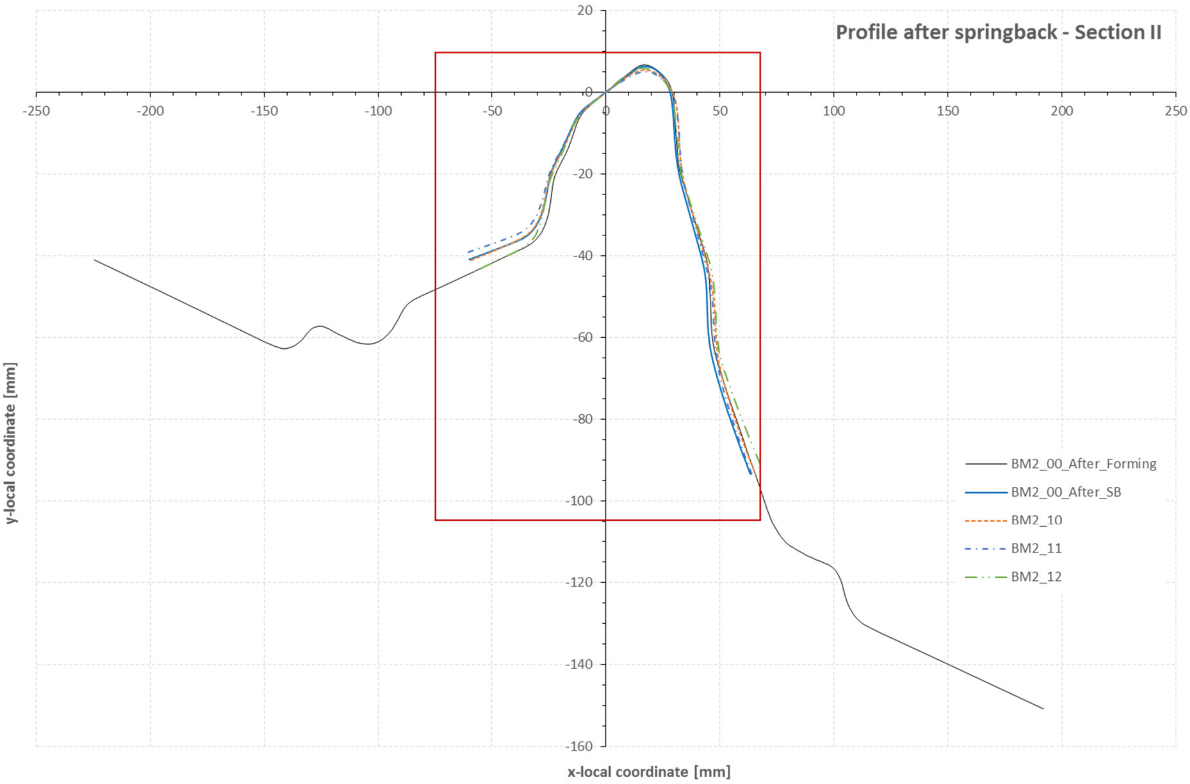


Figure 6.8. Profile after springback for Section II: BM2_08, BM2_09.



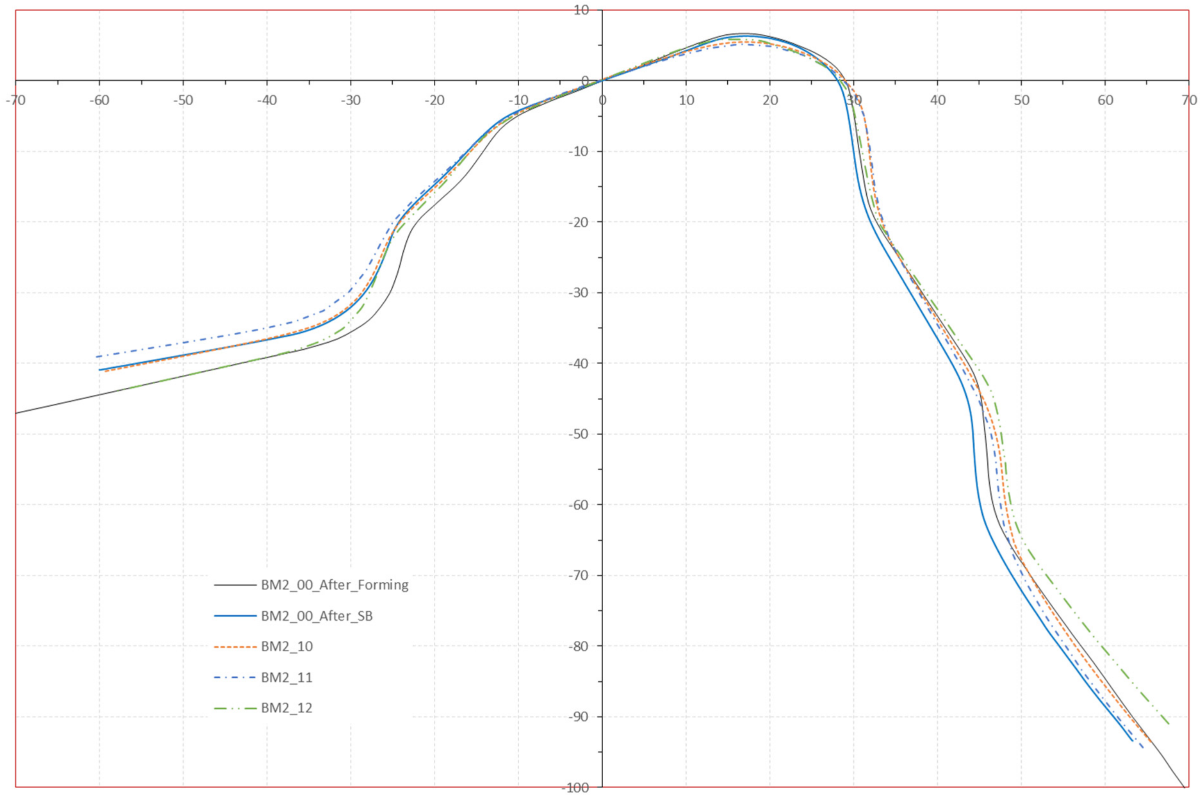
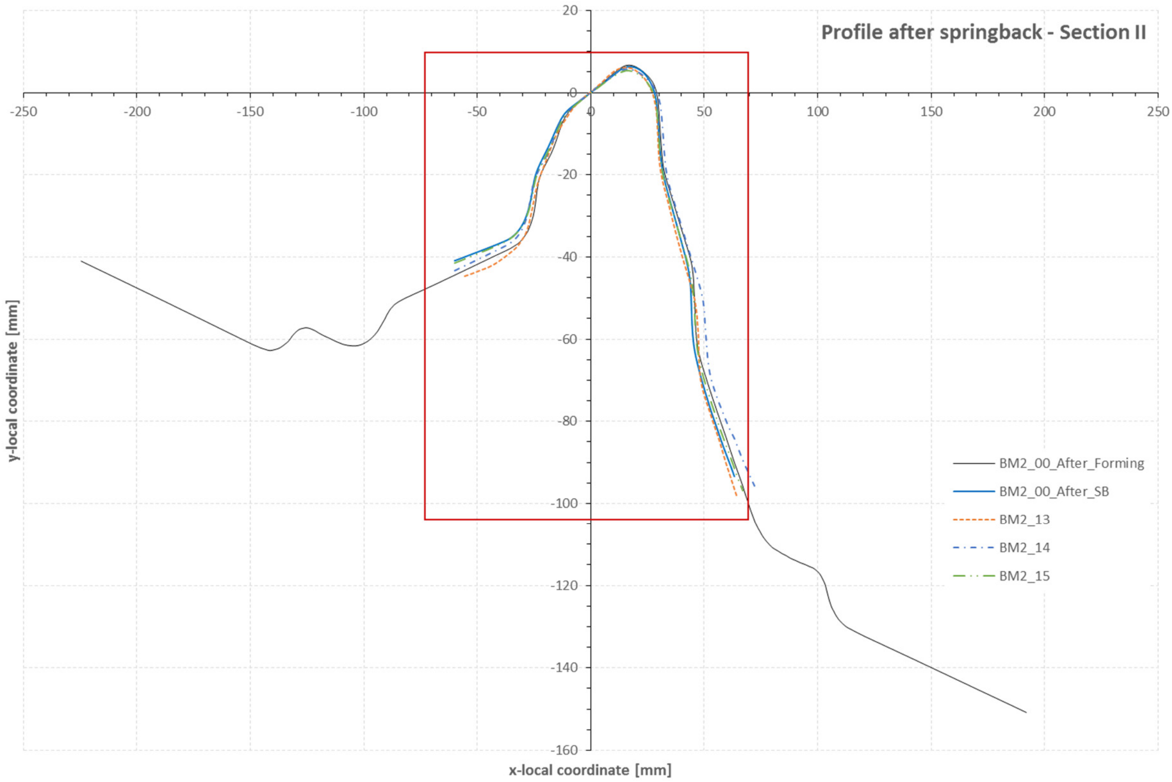


Figure 6.9. Profile after springback for Section II: BM2_10, BM2_11, BM2_12.



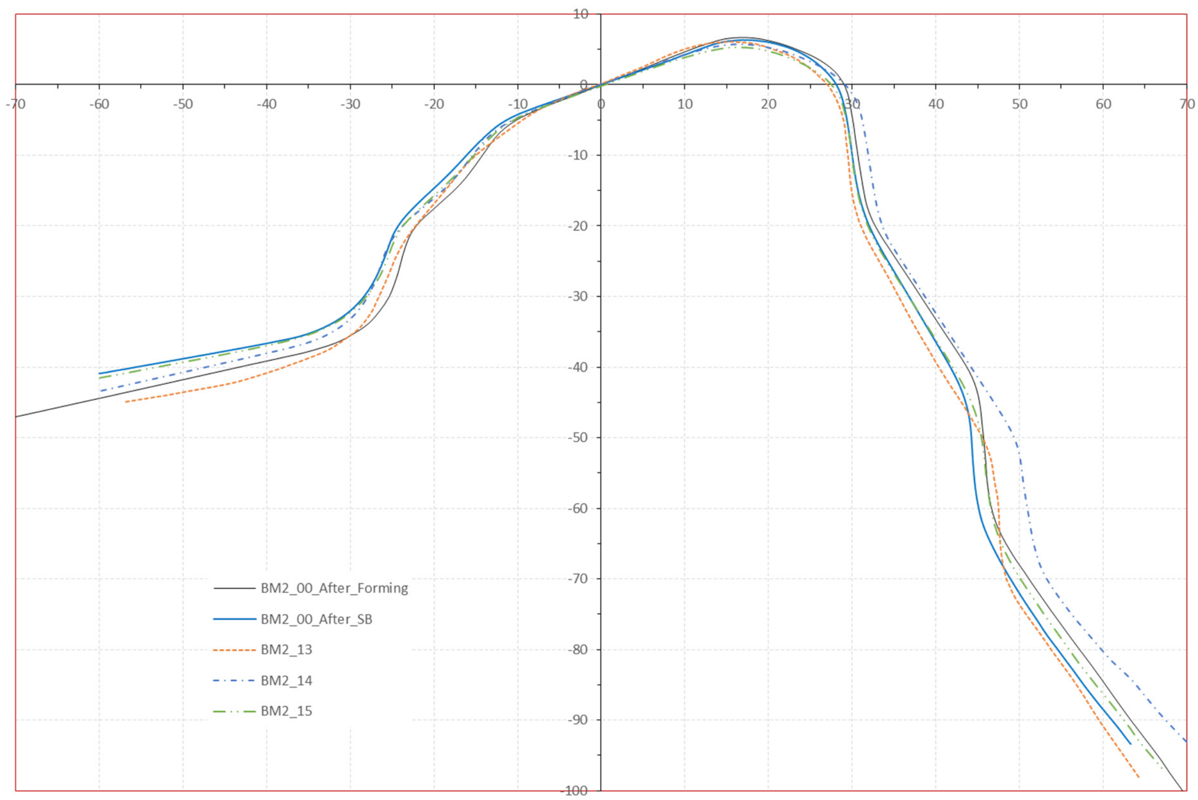


Figure 6.10. Profile after springback for Section II: BM2_13, BM2_14, BM2_15.

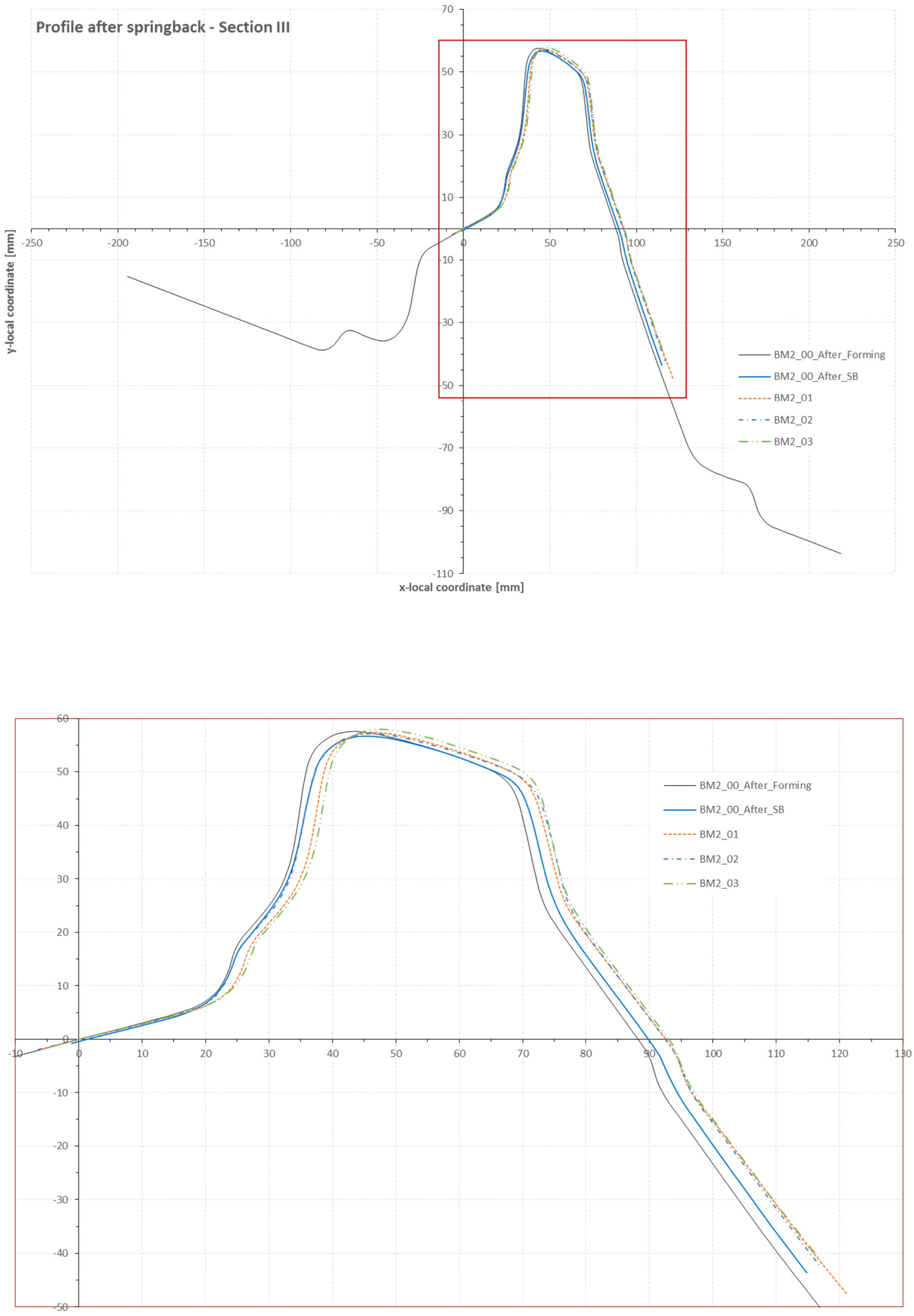
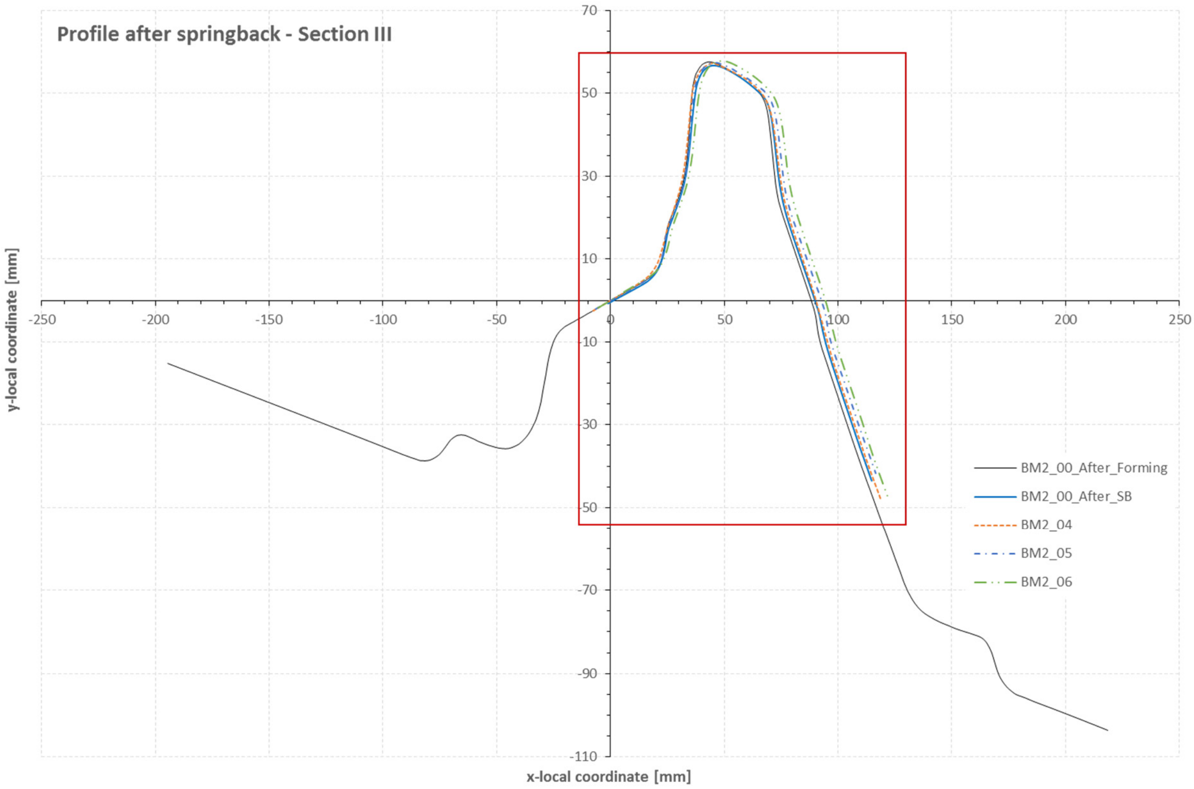


Figure 6.11. Profile after springback for Section III: BM2_01, BM2_02, BM2_03.



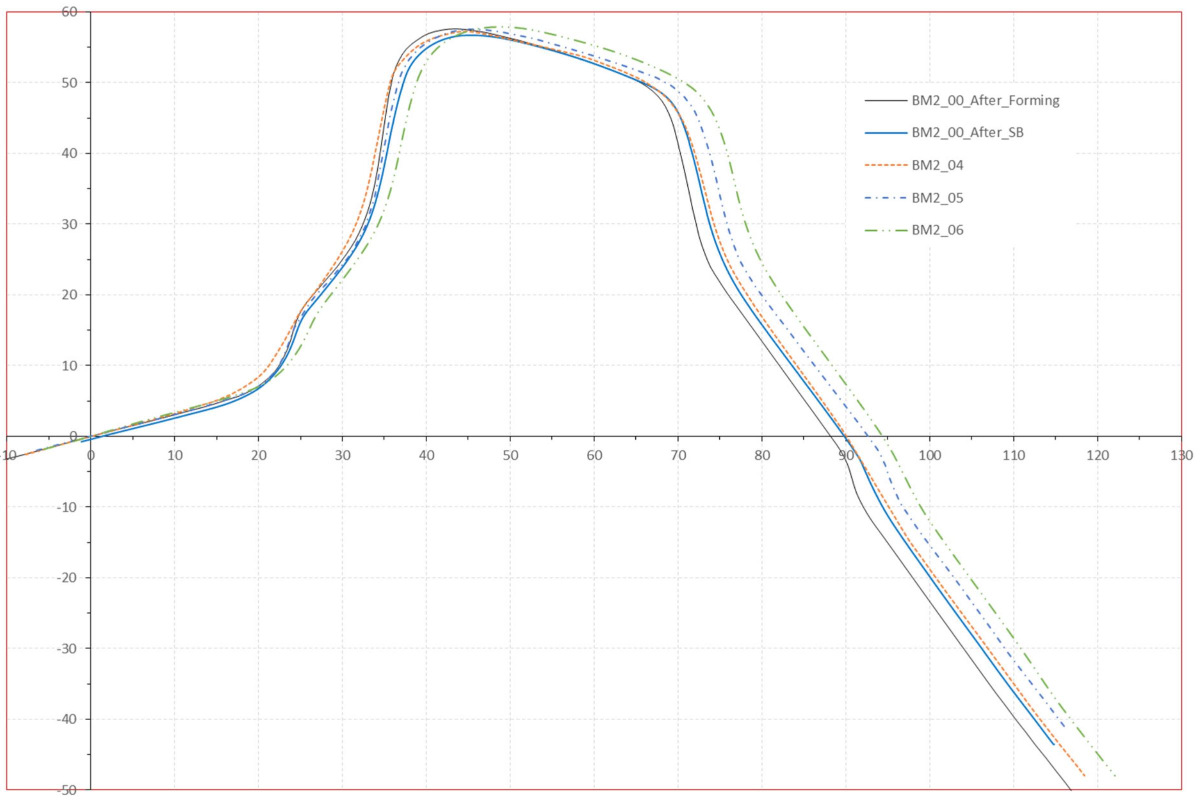
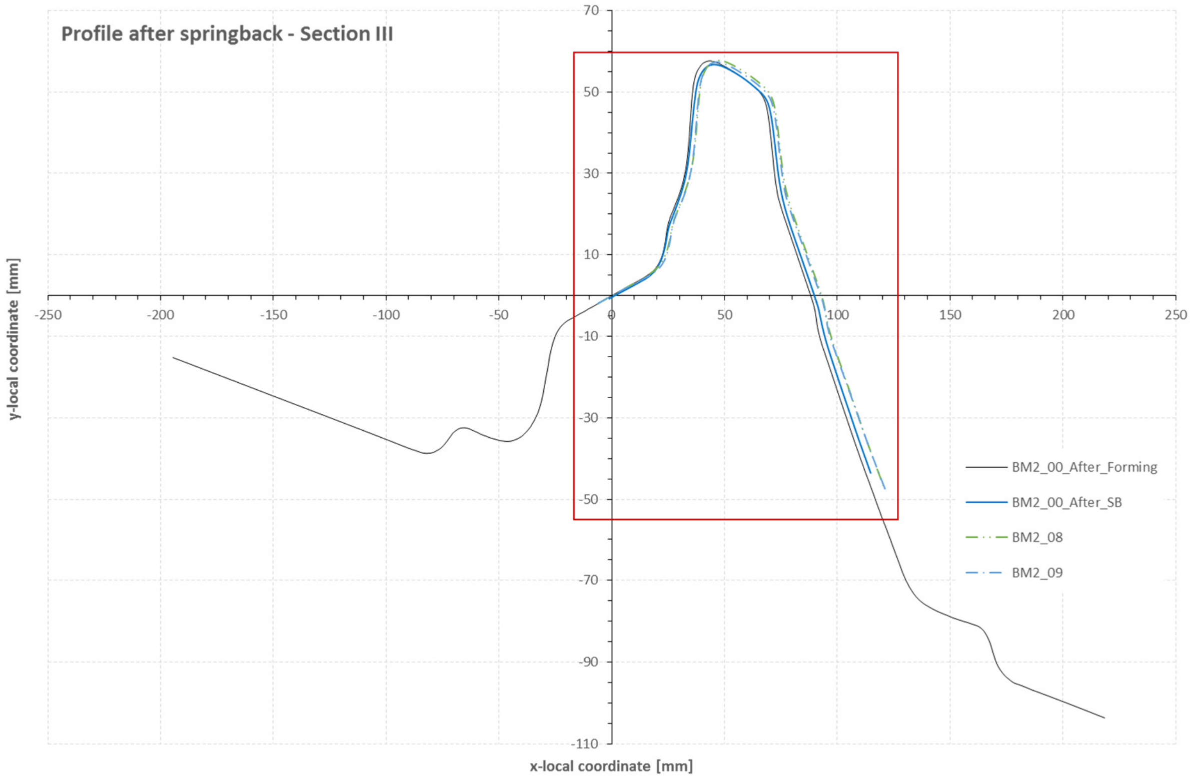


Figure 6.12. Profile after springback for Section III: BM2_04, BM2_05, BM2_06.



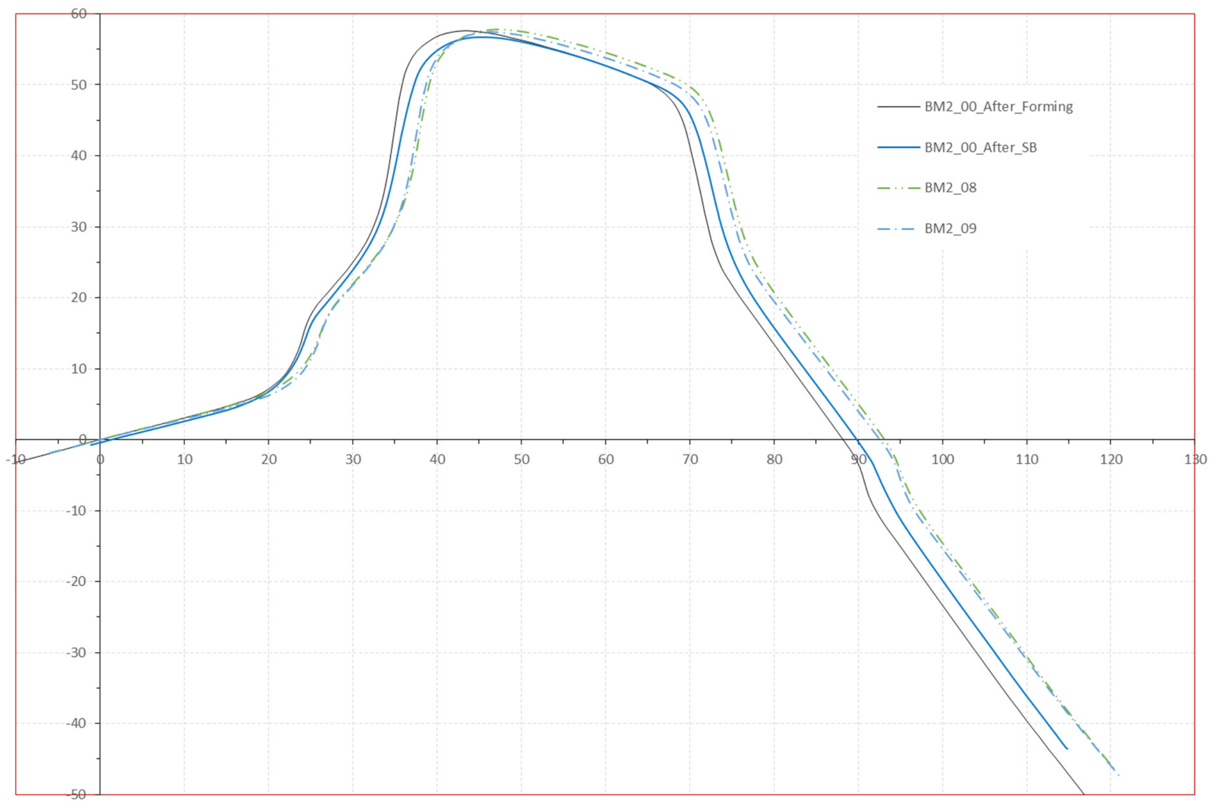
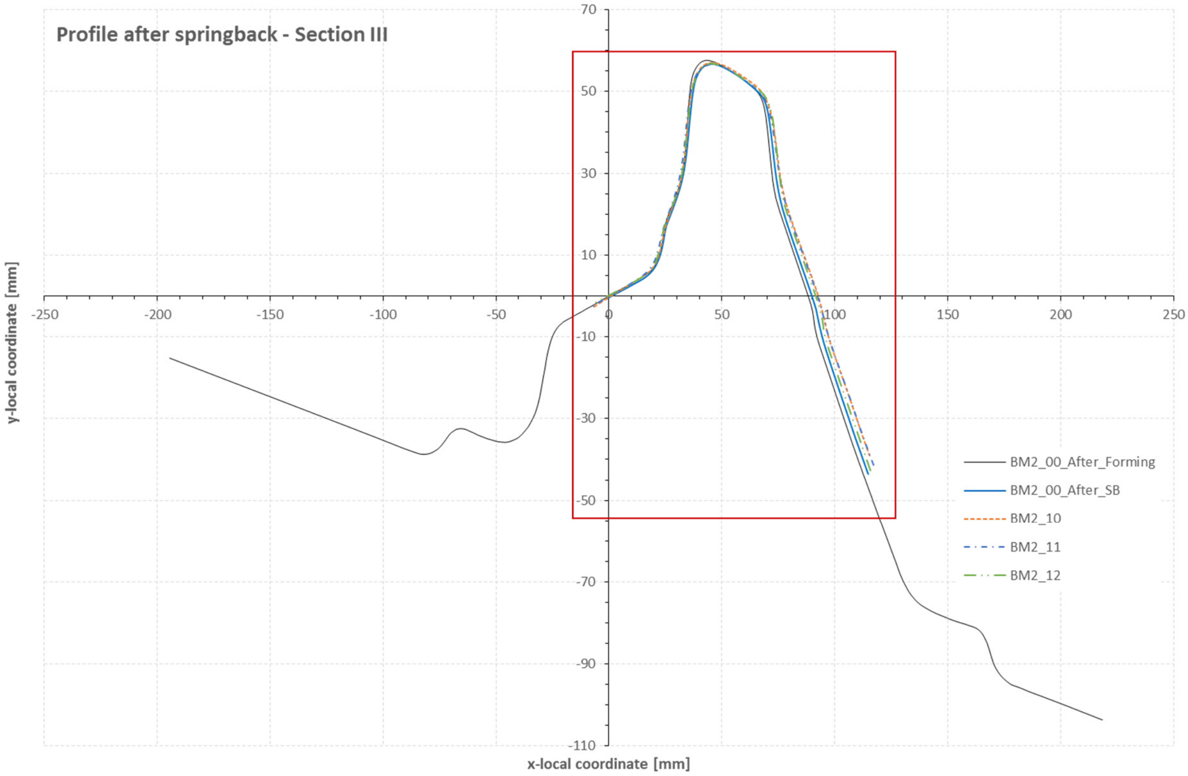


Figure 6.13. Profile after springback for Section III: BM2_08, BM2_09.



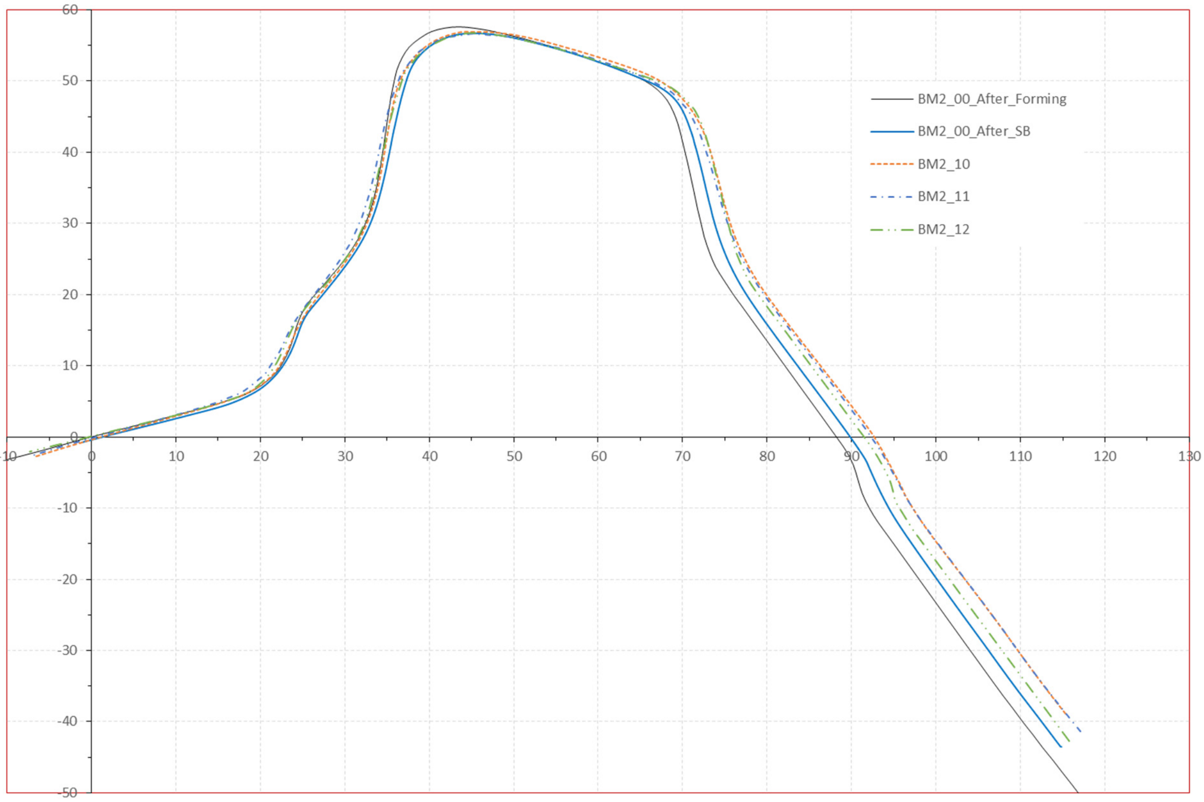


Figure 6.14. Profile after springback for Section III: BM2_10, BM2_11, BM2_12.

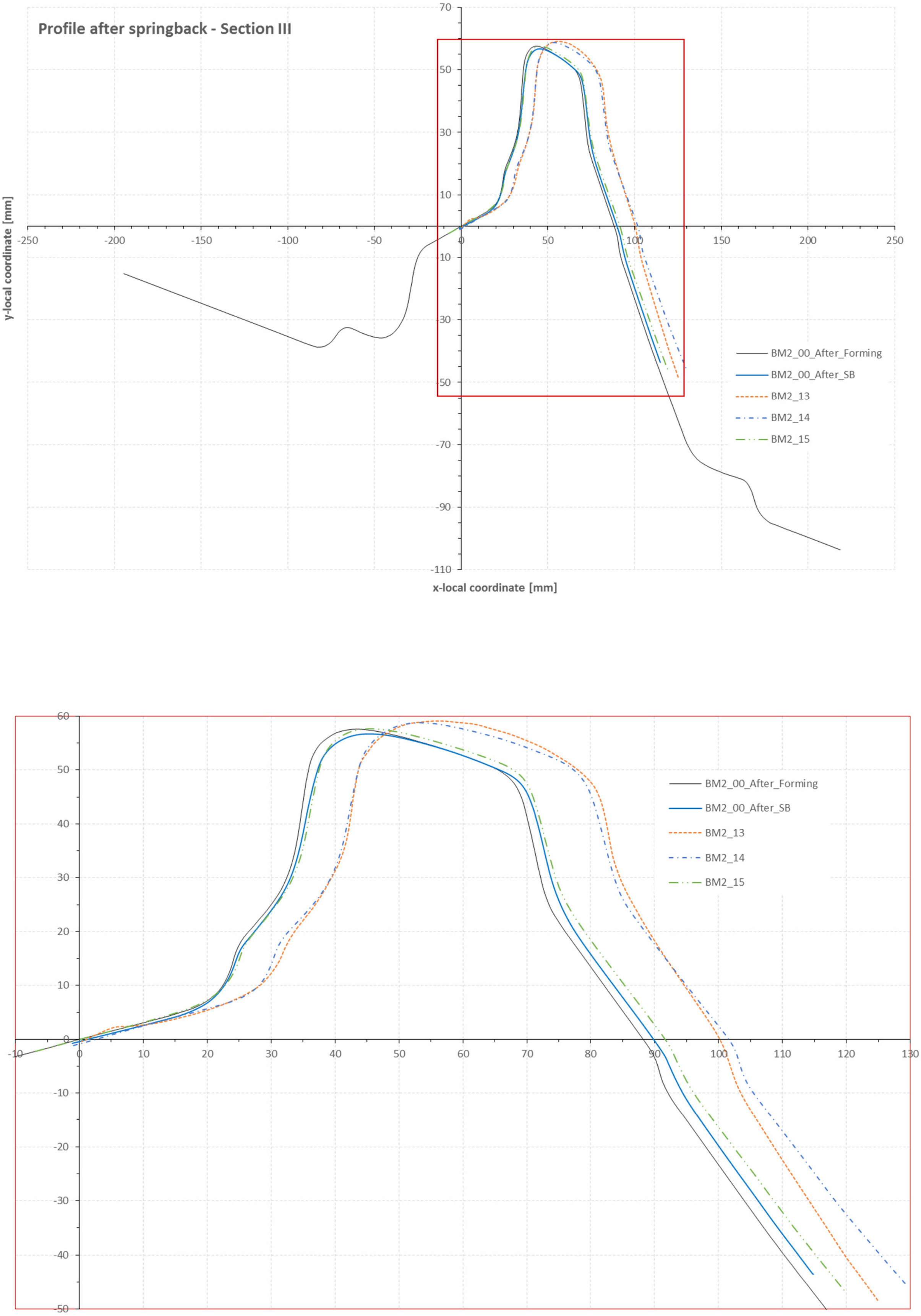


Figure 6.15. Profile after springback for Section III: BM2_13, BM2_14, BM2_15.

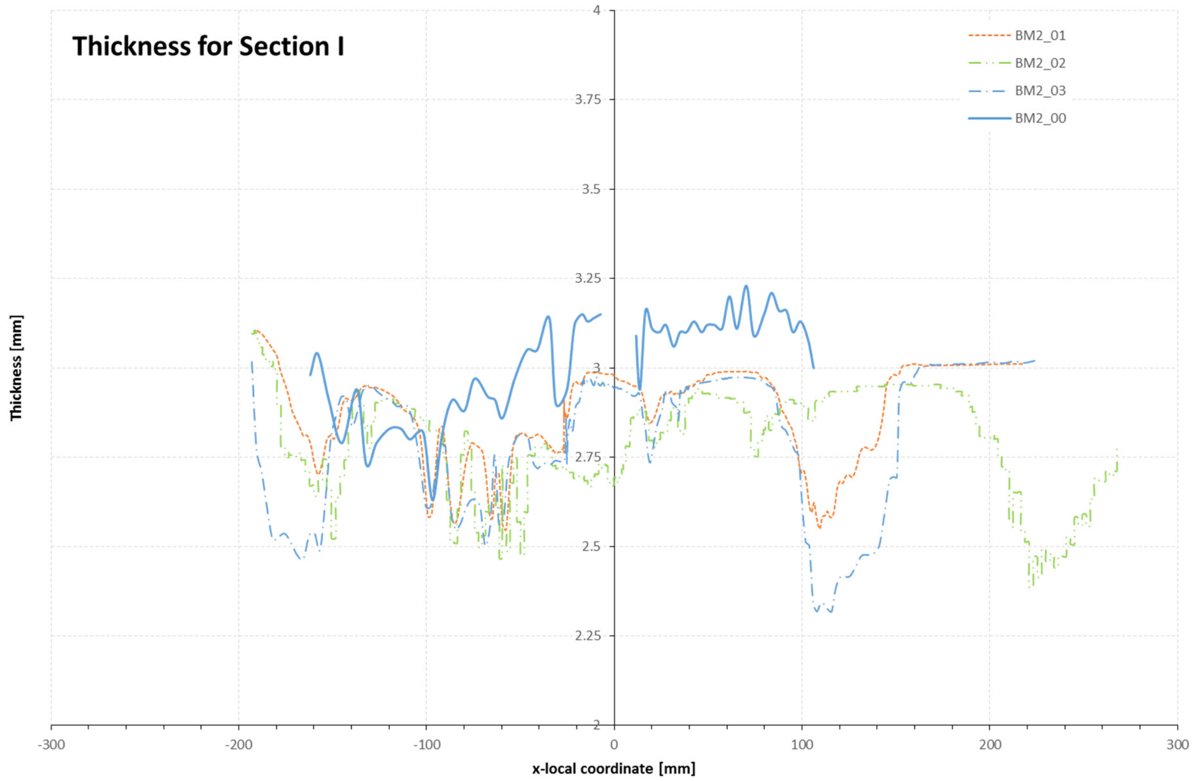


Figure 6.16. Thickness for Section I: BM2_01, BM2_02, BM2_03.

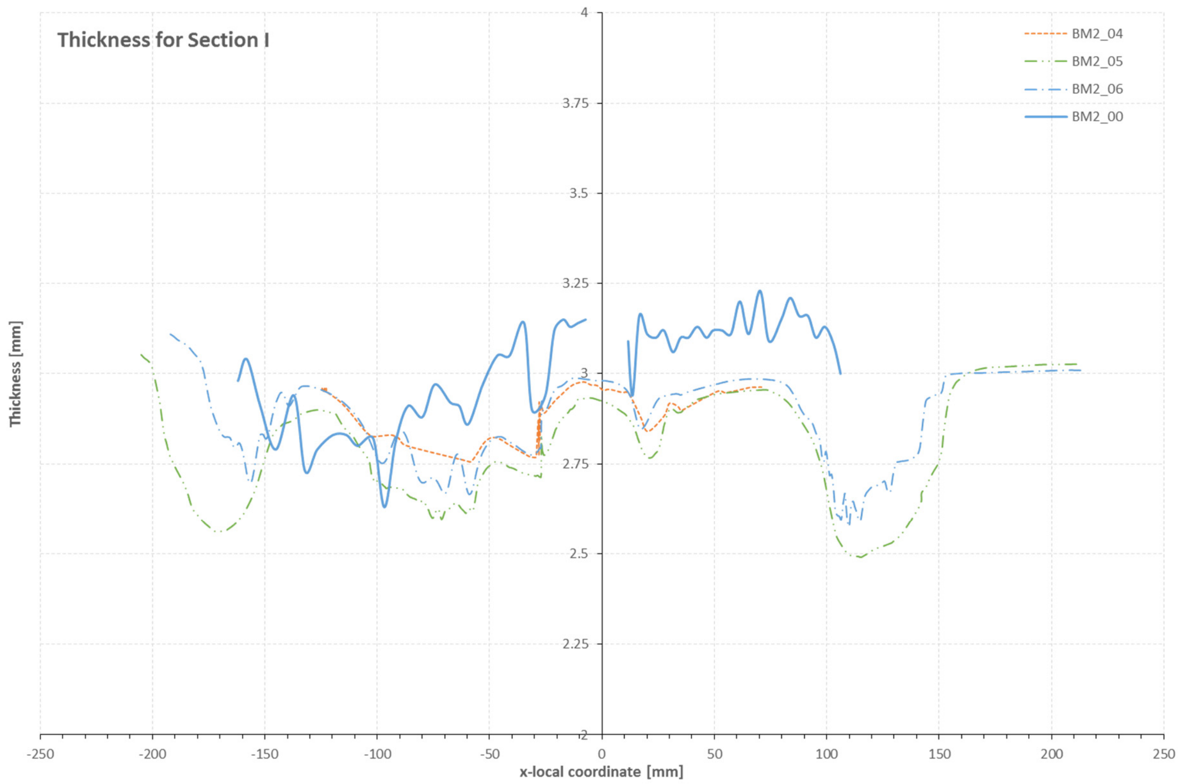


Figure 6.17. Thickness for Section I: BM2_04, BM2_05, BM2_06.

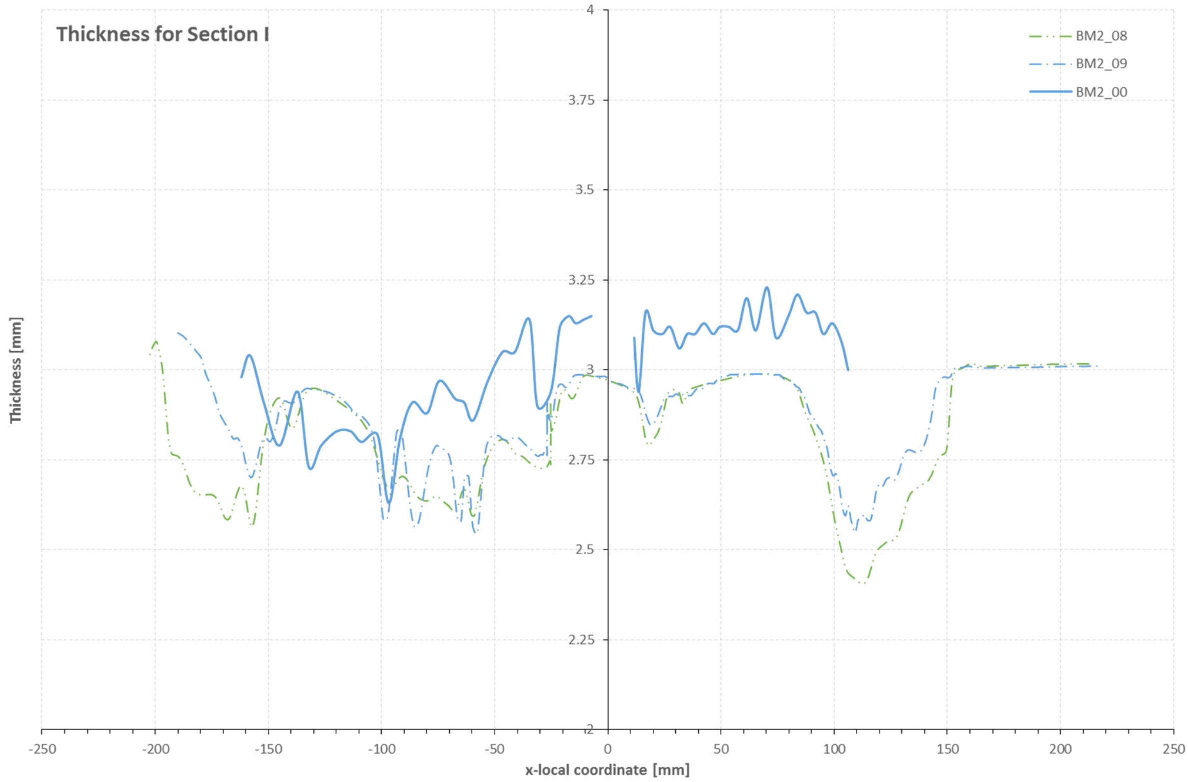


Figure 6.18. Thickness for Section I: BM2_08, BM2_09.

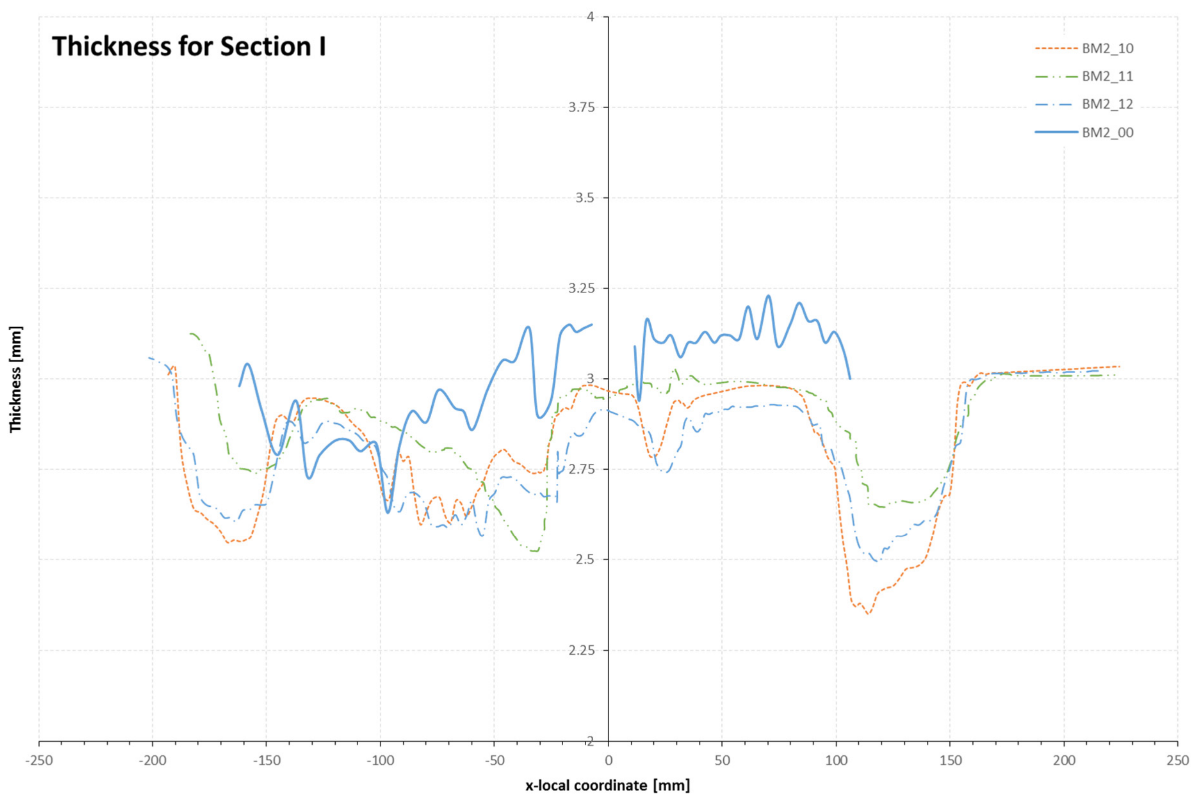


Figure 6.19. Thickness for Section I: BM2_10, BM2_11, BM2_12.

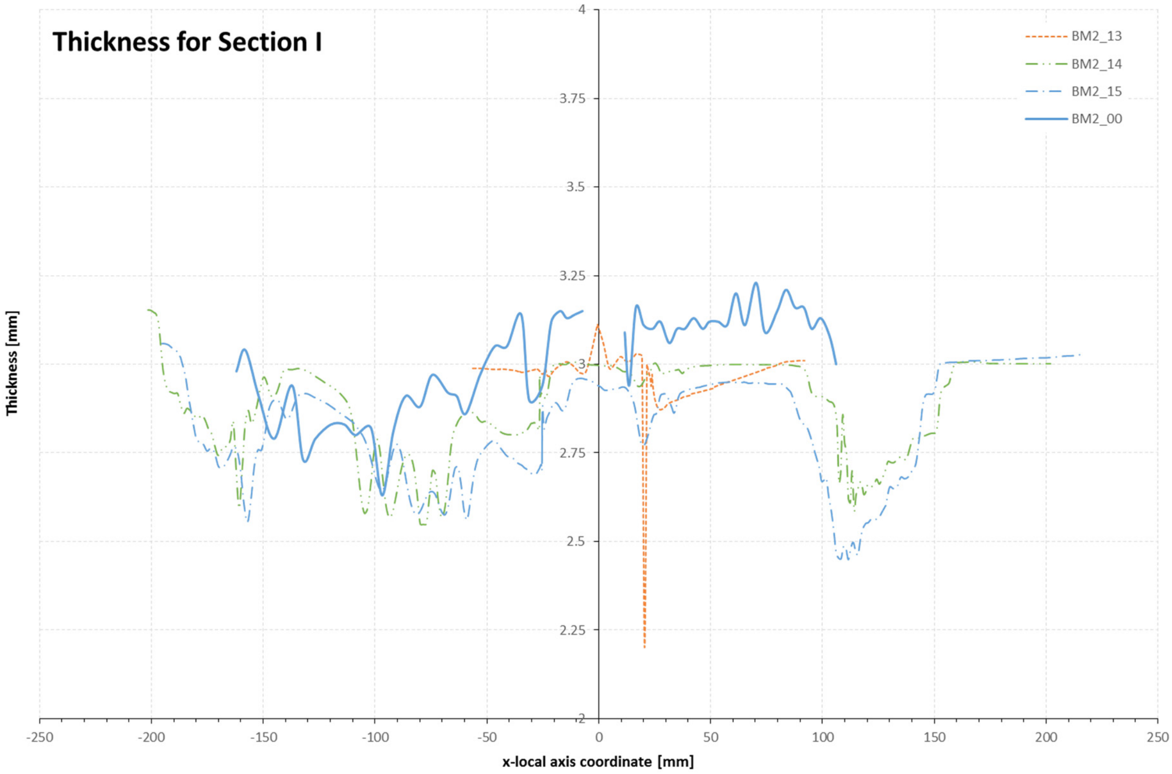


Figure 6.20. Thickness for Section I: BM2_13, BM2_14, BM2_15.

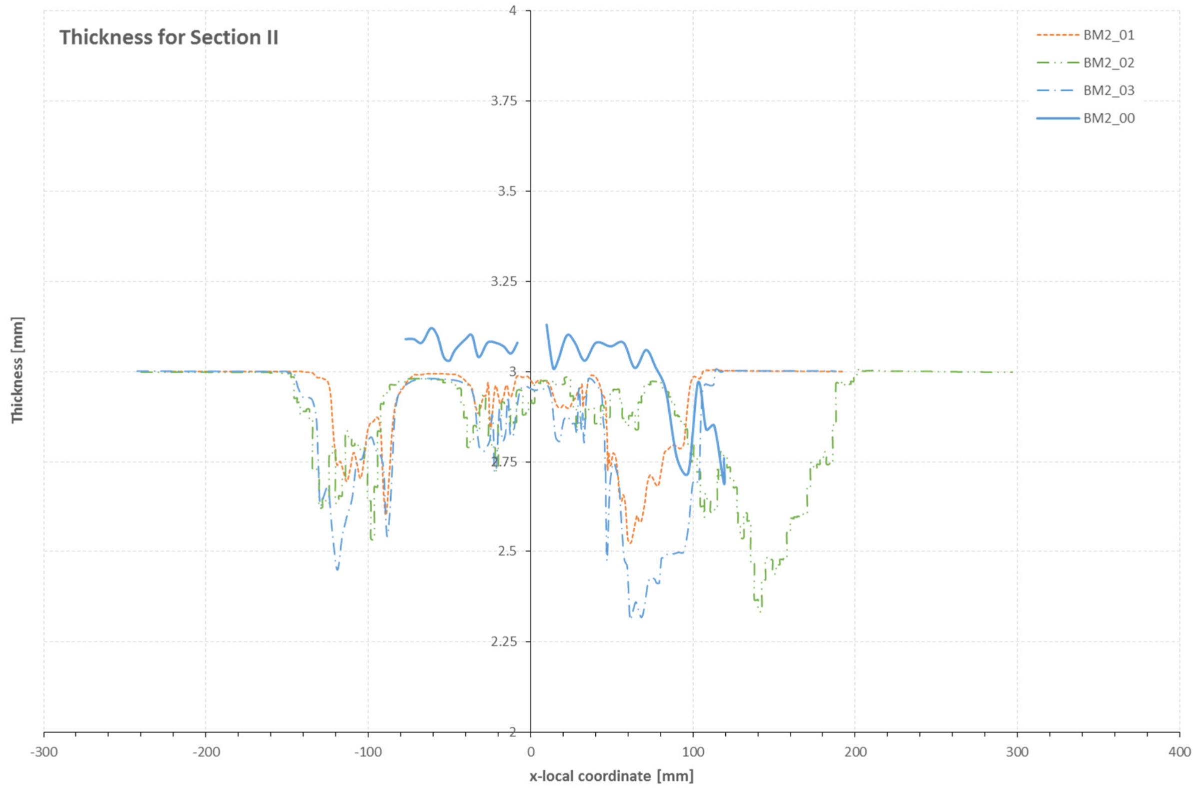


Figure 6.21. Thickness for Section II: BM2_01, BM2_02, BM2_03.

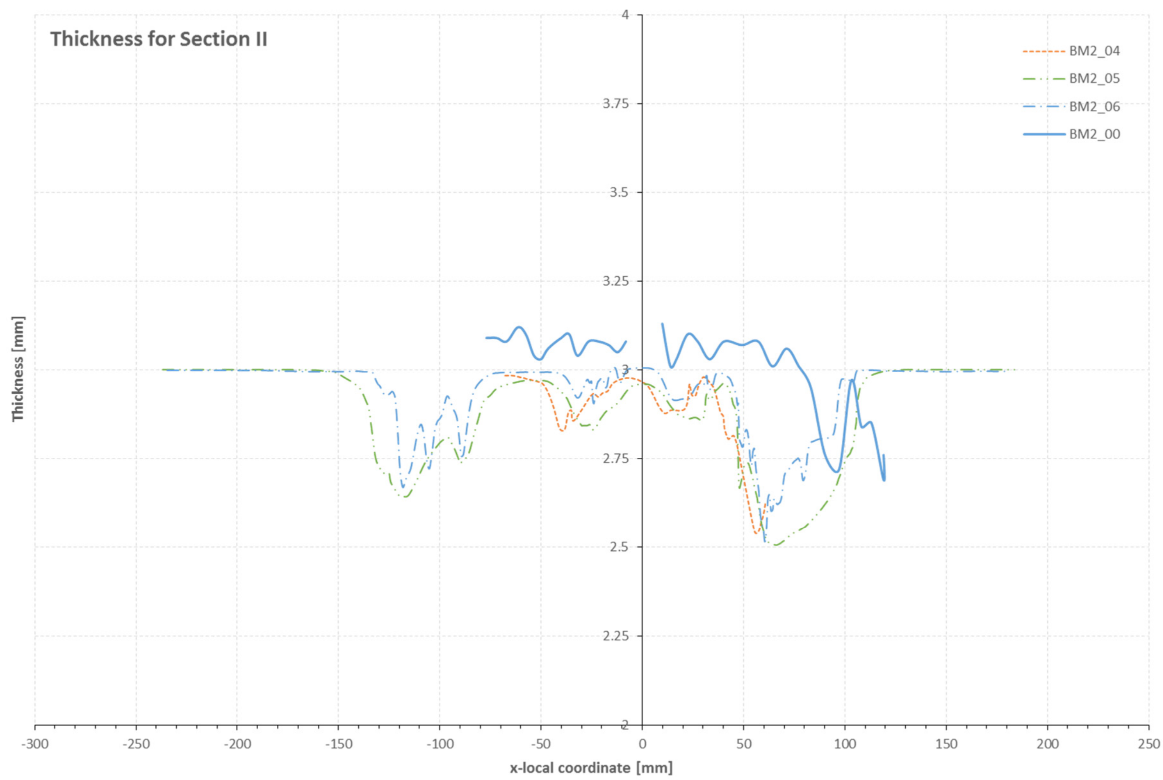


Figure 6.22. Thickness for Section II: BM2_04, BM2_05, BM2_06.

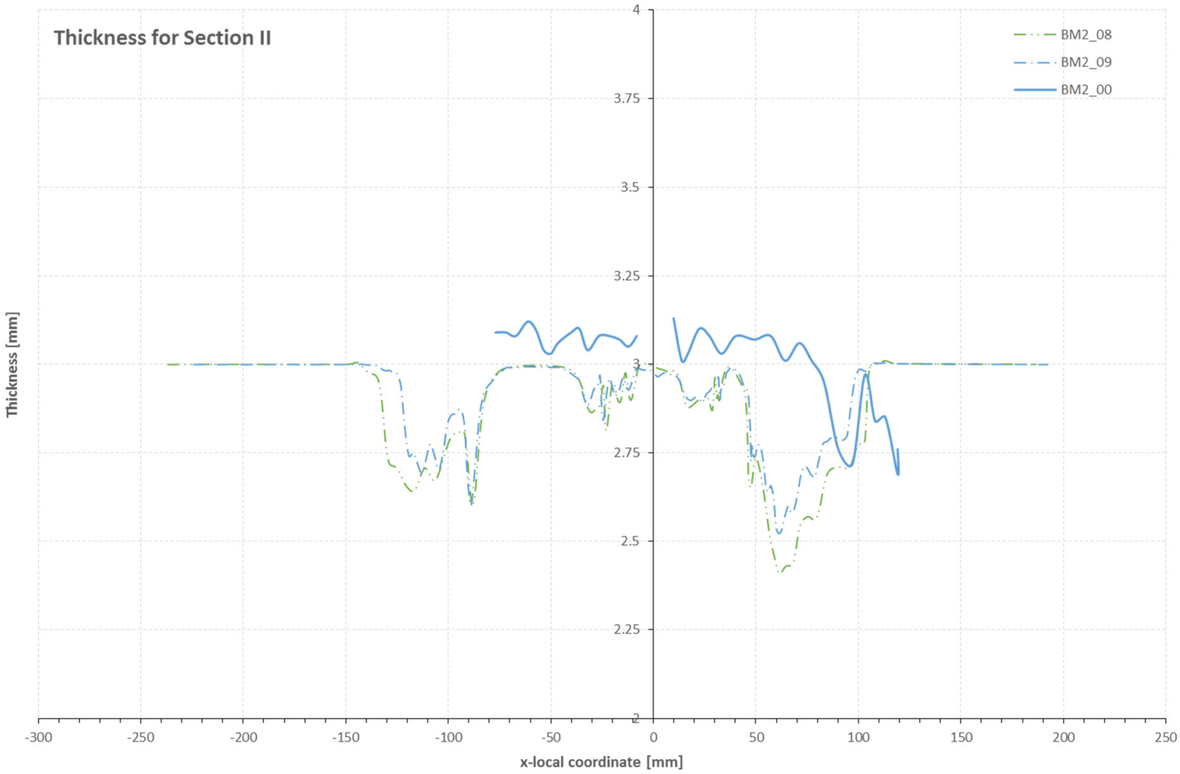


Figure 6.23. Thickness for Section II: BM2_08, BM2_09.

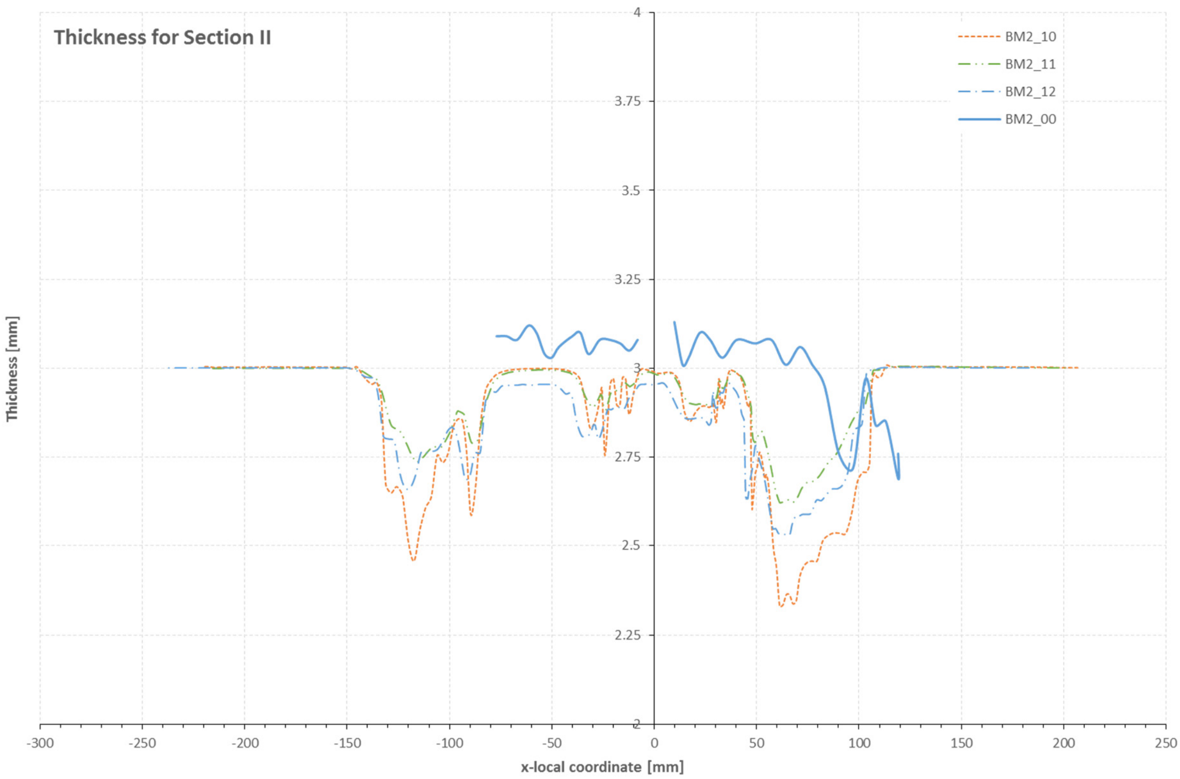


Figure 6.24. Thickness for Section II: BM2_10, BM2_11, BM2_12.

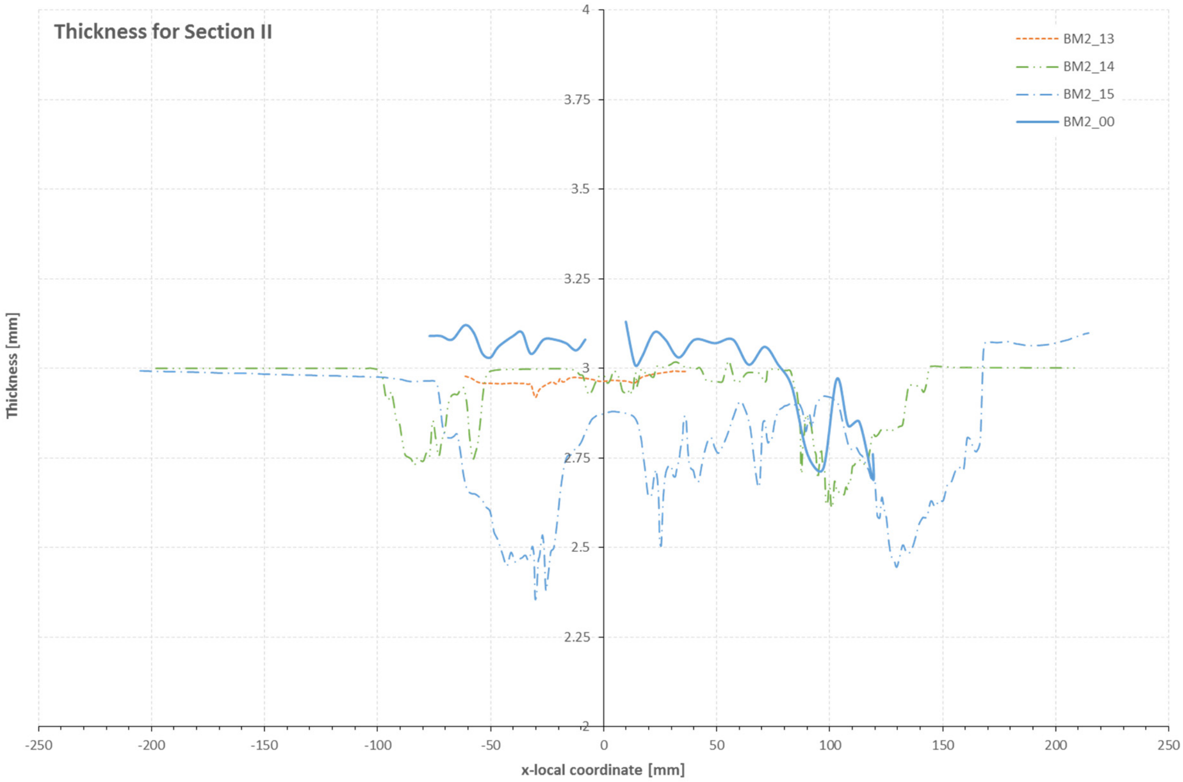


Figure 6.25. Thickness for Section II: BM2_13, BM2_14, BM2_15.

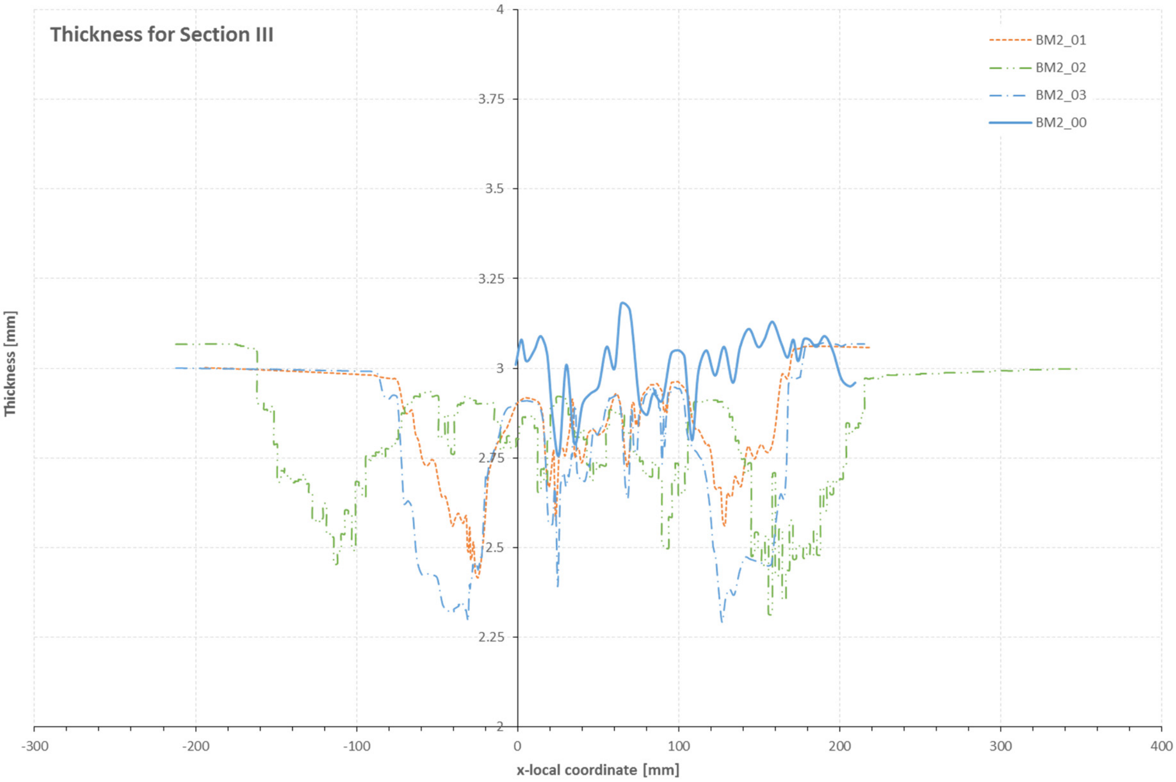


Figure 6.26. Thickness for Section III: BM2_01, BM2_02, BM2_03.

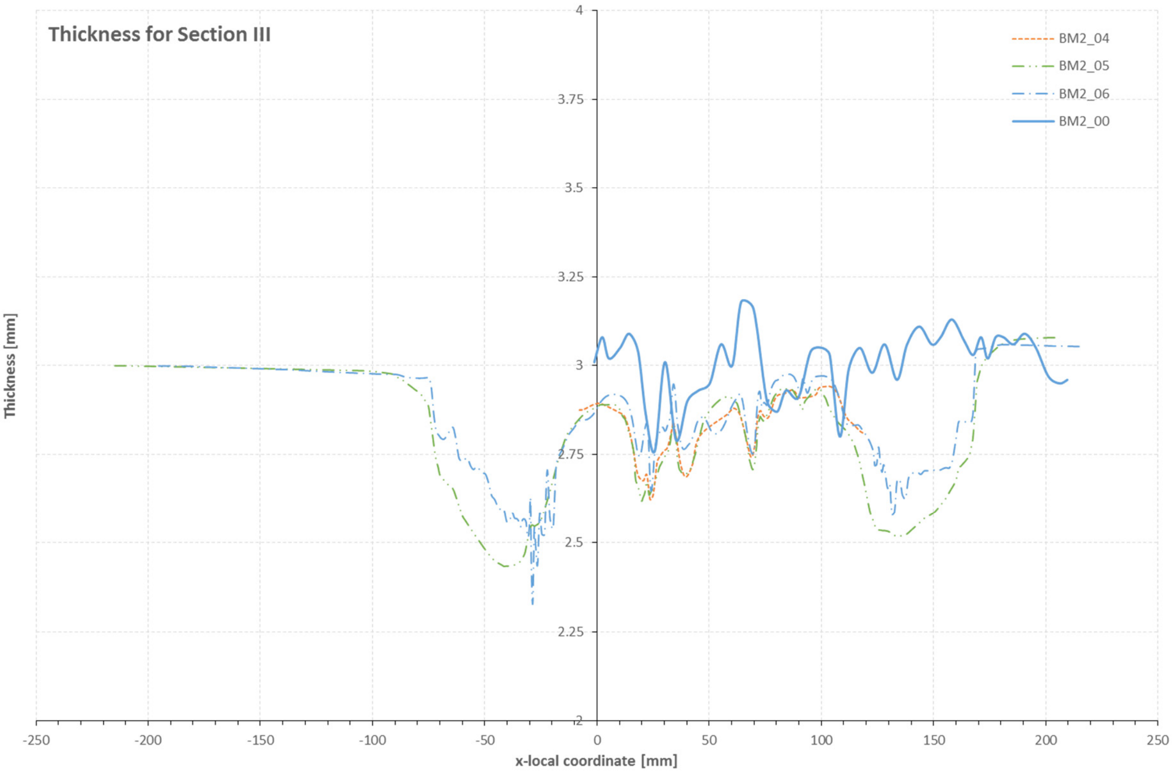


Figure 6.27. Thickness for Section III: BM2_04, BM2_05, BM2_06.

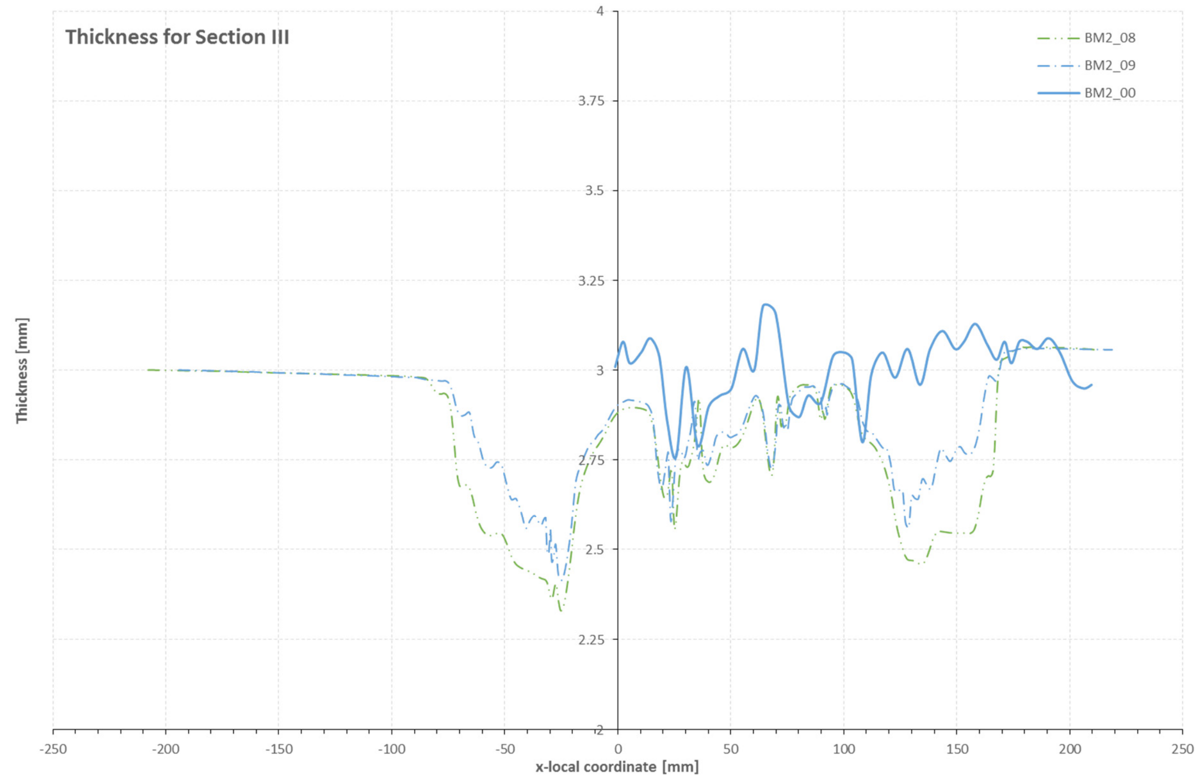


Figure 6.28. Thickness for Section III: BM2_08, BM2_09.

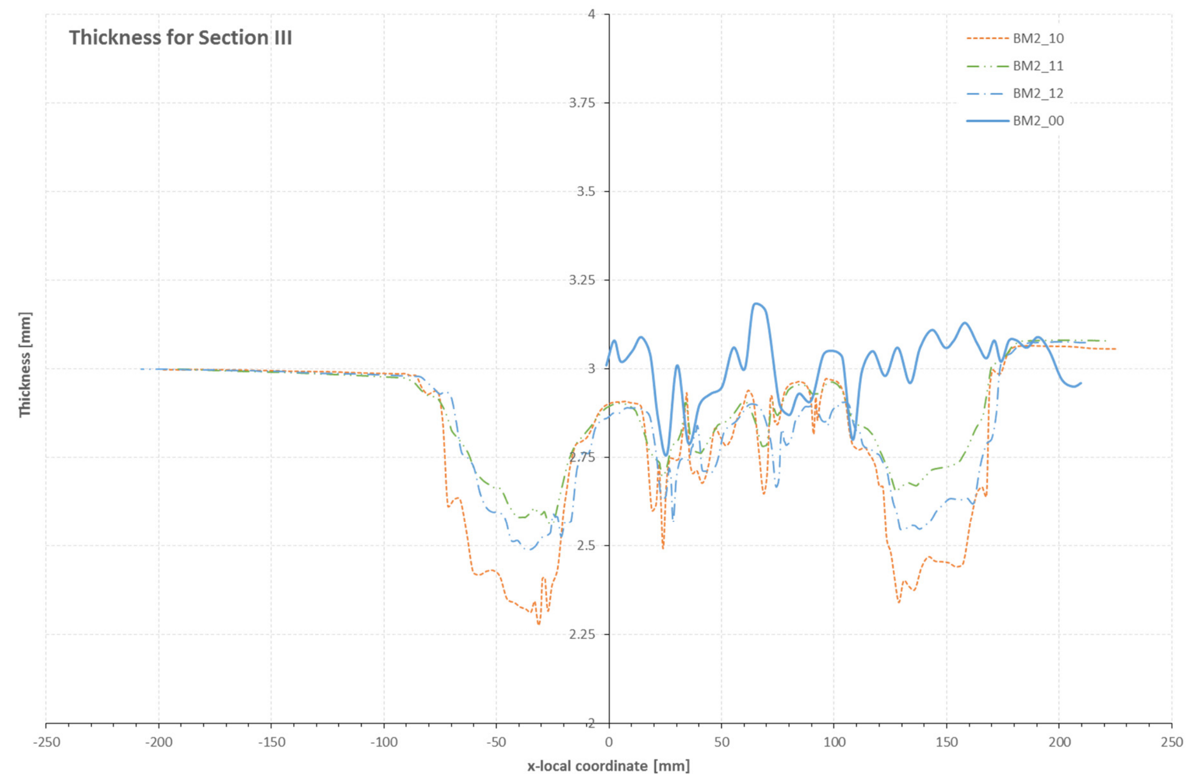


Figure 6.29. Thickness for Section III: BM2_10, BM2_11, BM2_12.

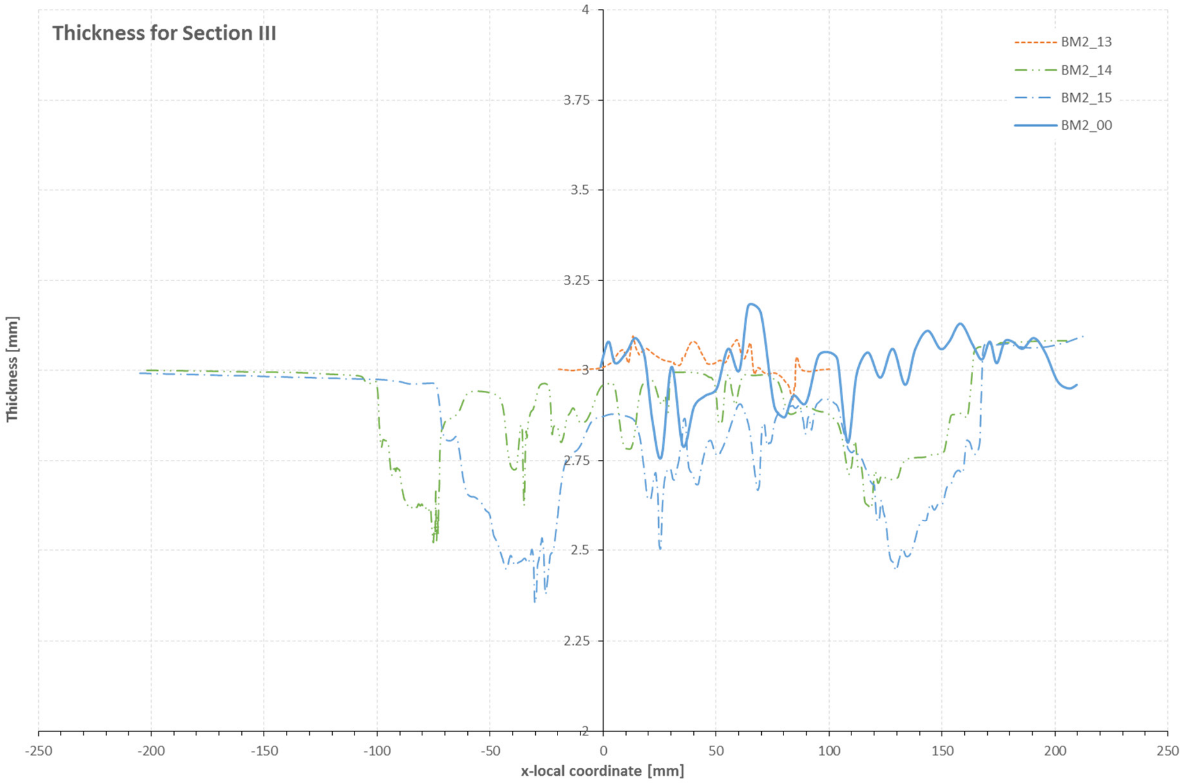


Figure 6.30. Thickness for Section III: BM2_13, BM2_14, BM2_15.

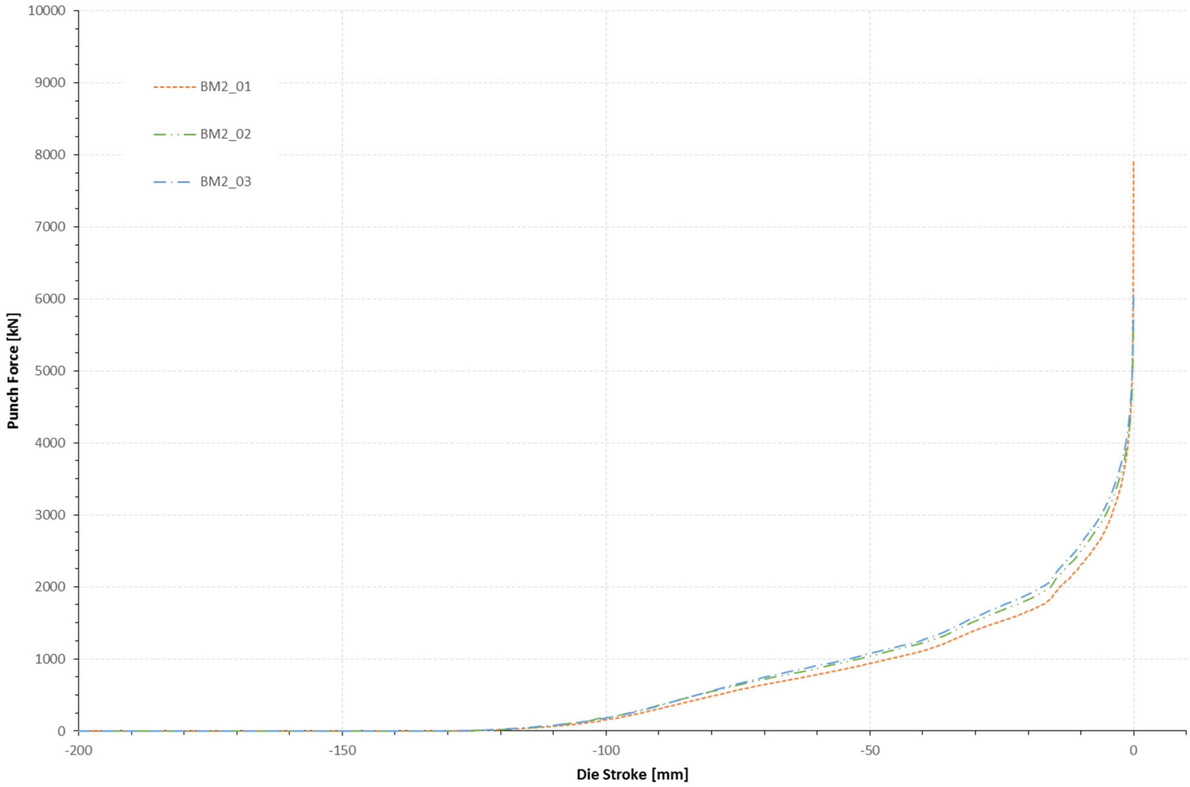


Figure 6.31. Punch Force: BM2_01, BM2_02, BM2_03.

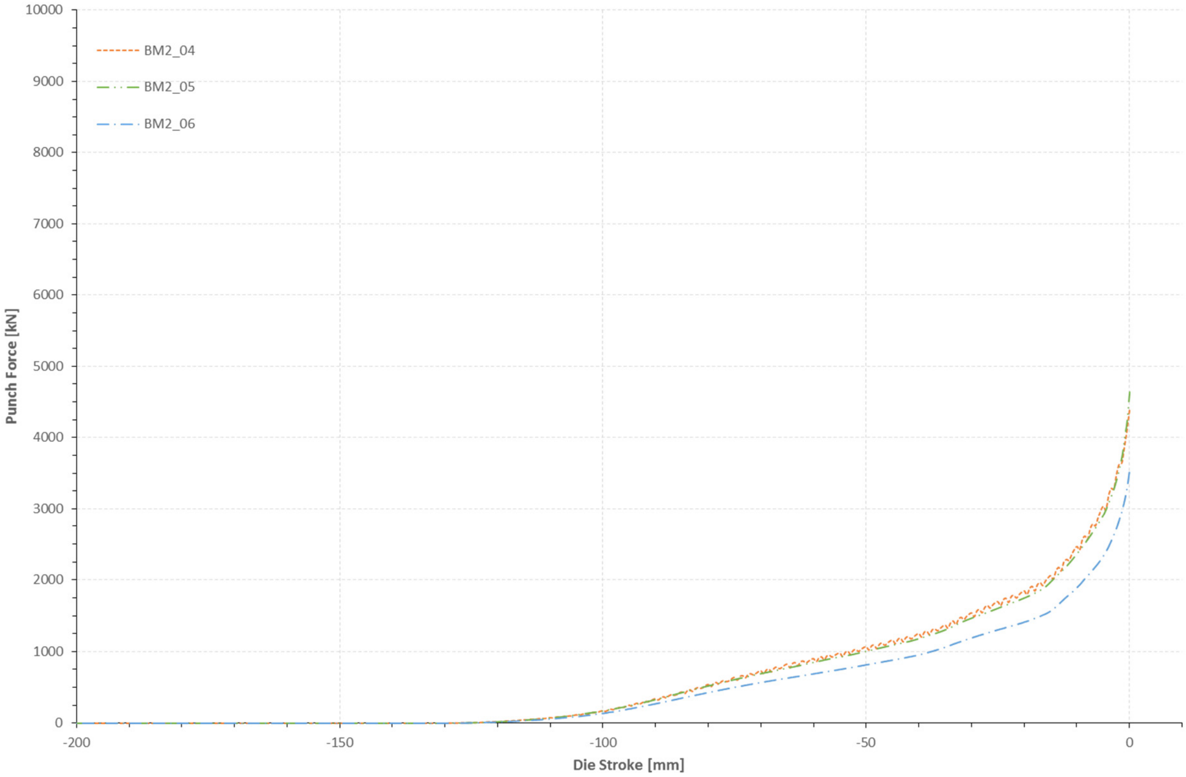


Figure 6.32. Punch Force: BM2_04, BM2_05, BM2_06.

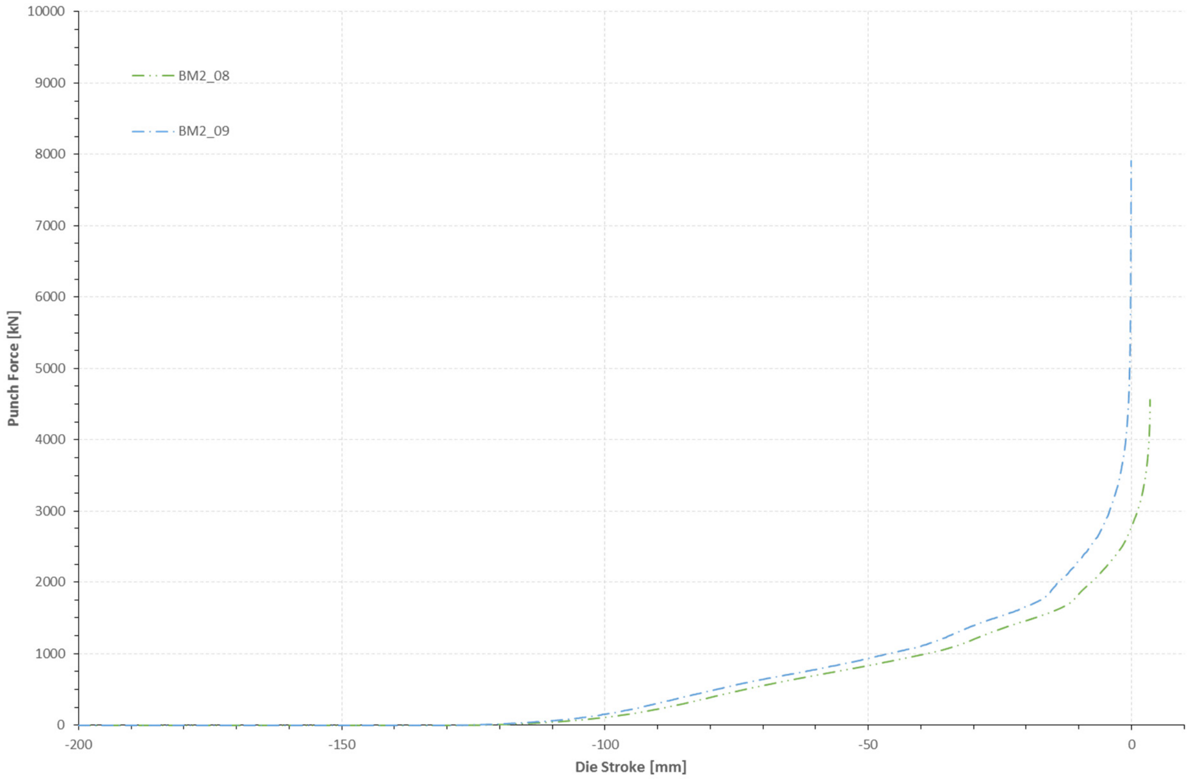


Figure 6.33. Punch Force: BM2_08, BM2_09.

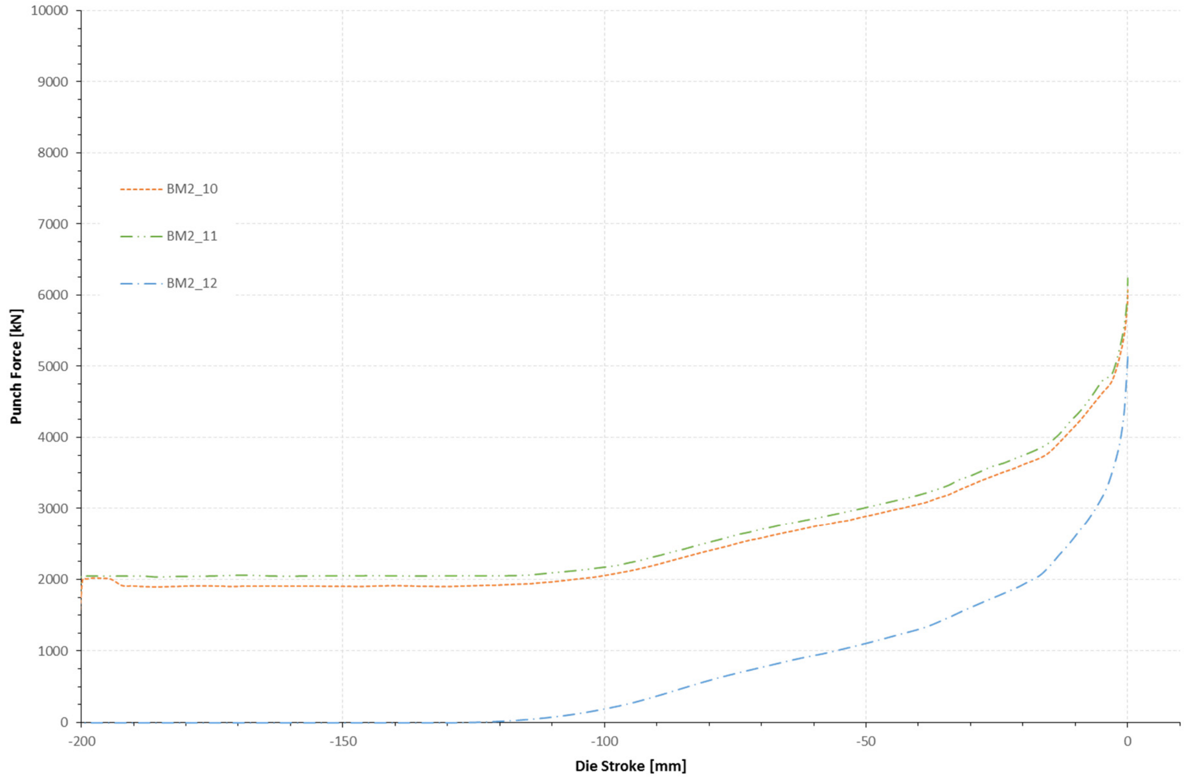


Figure 6.34. Punch Force: BM2_10, BM2_11, BM2_12.

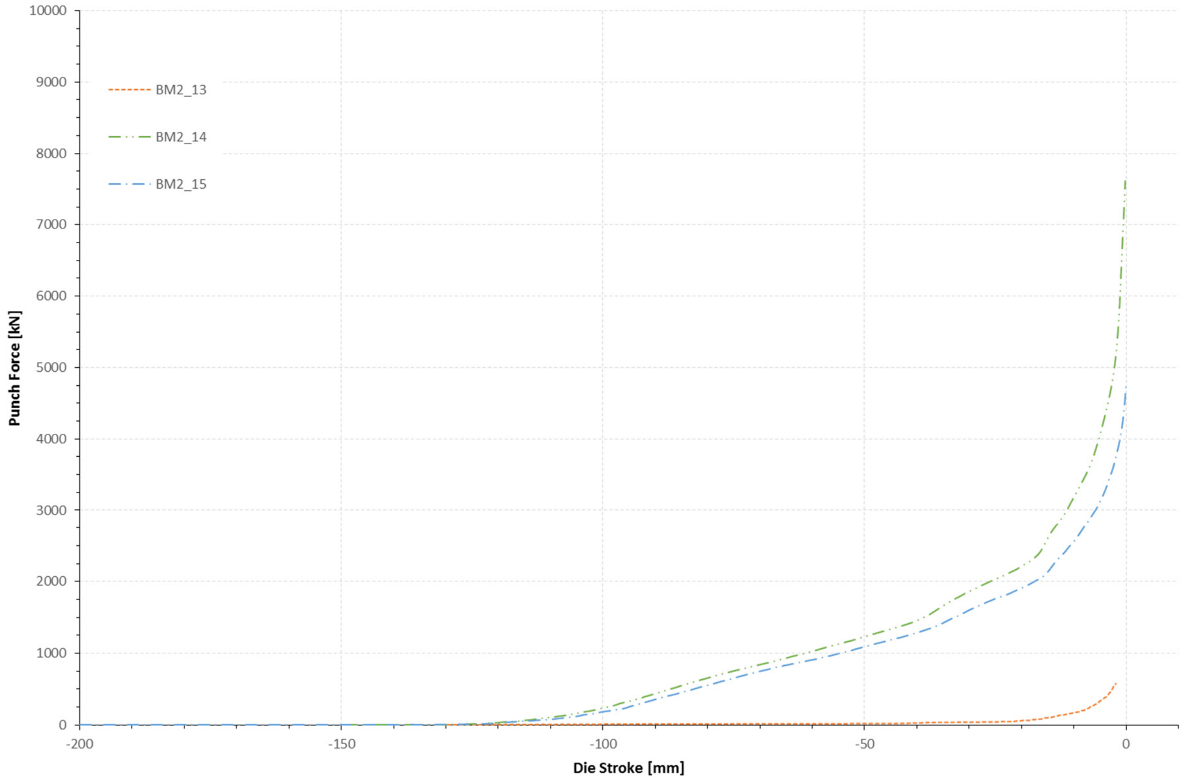


Figure 6.35. Punch Force: BM2_13, BM2_14, BM2_15.

Benchmark 2 – Springback of a Jaguar Land Rover Aluminium Panel

Martin Allen[1], Marta Oliveira[2], Sumit Hazra[3], Oluwamayokun Adetoro[4], Abhishek Das[3] and Rui Cardoso[5]

[1] Jaguar Land Rover, Coventry CV3 4LF, UK
[2] University of Coimbra, Coimbra 3030-790, Portugal
[3] University of Warwick, Coventry CV4 7AL, UK
[4] University of the West of England, Bristol BS16 1QY, UK
[5] Brunel University London, Uxbridge, UB8 3PH, UK

CORRIGENDUM TO: M Allen *et al* 2016 *J. Phys.: Conf. Ser.* **734** 022002

The editor would like to add additional material that was omitted from the original paper. The introduction of the new material results in all of the figures appearing after the new material being renumbered, the figures are not being overwritten. The new material and all renumbered figures are as follows:

BM2-16

1. Benchmark Participant	
Name	**Bart Carleer, Dave Ling, Igor Burchitz**
Affiliation	AutoForm Engineering B.V.
Address	Industrieweg 2, 2921 LB Krimpen aan den Ijssel, The Netherlands
Email	igor.burchitz@autoform.nl
Phone number	0031 180 668 255
Fax number	

2. Simulation Software	
Name of the FEM code	AutoForm^plus R6
General aspect of the code	Static Implicit
Basic formulations	
Element/Mesh technology	
Number of elements	Initial number of elements - 31555 Final number of elements due to adaptive mesh refinement - 213120
Type of elements	Triangular elastic plastic shell, 11 integration points through thickness
Contact property model	Penalty method
Friction formulation	Coulomb friction

3. Simulation Hardware	
CPU Type	Intel Core i7-5960X
CPU clock speed	3.0 GHz
Number of cores per CPU	8 cores used to run a simulation
Main memory	64 GB
Operating system	Windows 7 Pro
Total CPU time	Elapsed Time - 23 minutes 13 seconds

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	BBC Model (Banabic 2005). R-values are based on raw tensile test data provided by the organizing committee upon request
Hardening Rule (e.g. Isotropic, kinematic)	Isotropic hardening
Stress-Strain Relation (e.g. Swift, Voce)	Combined Swift - Hockett-Sherby formulation based on raw tensile test data provided by the organizing committee upon request

5. Remarks

Although boundary conditions were requested for analysis of springback, real measurement fixture was used in this submission. The main goal was to have a better comparison to reality. Simulated fixture included two pilots, supporting clamps and one double sided clamp. These elements were used to represent pin support, slot support and the simple clamp used in the real fixture.

BM2-17

1. Benchmark Participant	
Name	**Bart Carleer, Dave Ling, Igor Burchitz**
Affiliation	AutoForm Engineering B.V.
Address	Industrieweg 2, 2921 LB Krimpen aan den Ijssel, The Netherlands
Email	igor.burchitz@autoform.nl
Phone number	0031 180 668 255
Fax number	

2. Simulation Software	
Name of the FEM code	AutoForm^plus R6
General aspect of the code	Static Implicit
Basic formulations	
Element/Mesh technology	
Number of elements	Initial number of elements - 31555 Final number of elements due to adaptive mesh refinement - 211850
Type of elements	Triangular elastic plastic shell, 11 integration points through thickness
Contact property model	Penalty method
Friction formulation	Coulomb friction

3. Simulation Hardware	
CPU Type	Intel Core i7-5960X
CPU clock speed	3.0 GHz
Number of cores per CPU	8 cores used to run a simulation
Main memory	64 GB
Operating system	Windows 7 Pro
Total CPU time	Elapsed Time - 24 minutes 44 seconds

4. Describe the material model used for each material	
Material	**AA6451-T4**
Yield Function/ Plastic Potential	BBC Model (Banabic 2005). R-values are based on raw tensile test data provided by the organizing committee upon request
Hardening Rule (e.g. Isotropic, kinematic)	Kinematic hardening considering early re-plastification, transient softening and work hardening stagnation formulated under plane stress condition
Stress-Strain Relation (e.g. Swift, Voce)	Combined Swift - Hockett-Sherby formulation based on raw tensile test data provided by the organizing committee upon request

5. Remarks
In this submission, springback analysis was performed with boundary conditions requested in the benchmark briefing.

BM2-18

1. Benchmark Participant	
Name	**Bart Carleer, Dave Ling, Igor Burchitz**
Affiliation	AutoForm Engineering B.V.
Address	Industrieweg 2, 2921 LB Krimpen aan den Ijssel, The Netherlands
Email	igor.burchitz@autoform.nl
Phone number	0031 180 668 255
Fax number	

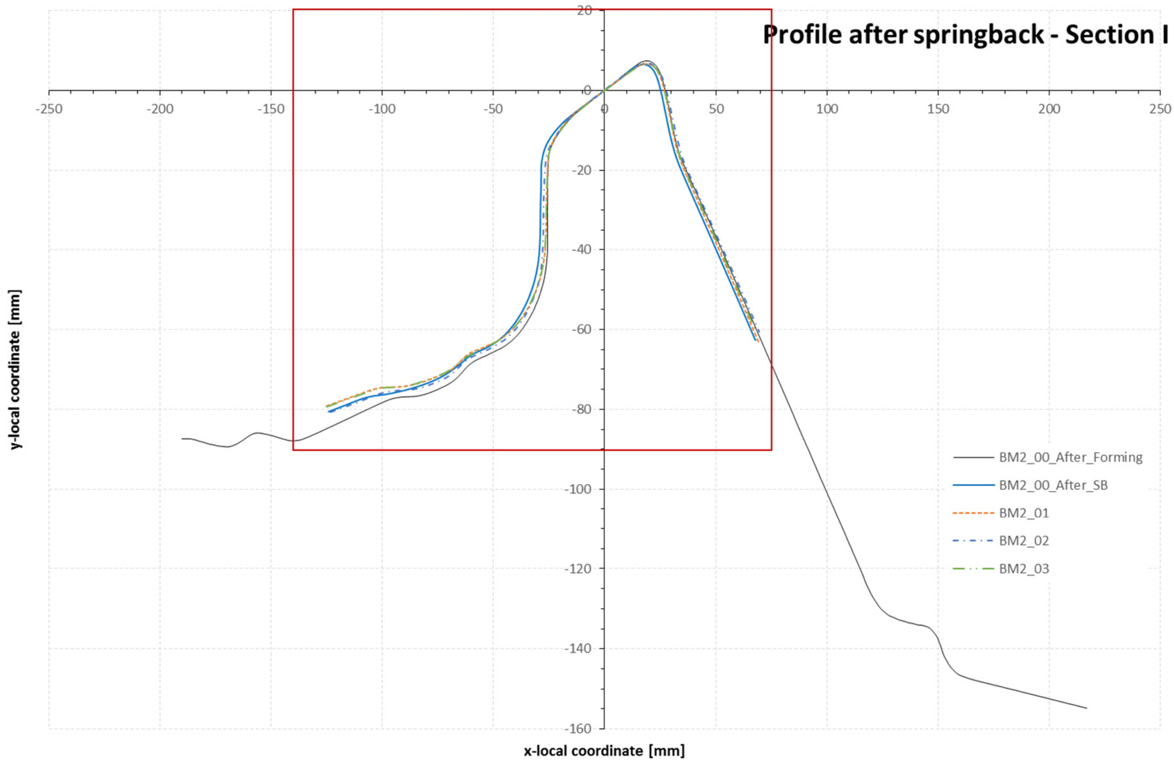
2. Simulation Software	
Name of the FEM code	AutoForm^plus R6
General aspect of the code	Static Implicit
Basic formulations	
Element/Mesh technology	
Number of elements	Initial number of elements - 31555 Final number of elements due to adaptive mesh refinement - 211460
Type of elements	Triangular elastic plastic shell, 11 integration points through thickness
Contact property model	Penalty method
Friction formulation	Pressure dependent coefficient of friction

3. Simulation Hardware	
CPU Type	Intel Core i7-5960X
CPU clock speed	3.0 GHz
Number of cores per CPU	8 cores used to run a simulation
Main memory	64 GB
Operating system	Windows 7 Pro
Total CPU time	Elapsed Time - 25 minutes 58 seconds

4. Describe the material model used for each material	
Material	AA6451-T4
Yield Function/ Plastic Potential	BBC Model (Banabic 2005). R-values are based on raw tensile test data provided by the organizing committee upon request
Hardening Rule (e.g. Isotropic, kinematic)	Kinematic hardening considering early re-plastification, transient softening and work hardening stagnation formulated under plane stress condition
Stress-Strain Relation (e.g. Swift, Voce)	Combined Swift - Hockett-Sherby formulation based on raw tensile test data provided by the organizing committee upon request

5. Remarks

Main goal was to investigate influence of friction on springback prediction of the part. Pressure dependent friction was described by a power law, i.e. Reference Pressure – 4MPa; Pressure Exponent – 0.85; Reference friction coefficient – 0.12.
In this submission, springback analysis was performed with boundary conditions requested in the benchmark briefing.



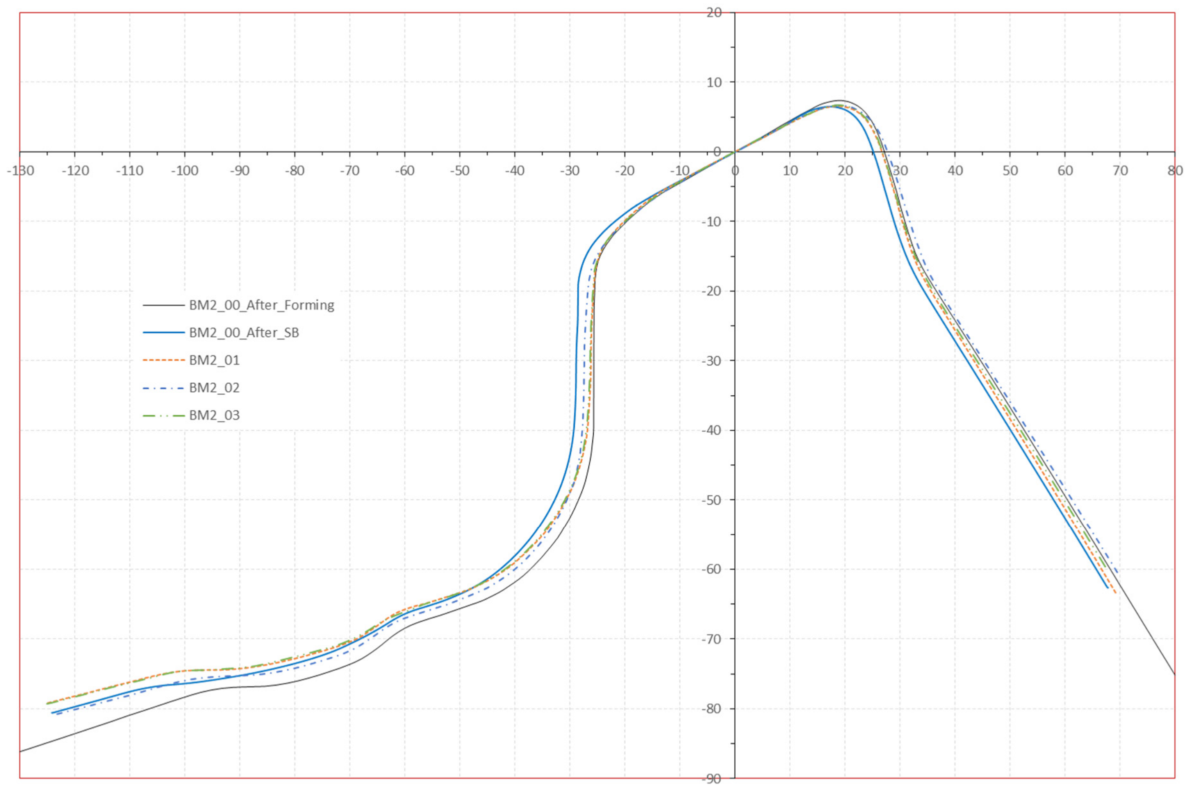
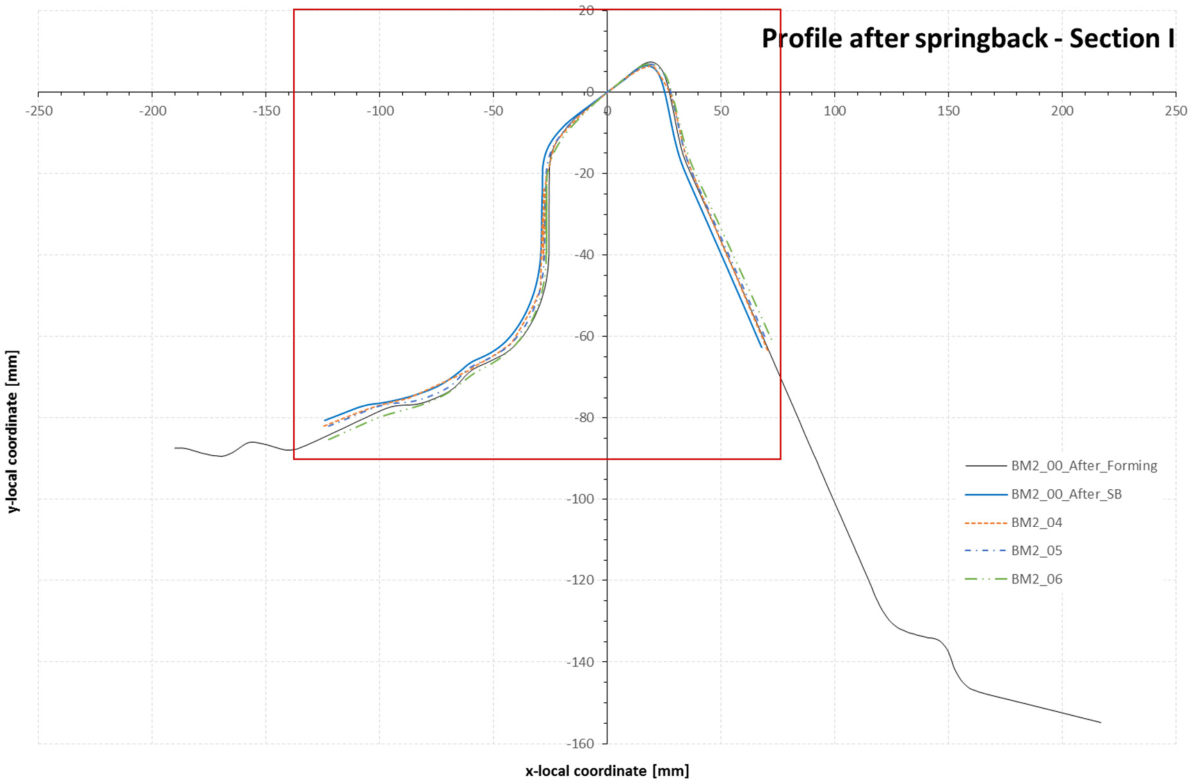


Figure 6.1. Profile after springback for Section I: BM2_01, BM2_02, BM2_03.



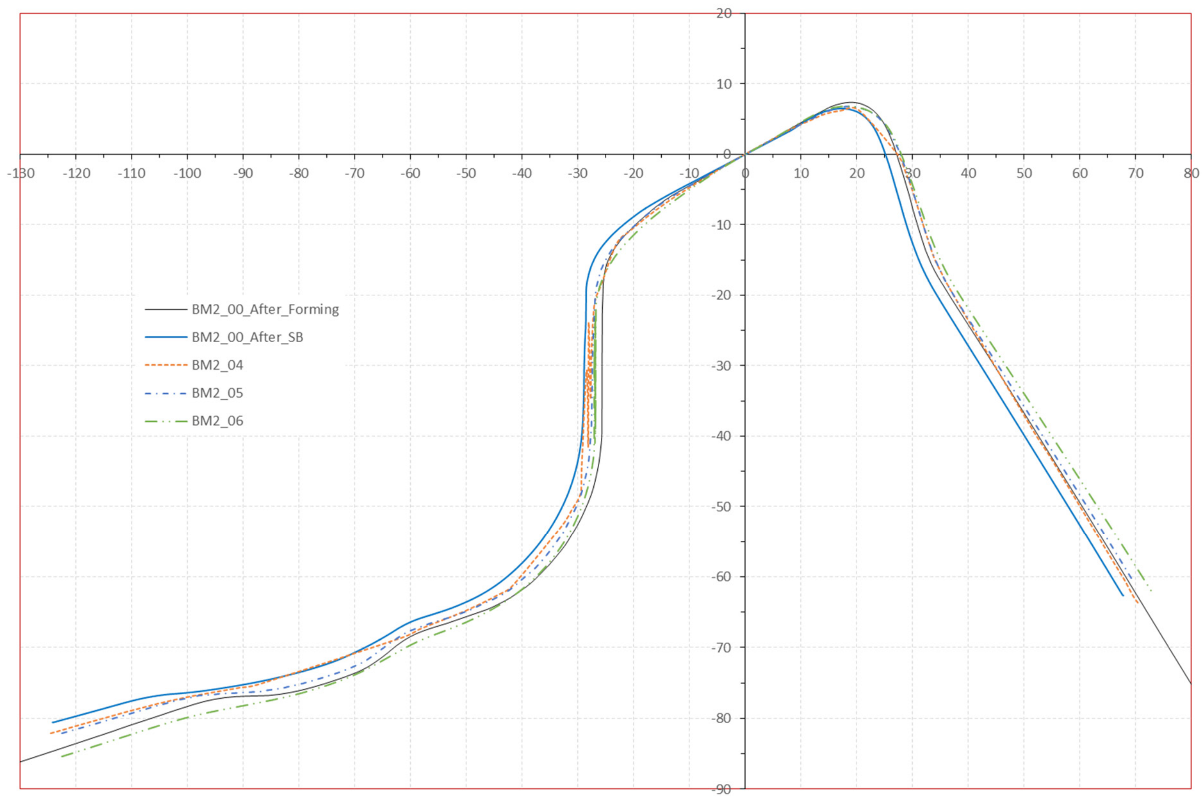
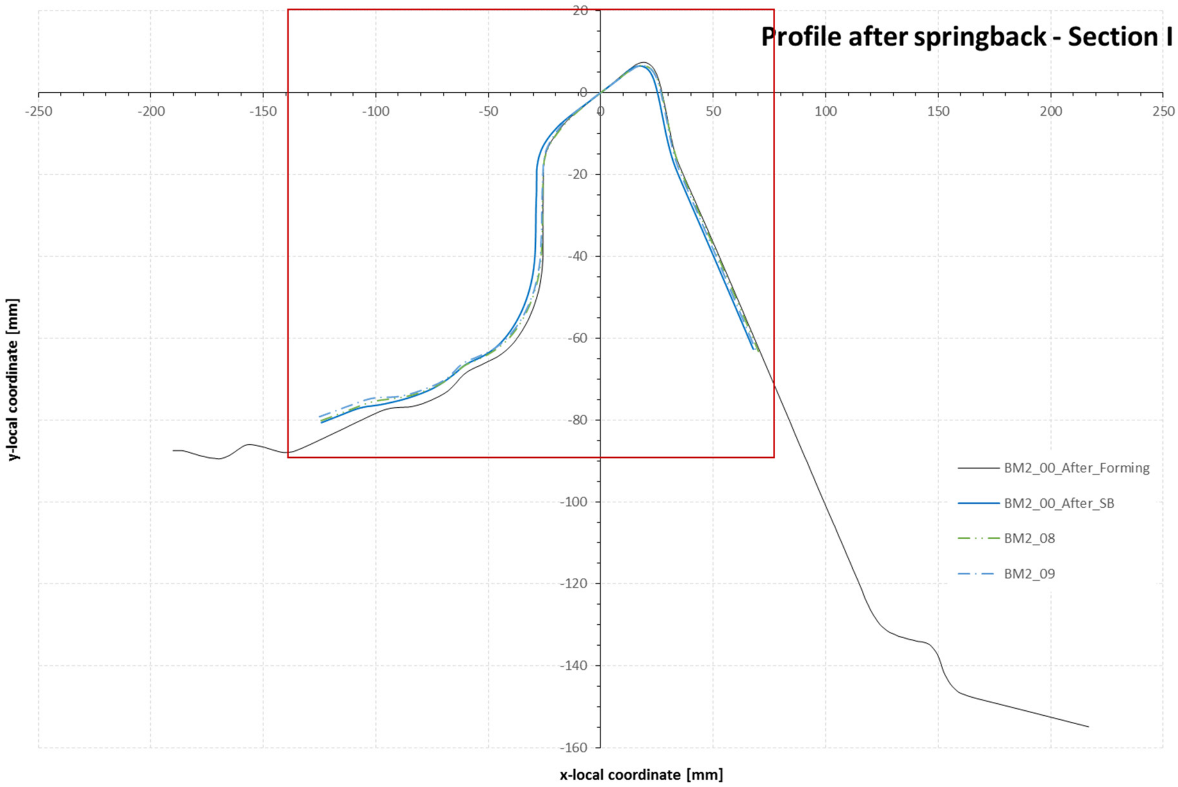


Figure 6.2. Profile after springback for Section I: BM2_04, BM2_05, BM2_06.



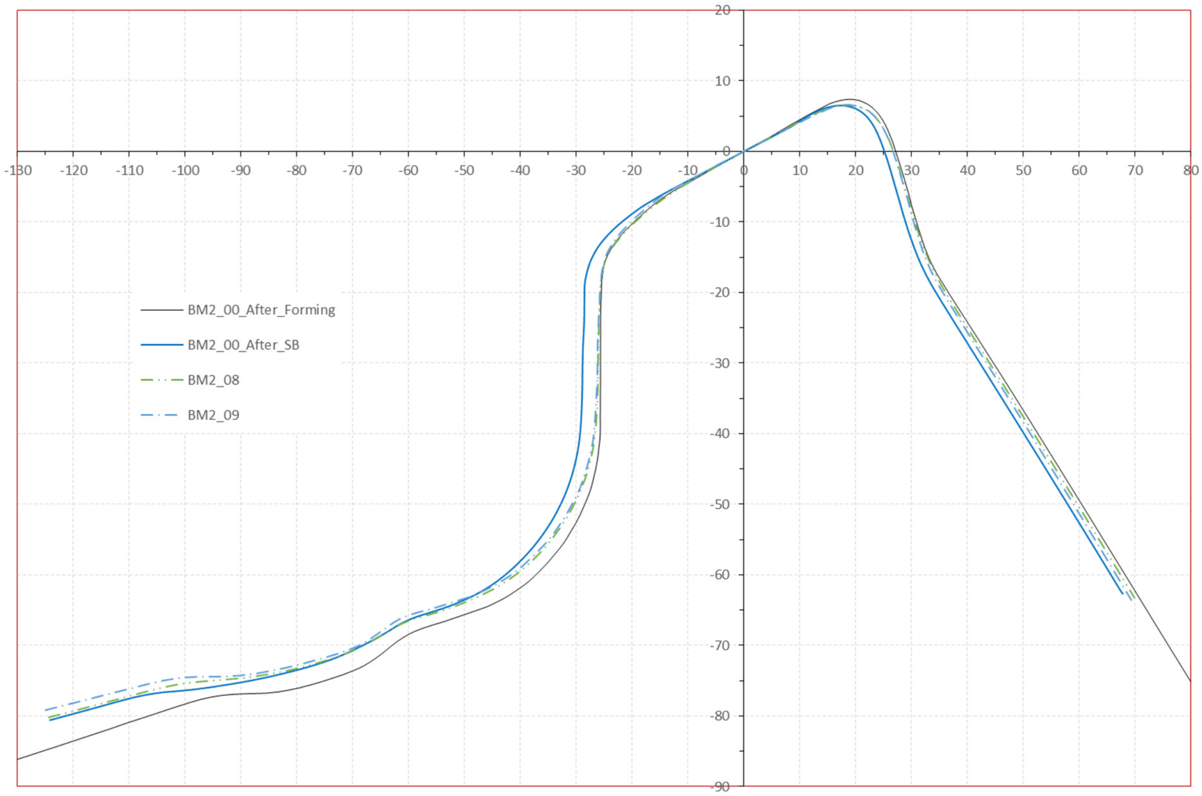


Figure 6.3. Profile after springback for Section I: BM2_08, BM2_09.

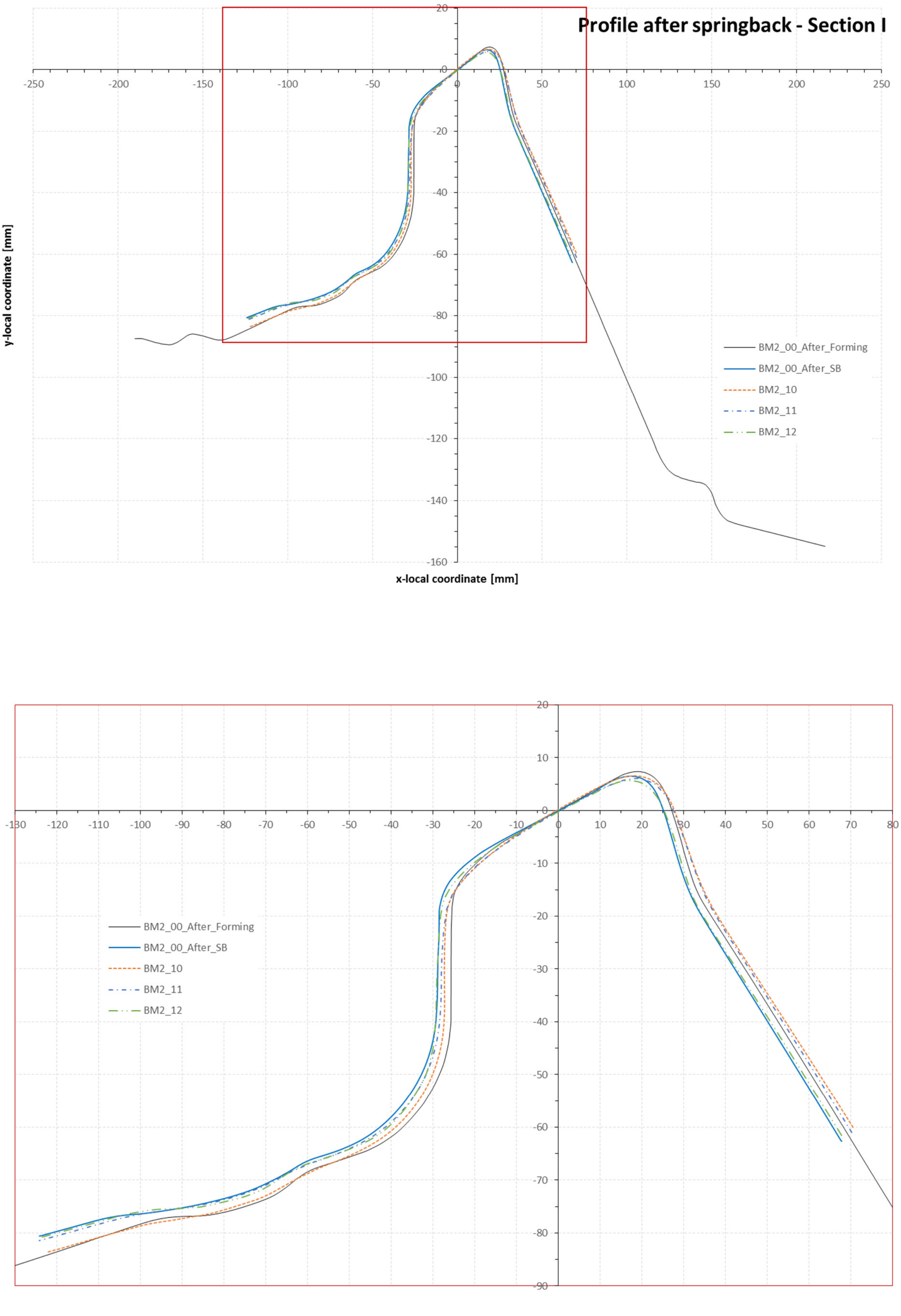
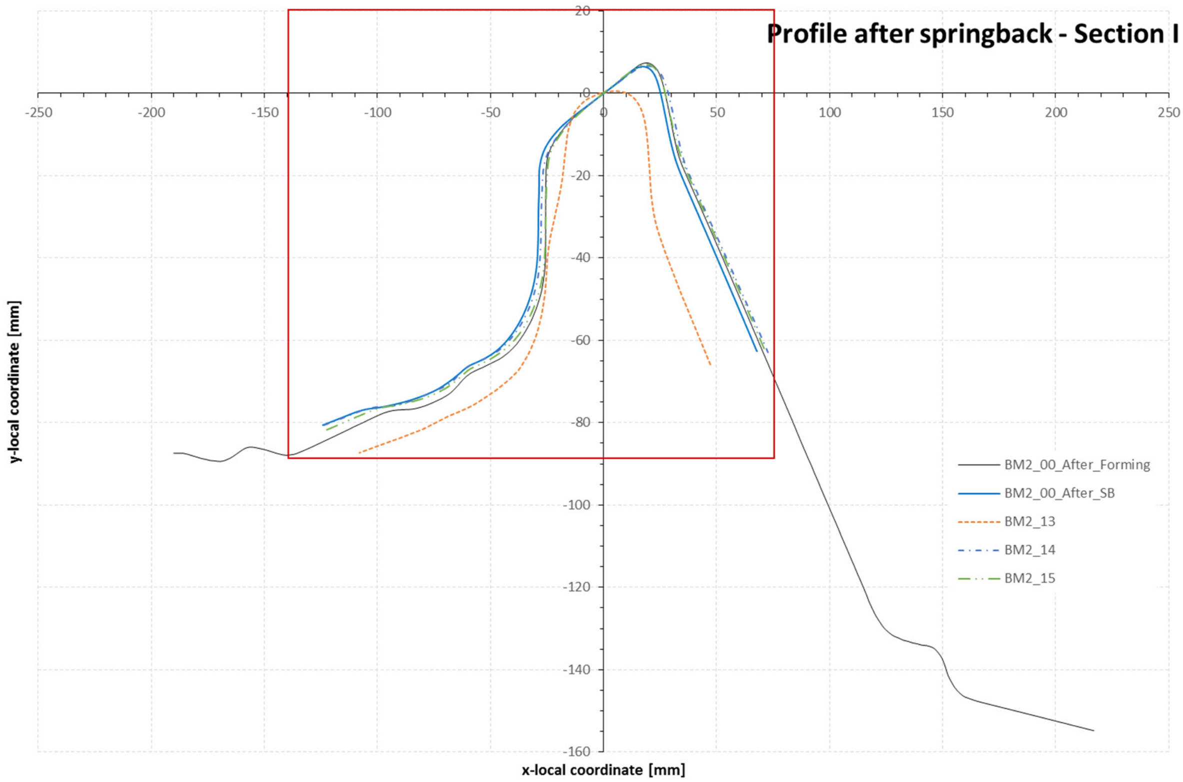


Figure 6.4. Profile after springback for Section I: BM2_10, BM2_11, BM2_12.



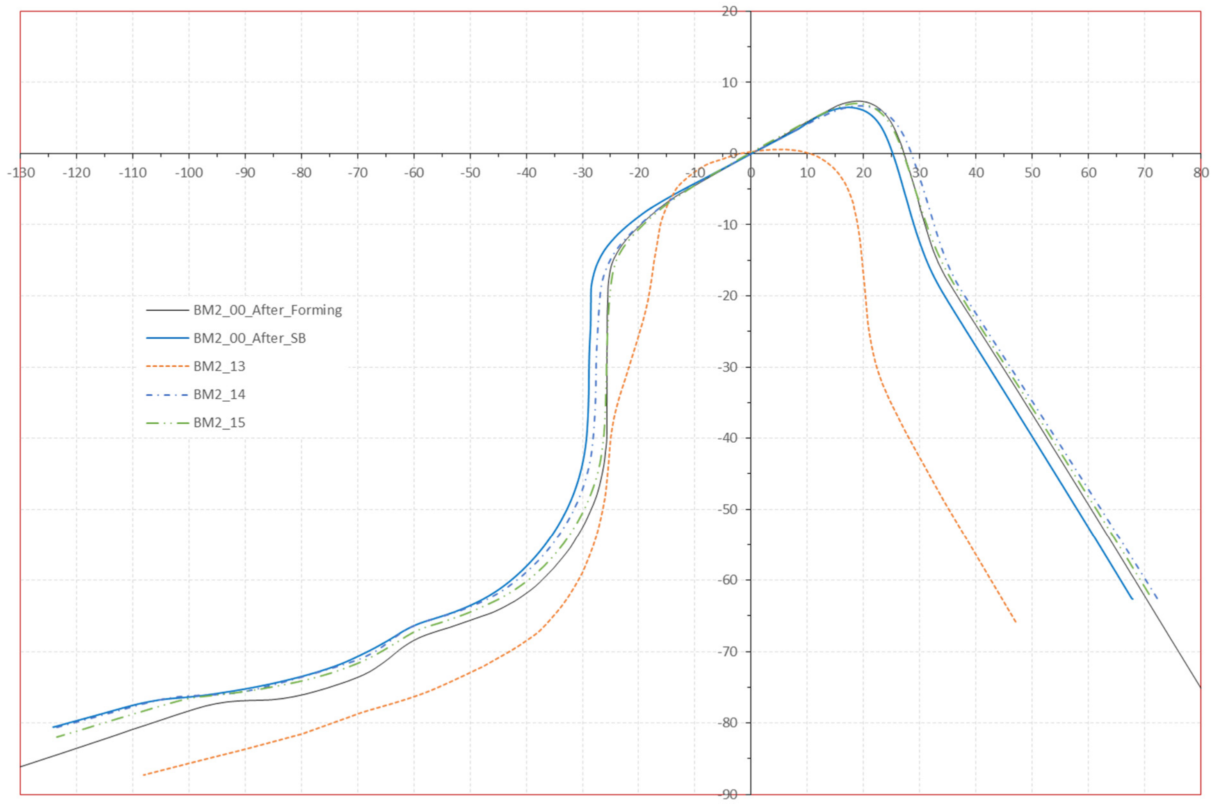
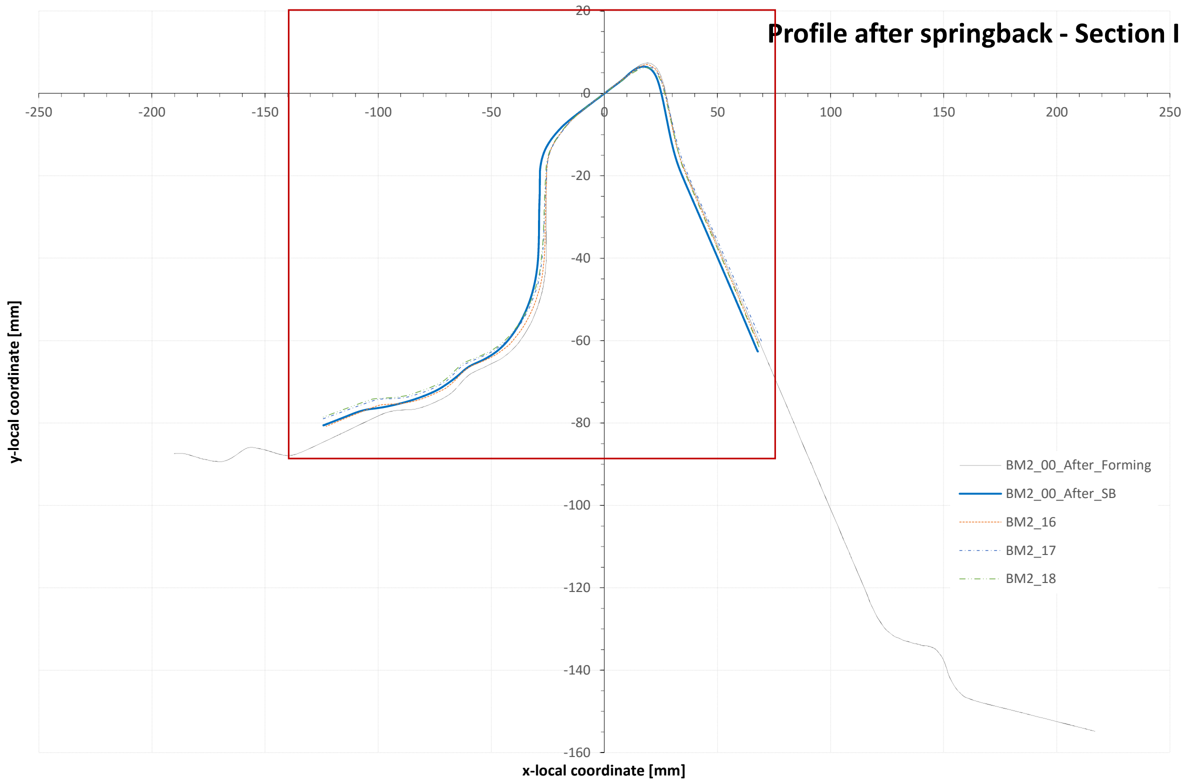


Figure 6.5. Profile after springback for Section I: BM2_13, BM2_14, BM2_15.



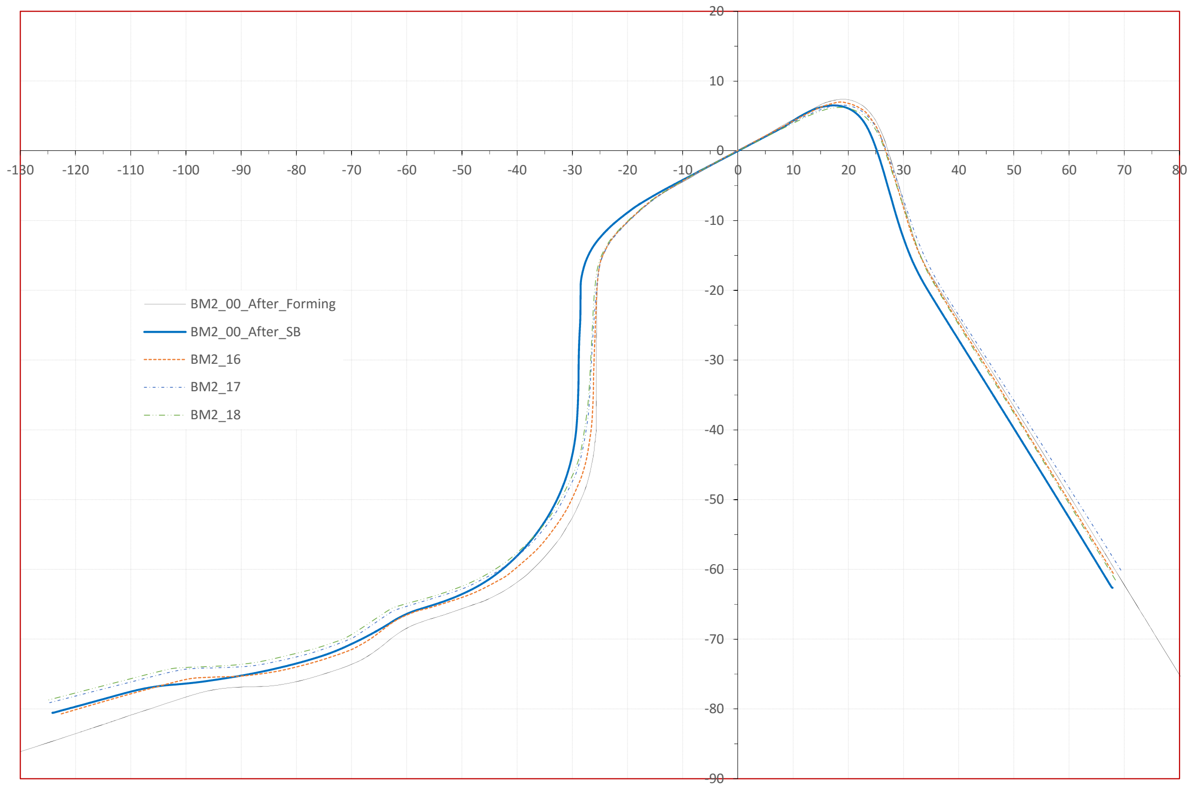
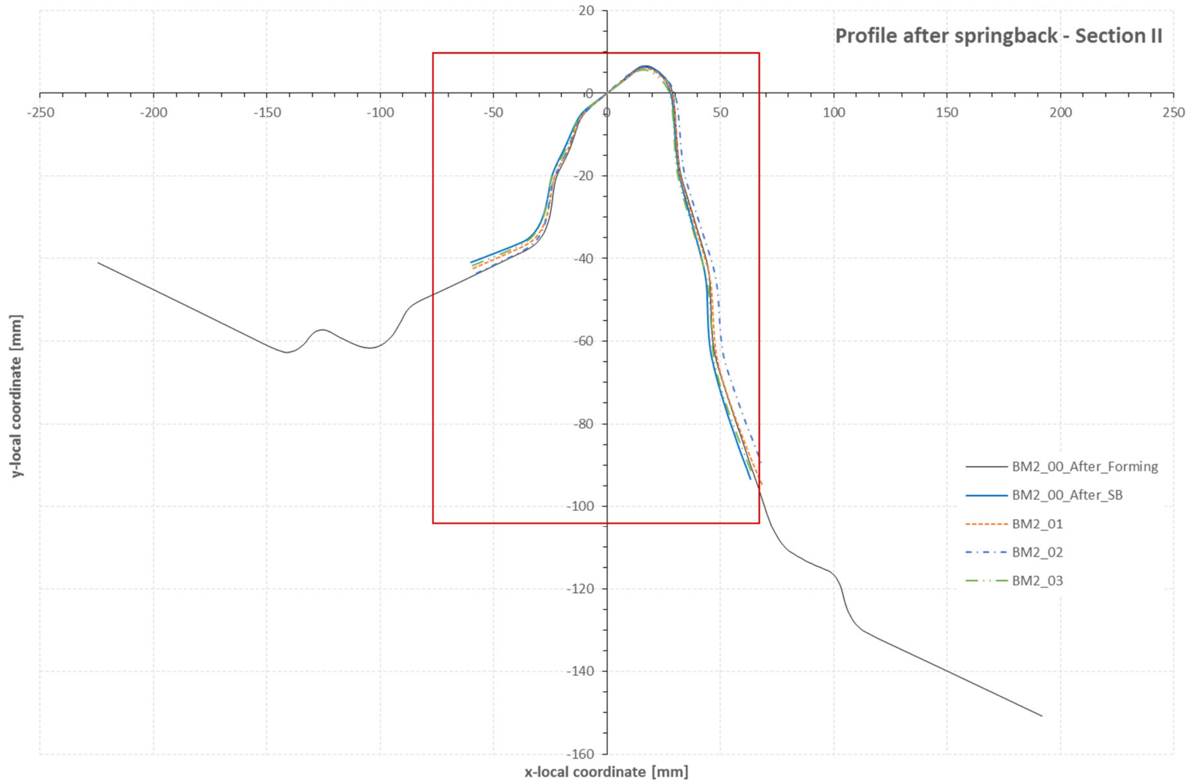


Figure 6.6. Profile after springback for Section I: BM2_16, BM2_17, BM2_18.



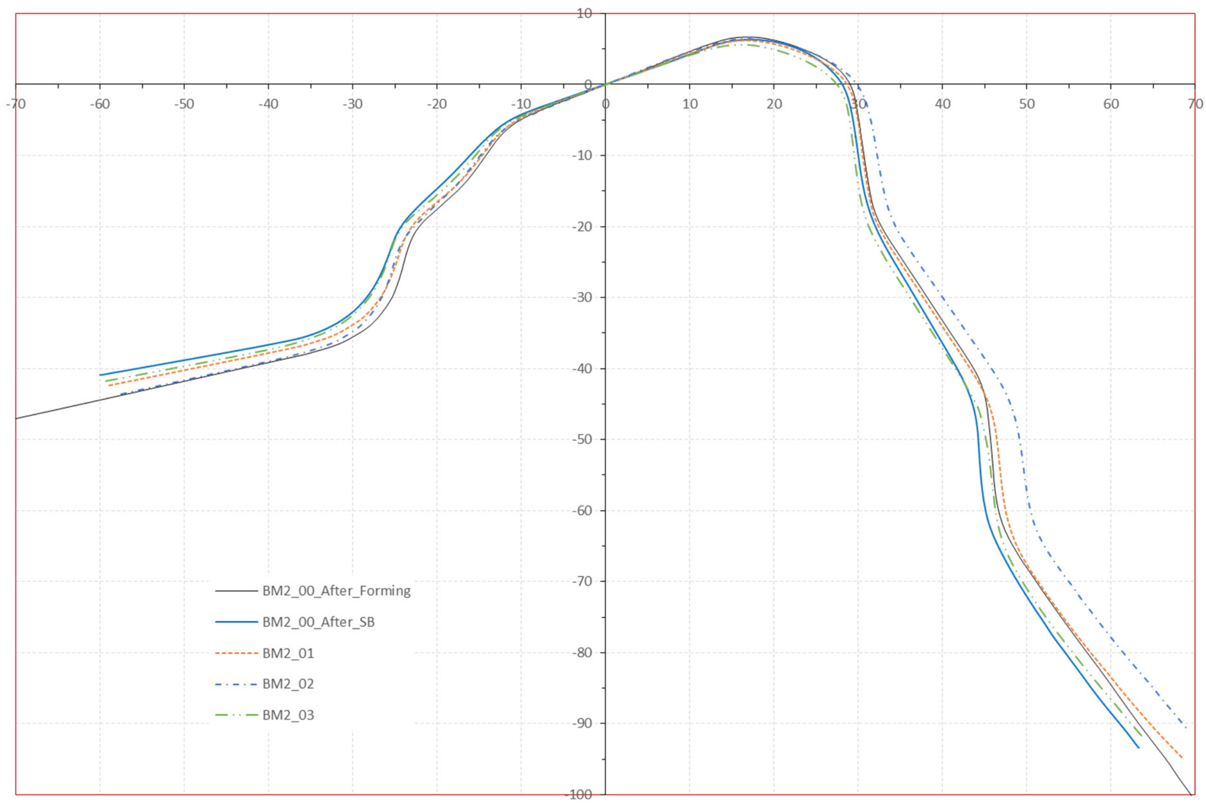


Figure 6.7. Profile after springback for Section II: BM2_01, BM2_02, BM2_03.

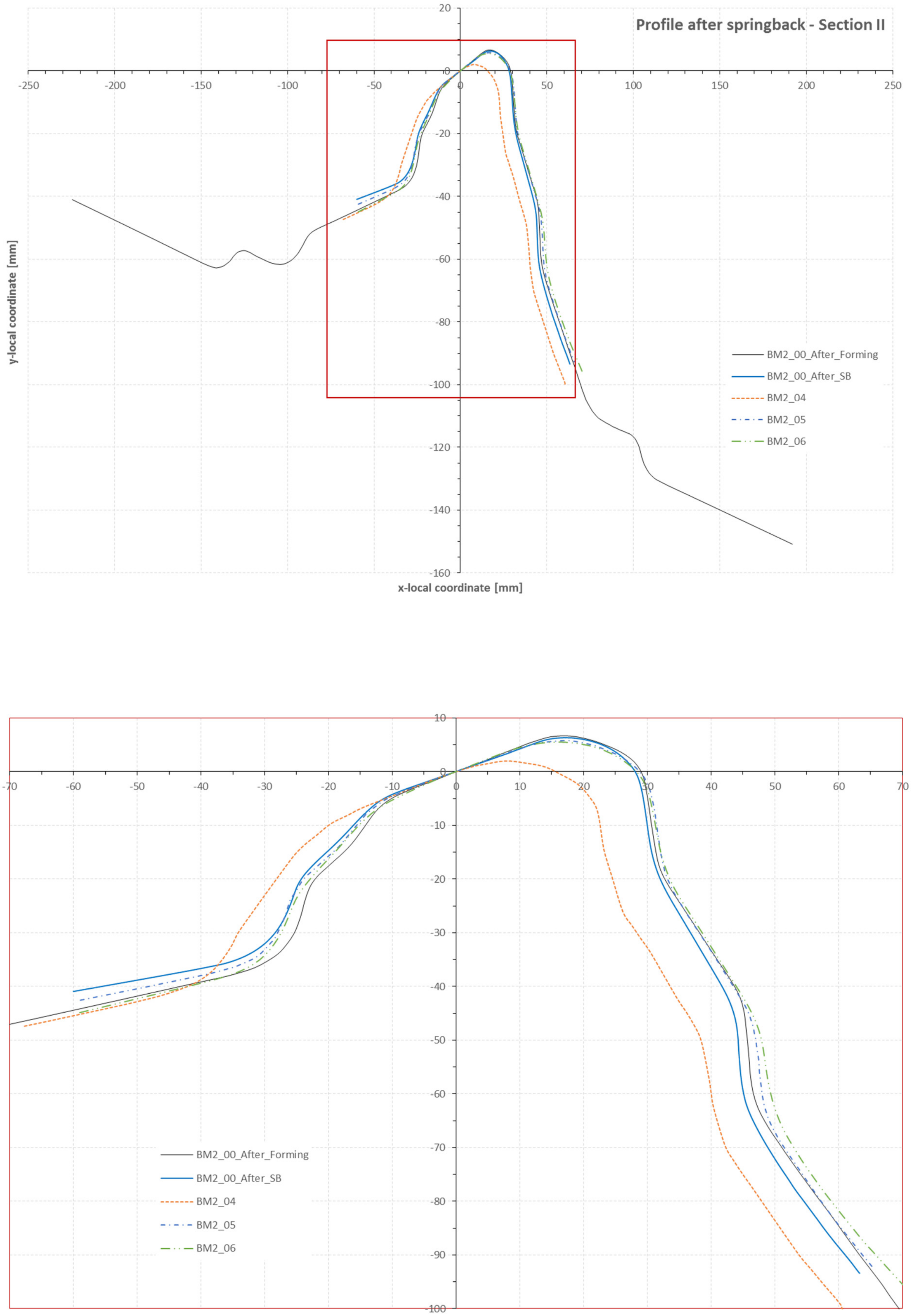


Figure 6.8. Profile after springback for Section II: BM2_04, BM2_05, BM2_06.

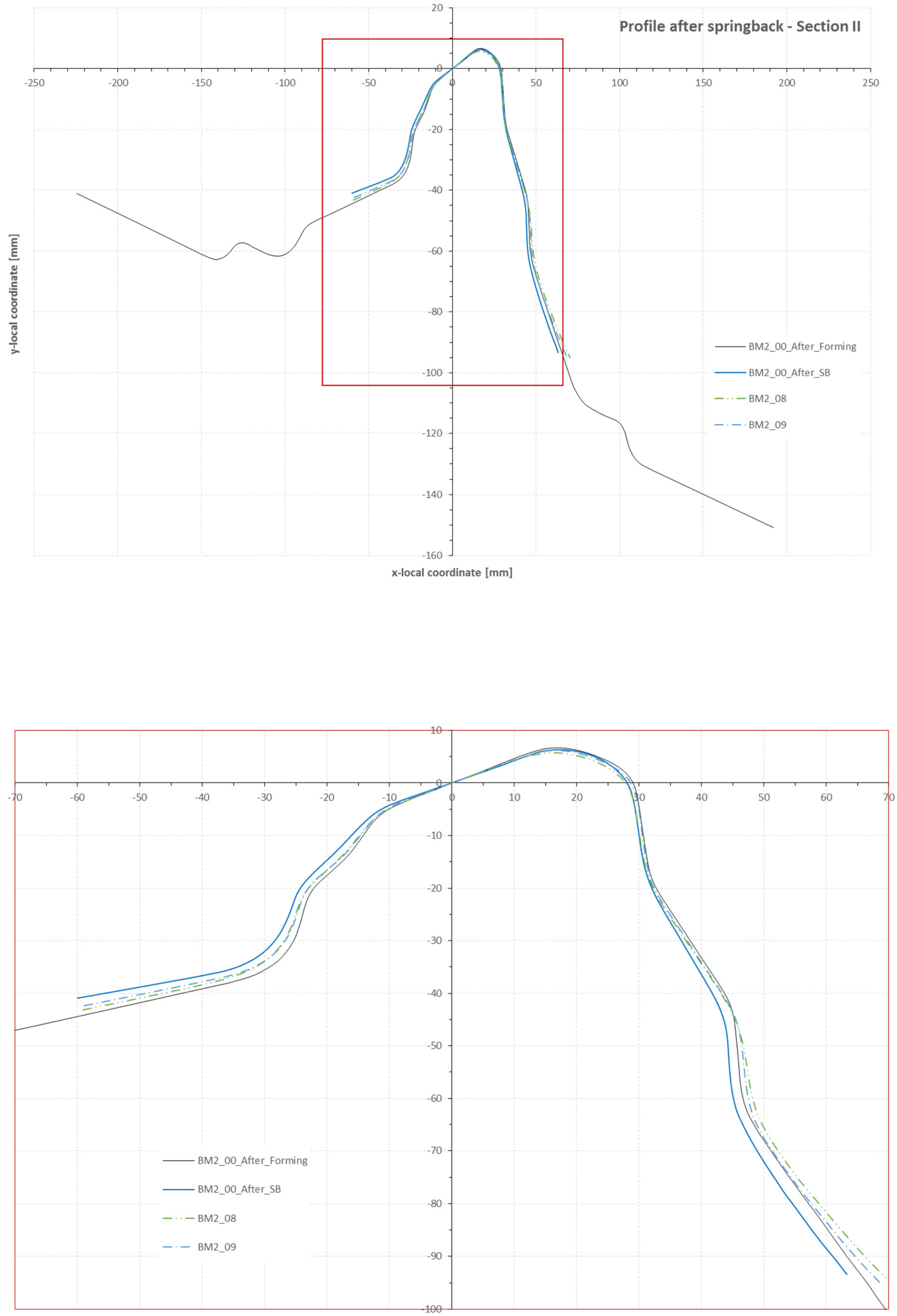
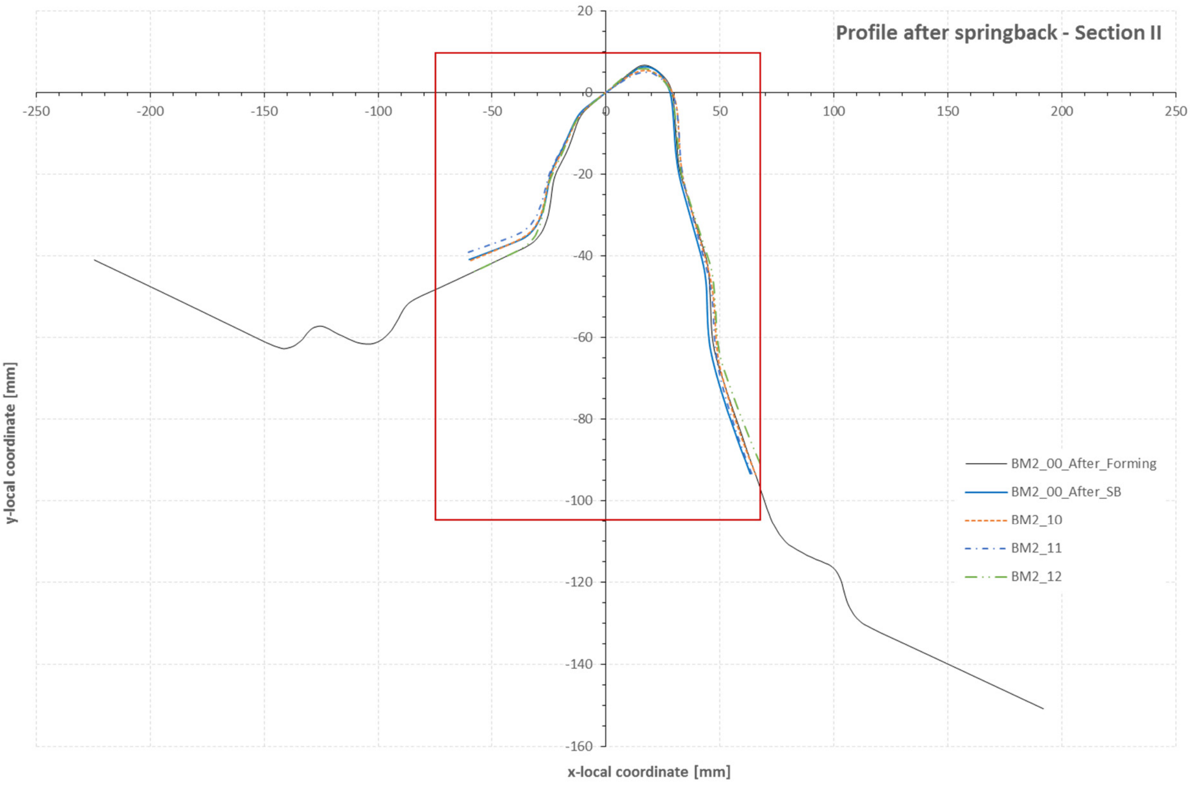


Figure 6.9. Profile after springback for Section II: BM2_08, BM2_09.



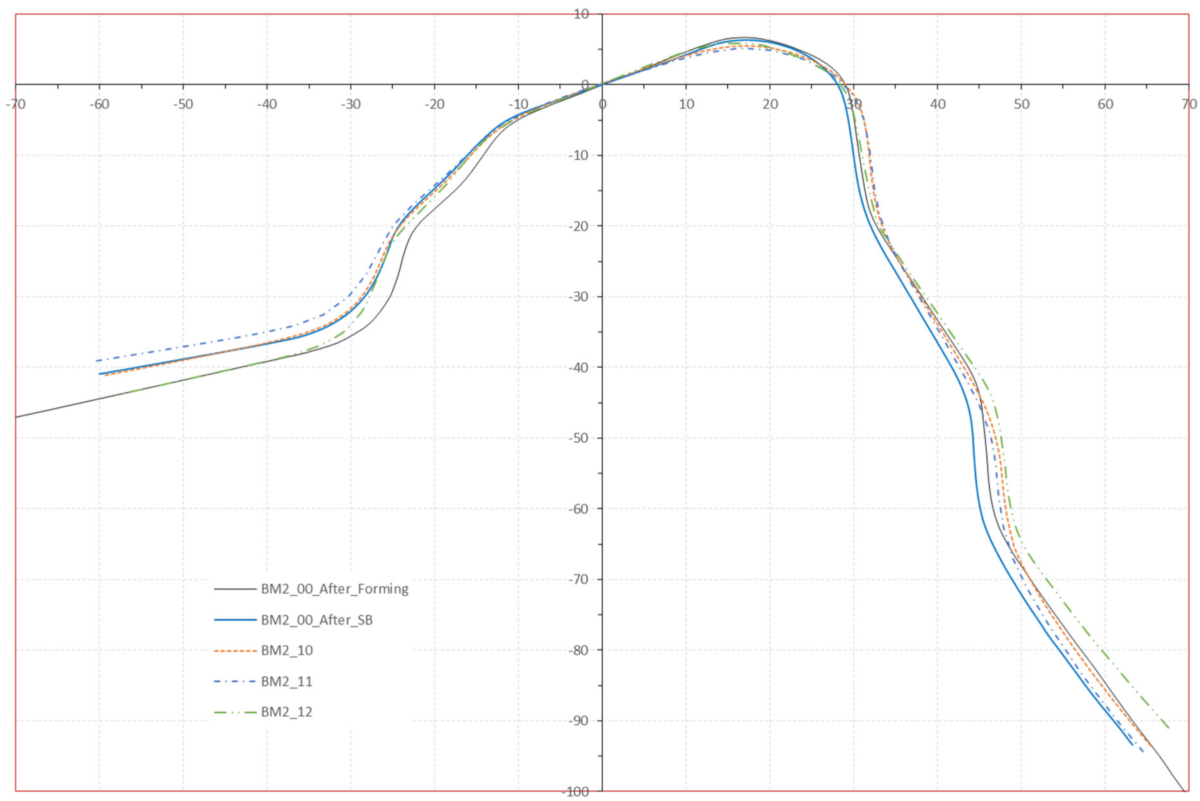


Figure 6.10. Profile after springback for Section II: BM2_10, BM2_11, BM2_12.

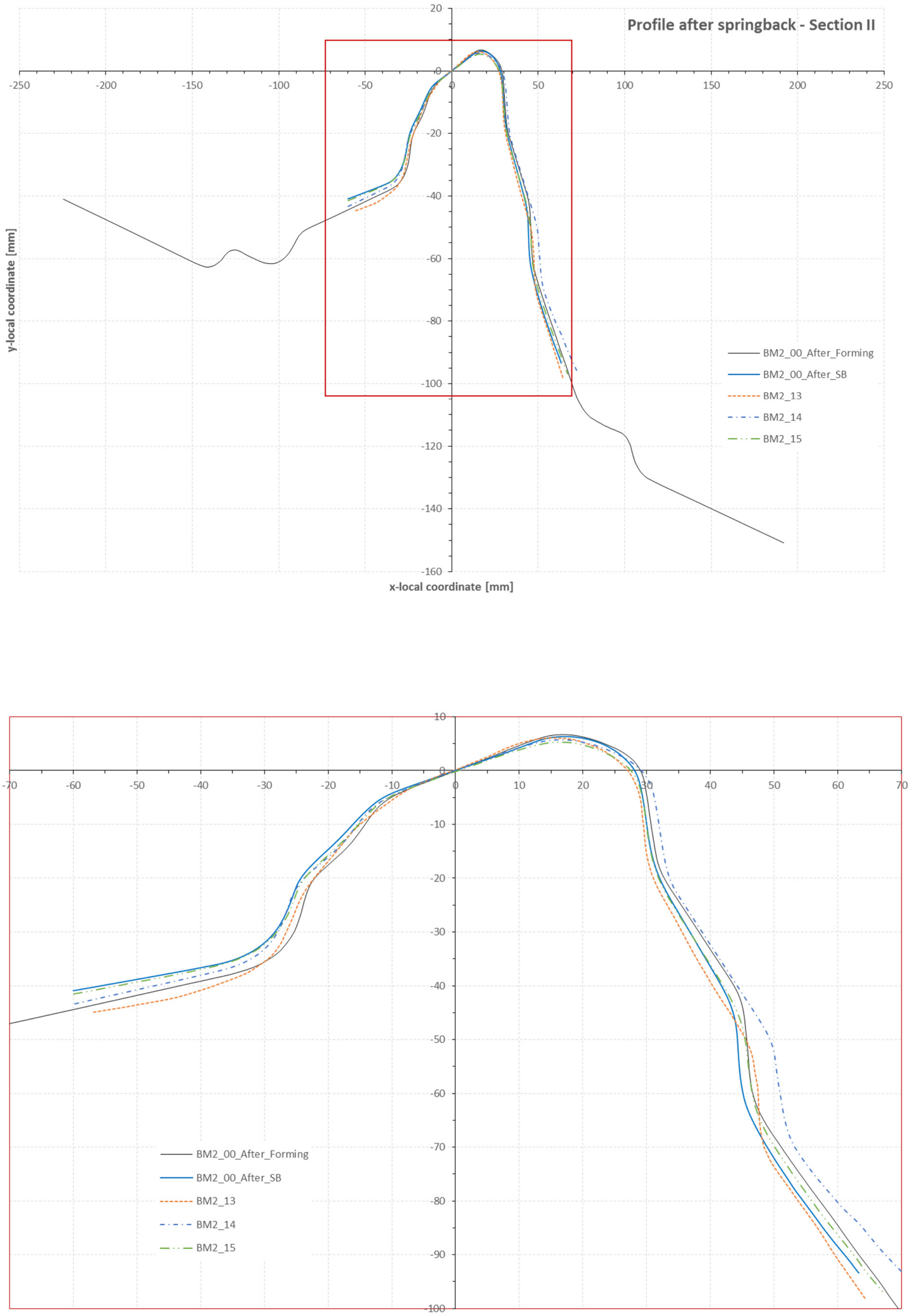
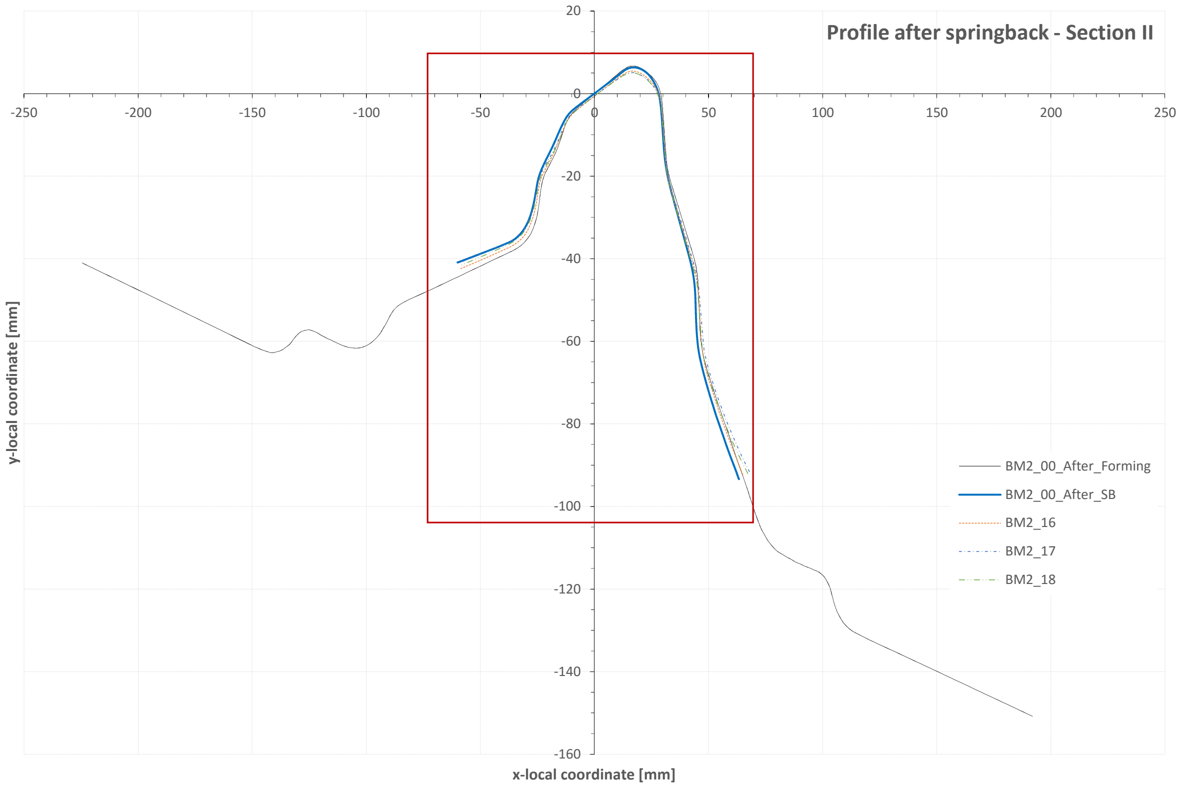


Figure 6.11. Profile after springback for Section II: BM2_13, BM2_14, BM2_15.



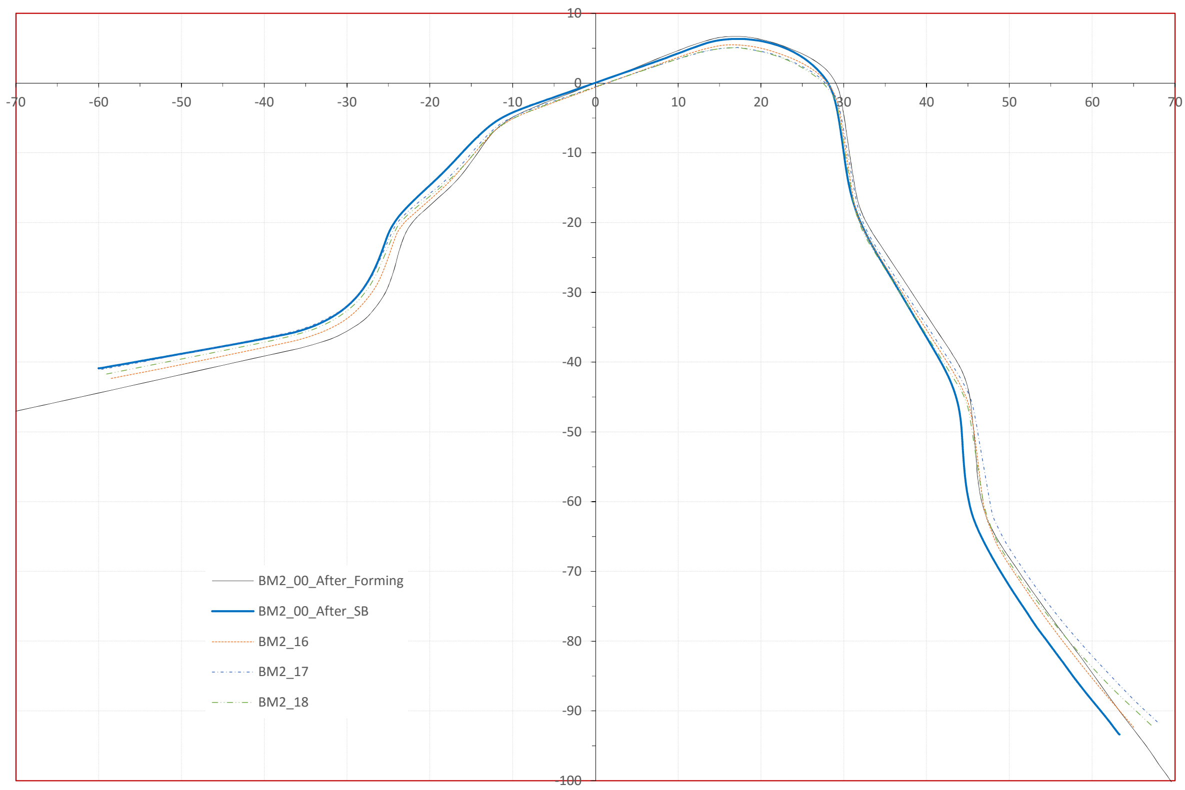


Figure 6.12. Profile after springback for Section II: BM2_16, BM2_17, BM2_18.

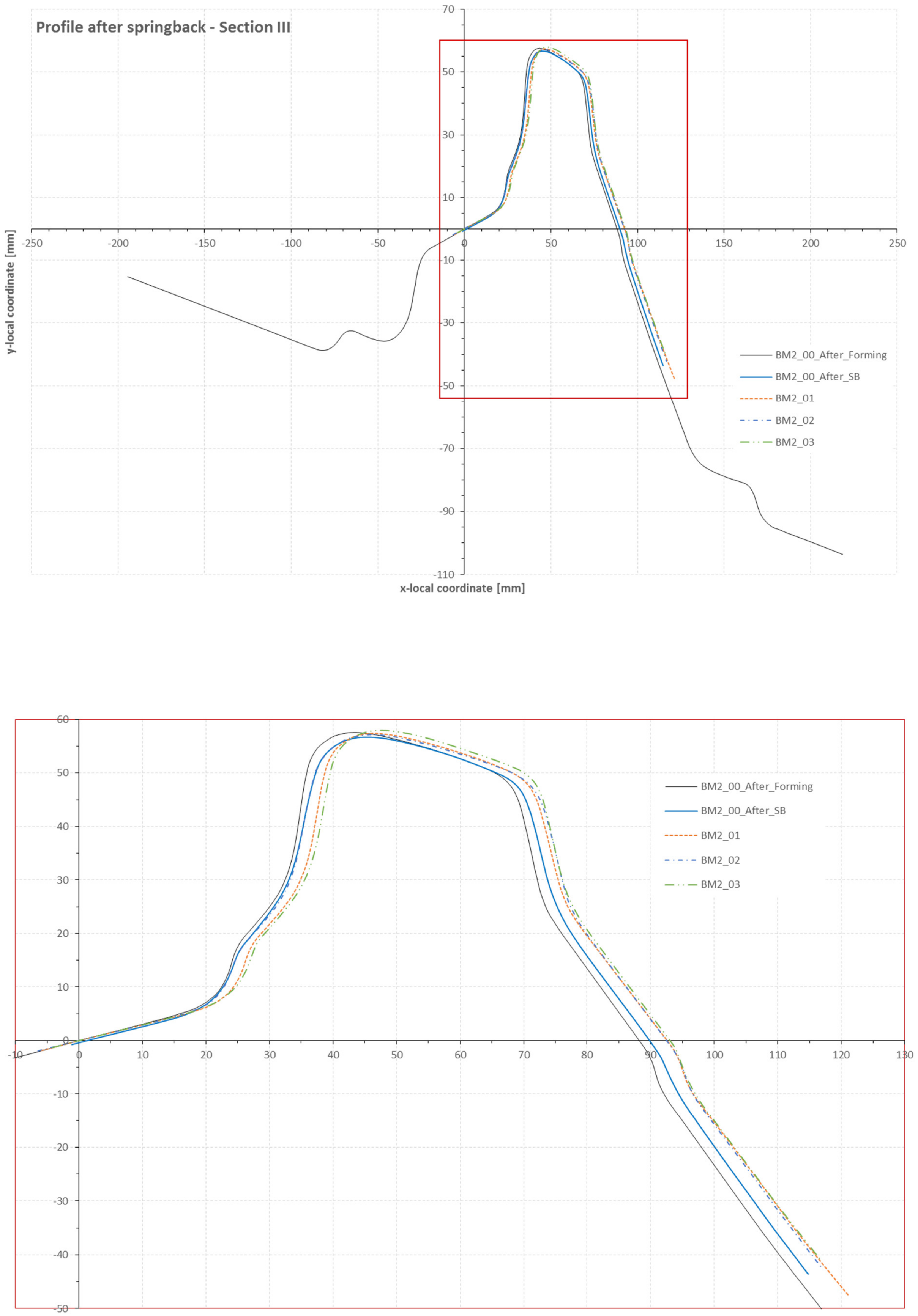


Figure 6.13. Profile after springback for Section III: BM2_01, BM2_02, BM2_03.

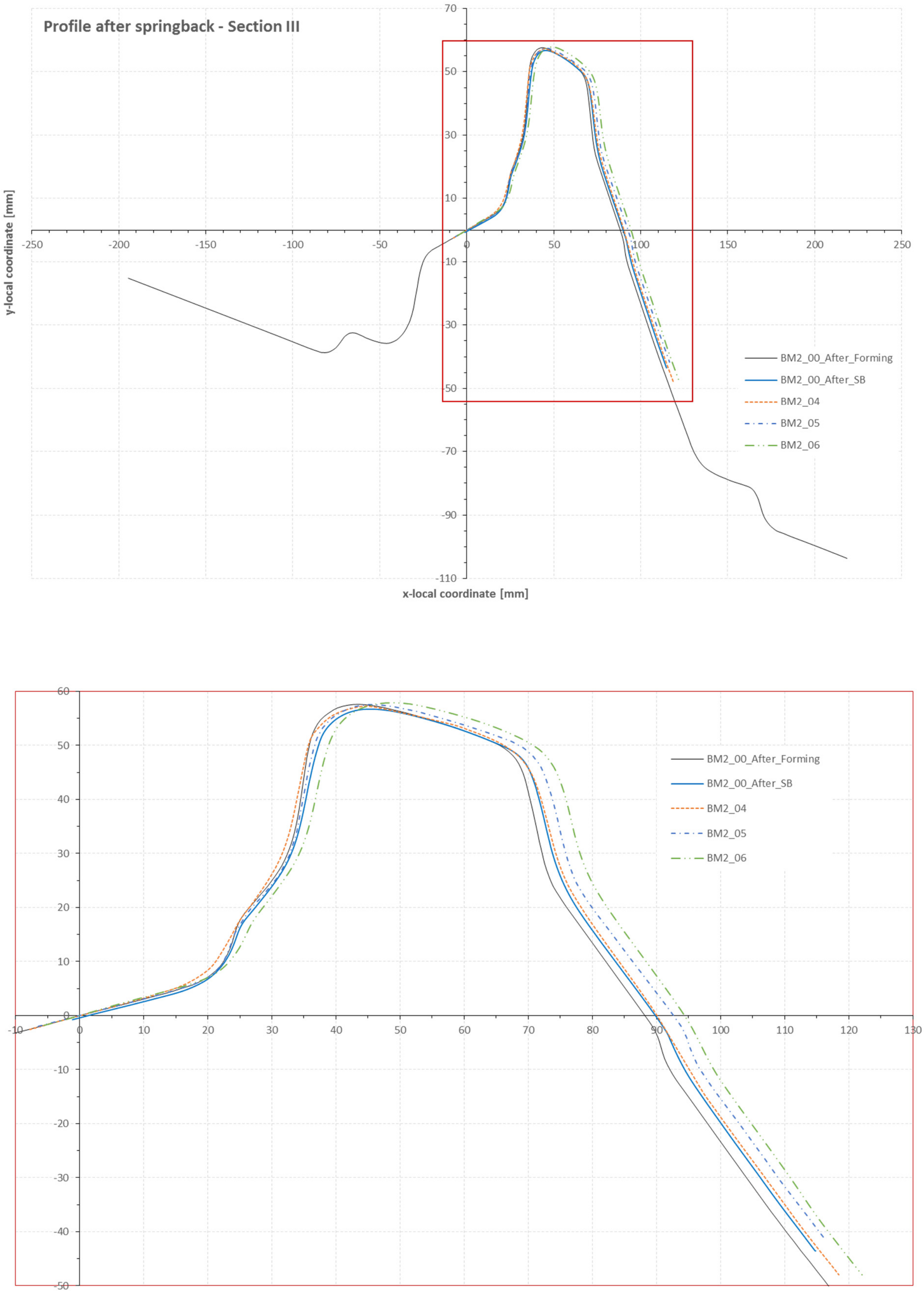


Figure 6.14. Profile after springback for Section III: BM2_04, BM2_05, BM2_06.

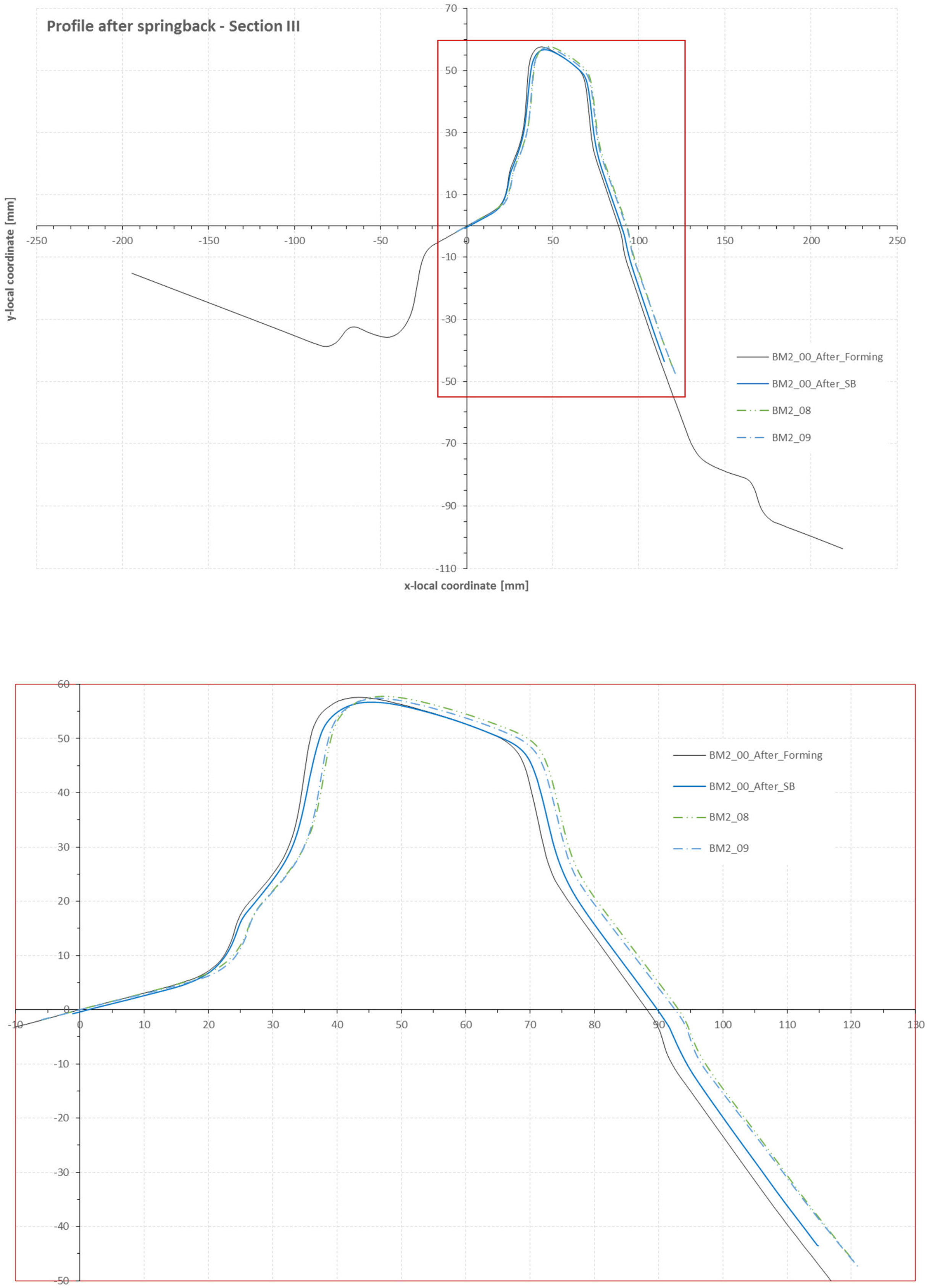


Figure 6.15. Profile after springback for Section III: BM2_08, BM2_09.

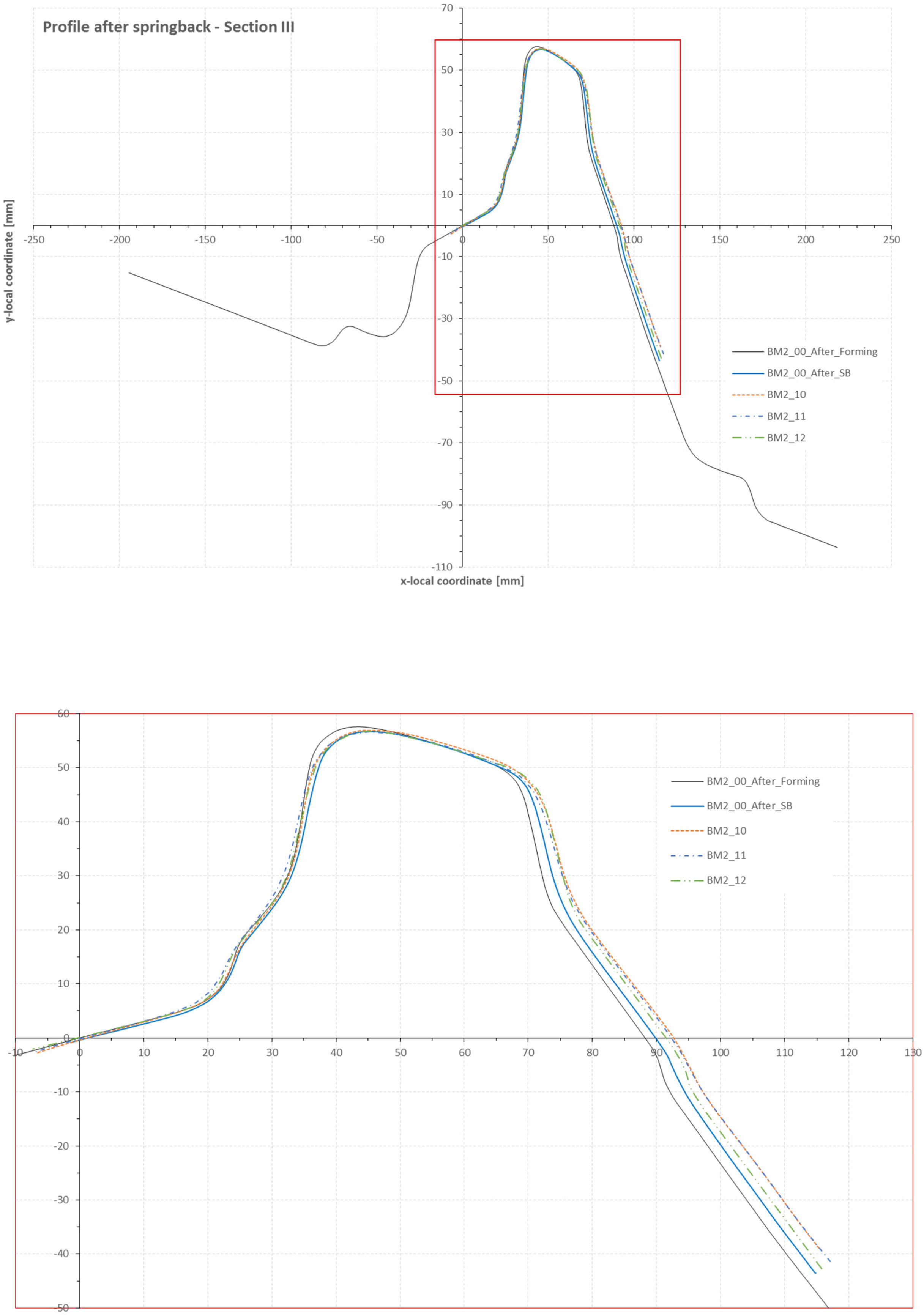
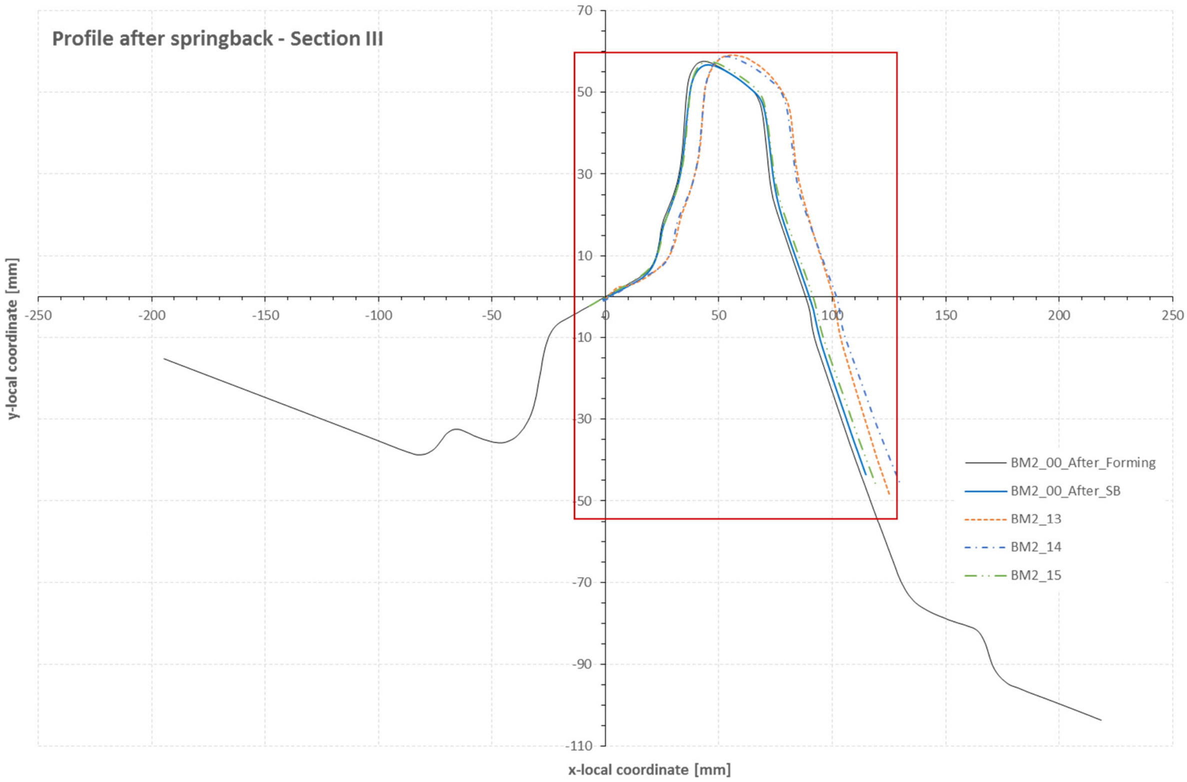


Figure 6.16. Profile after springback for Section III: BM2_10, BM2_11, BM2_12.



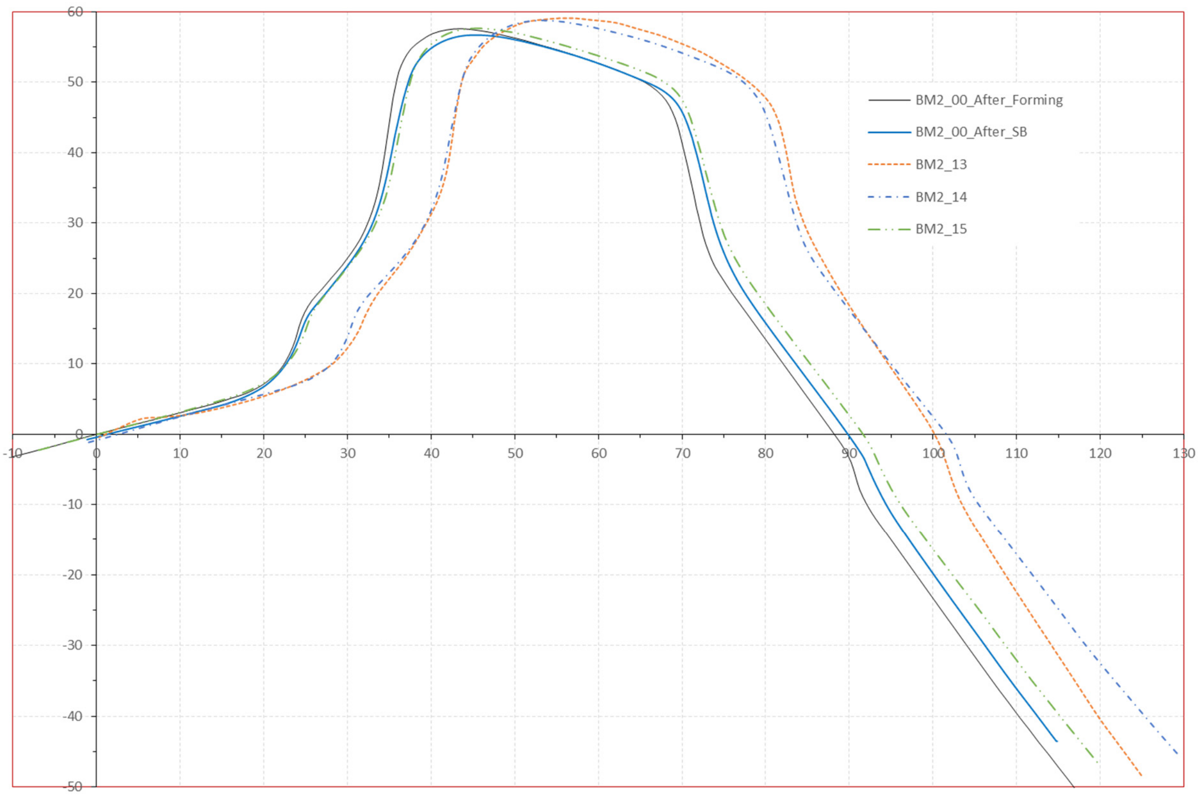
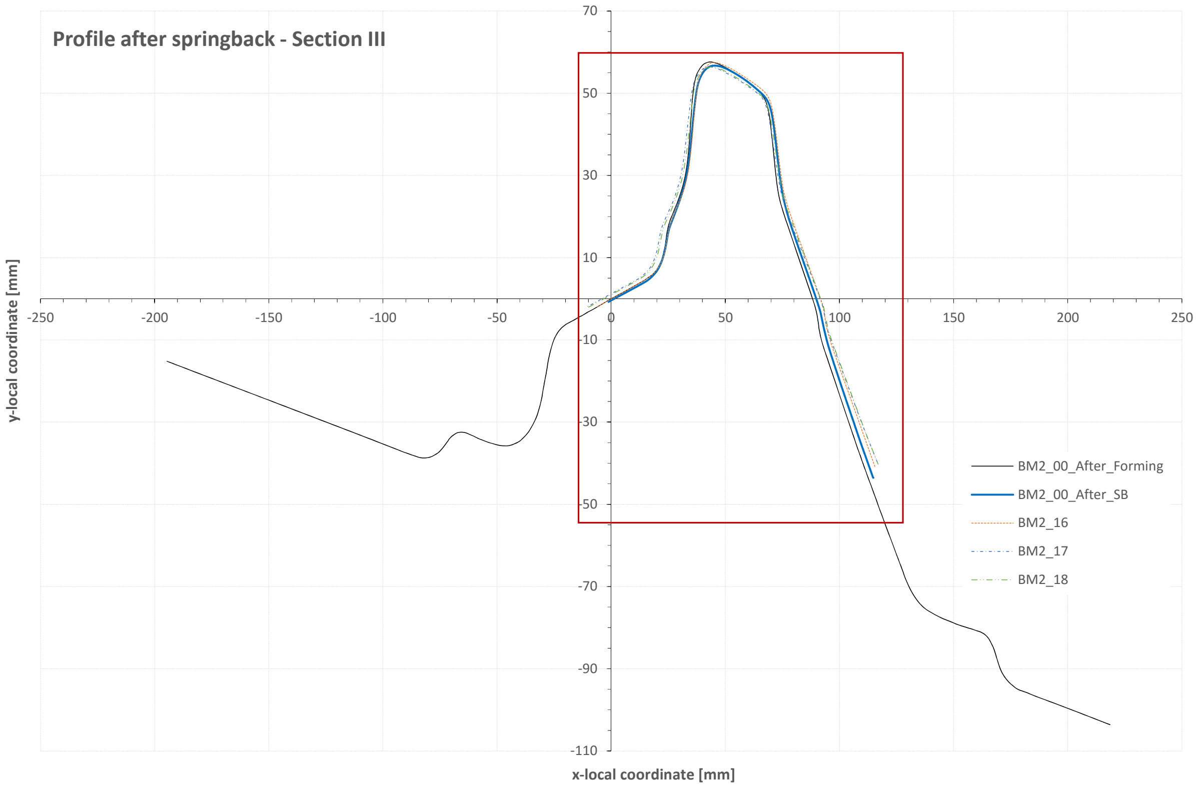


Figure 6.17. Profile after springback for Section III: BM2_13, BM2_14, BM2_15.



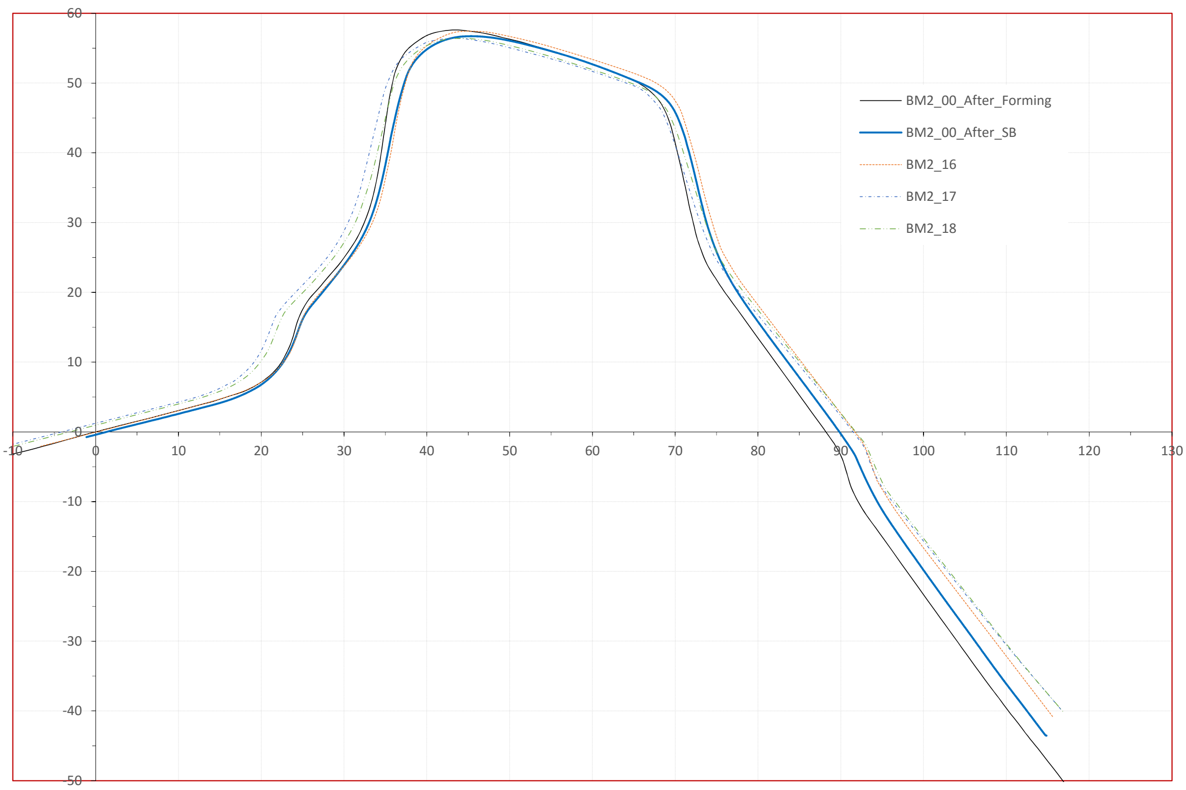


Figure 6.18. Profile after springback for Section III: BM2_16, BM2_17, BM2_18.

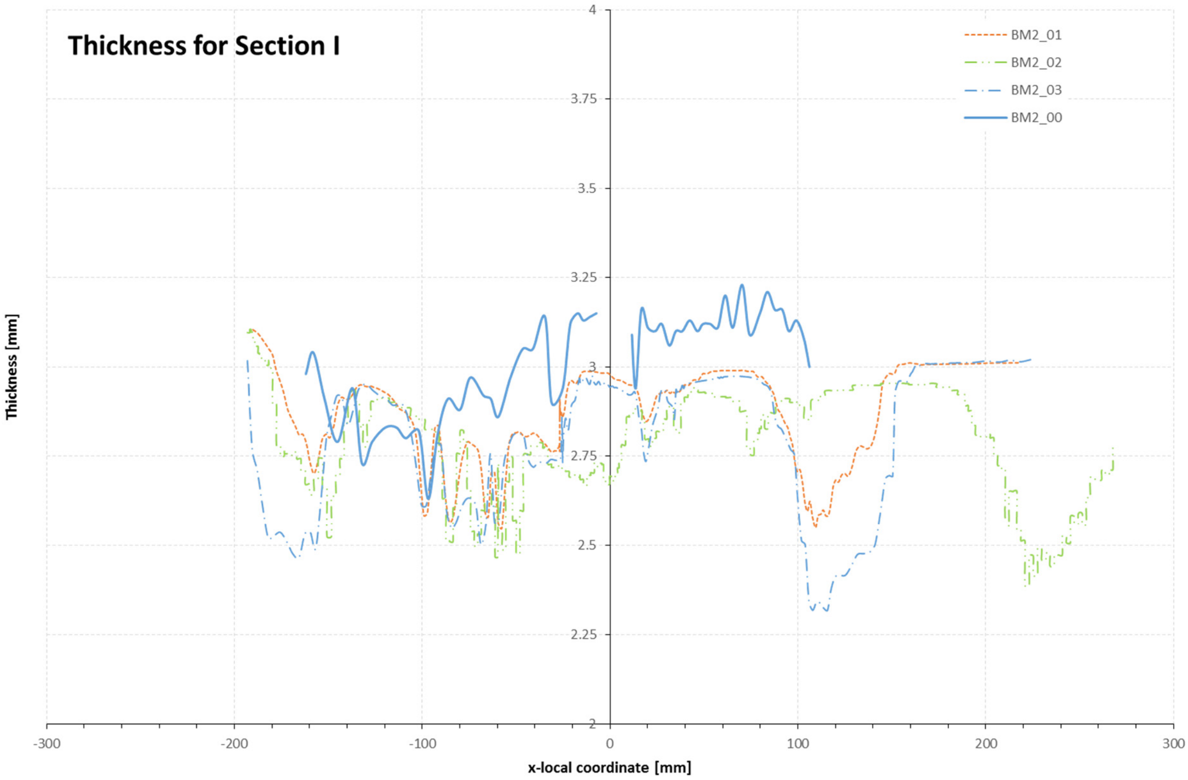


Figure 6.19. Thickness for Section I: BM2_01, BM2_02, BM2_03.

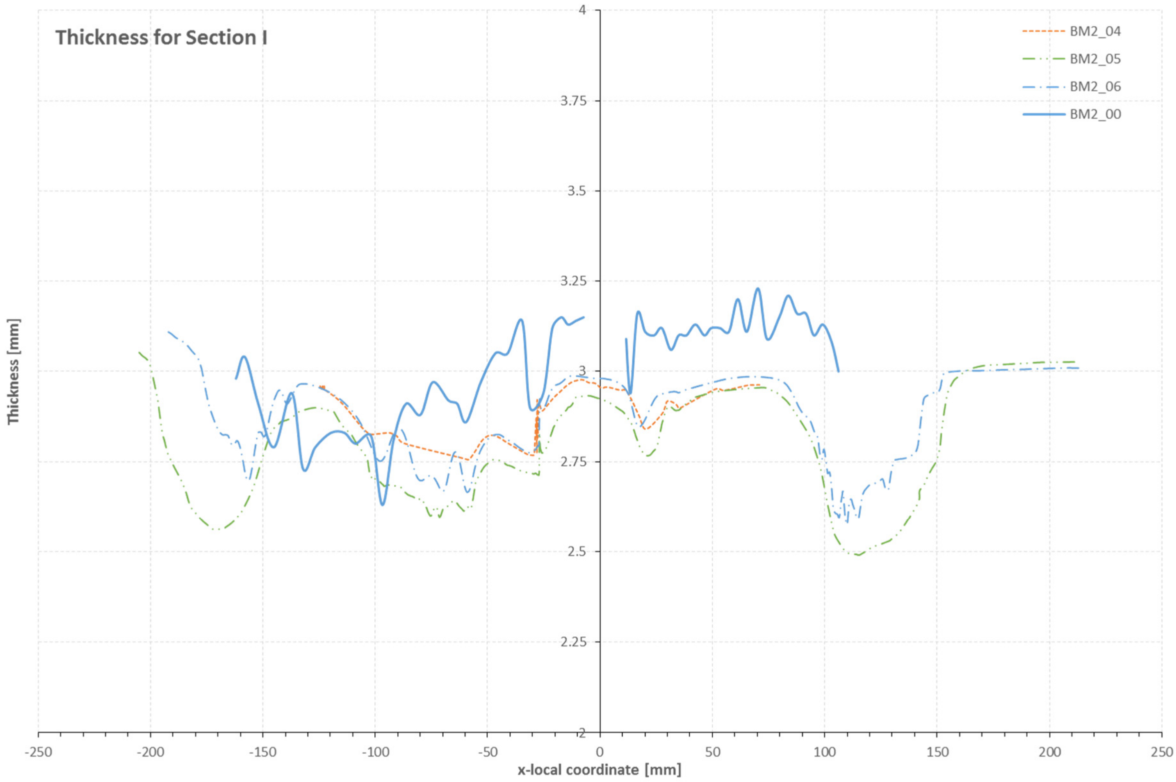


Figure 6.20. Thickness for Section I: BM2_04, BM2_05, BM2_06.

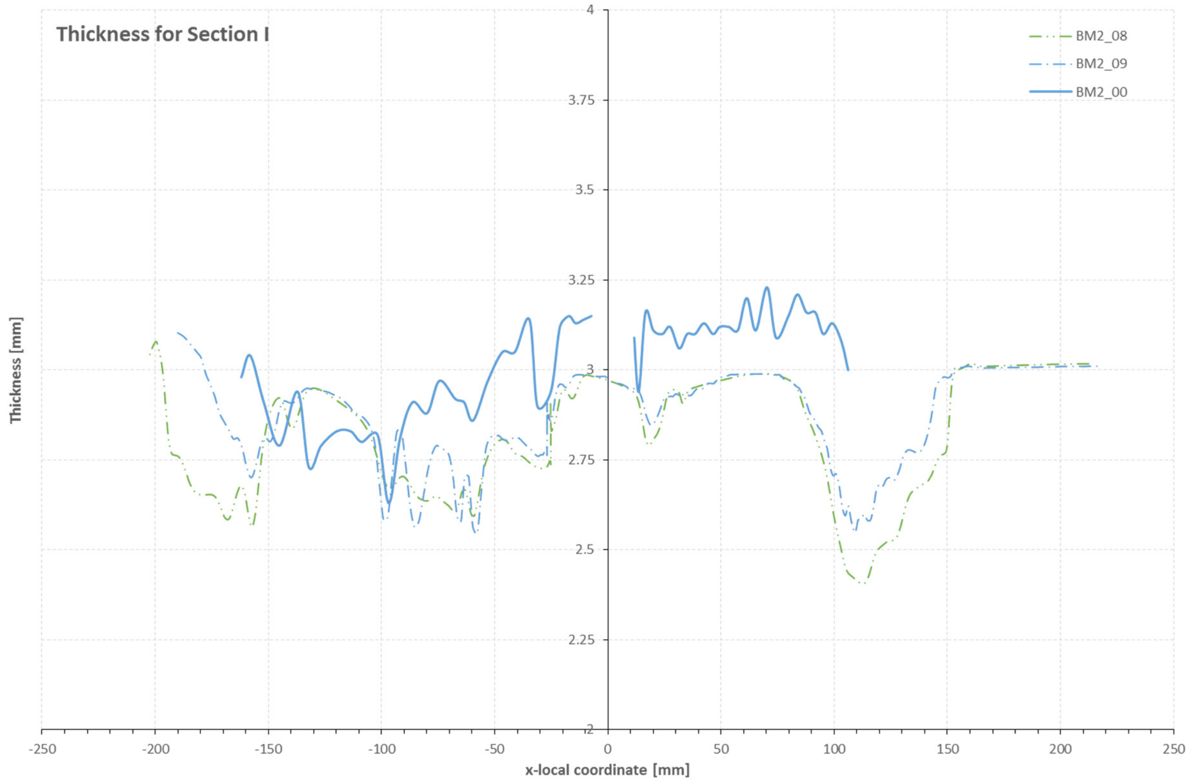


Figure 6.21. Thickness for Section I: BM2_08, BM2_09.

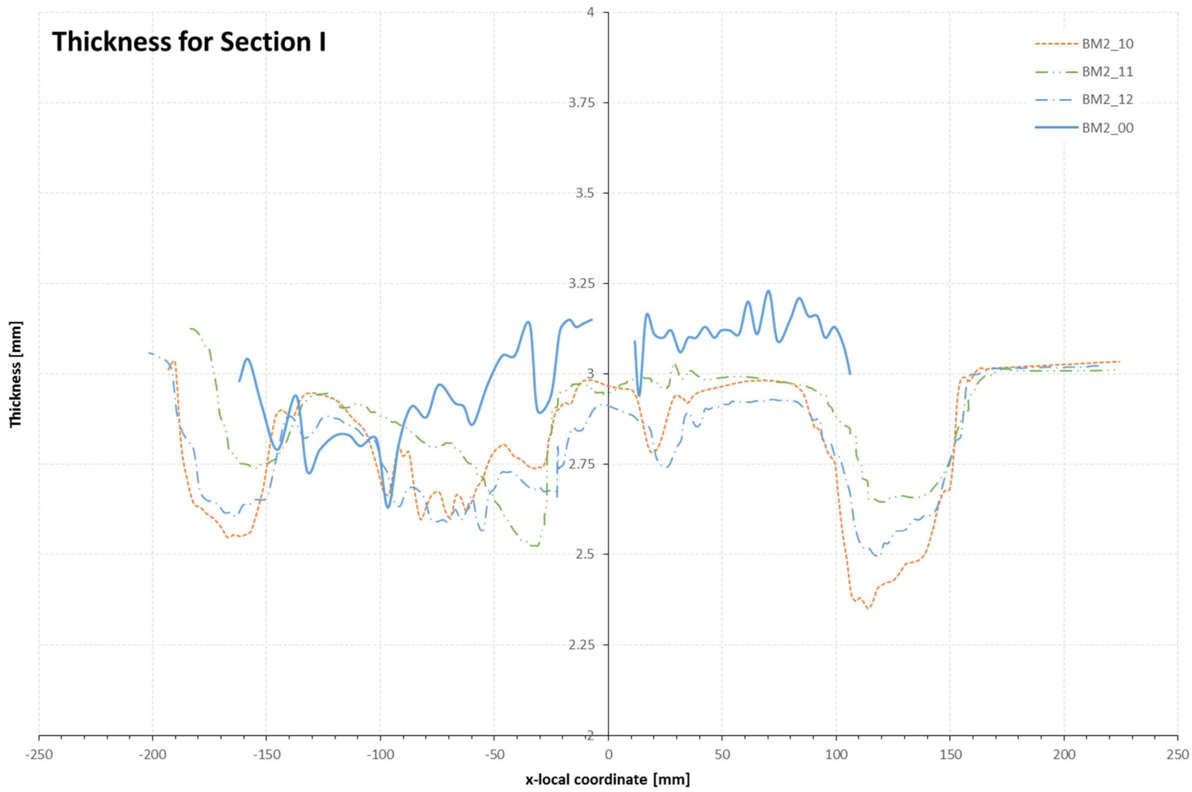


Figure 6.22. Thickness for Section I: BM2_10, BM2_11, BM2_12.

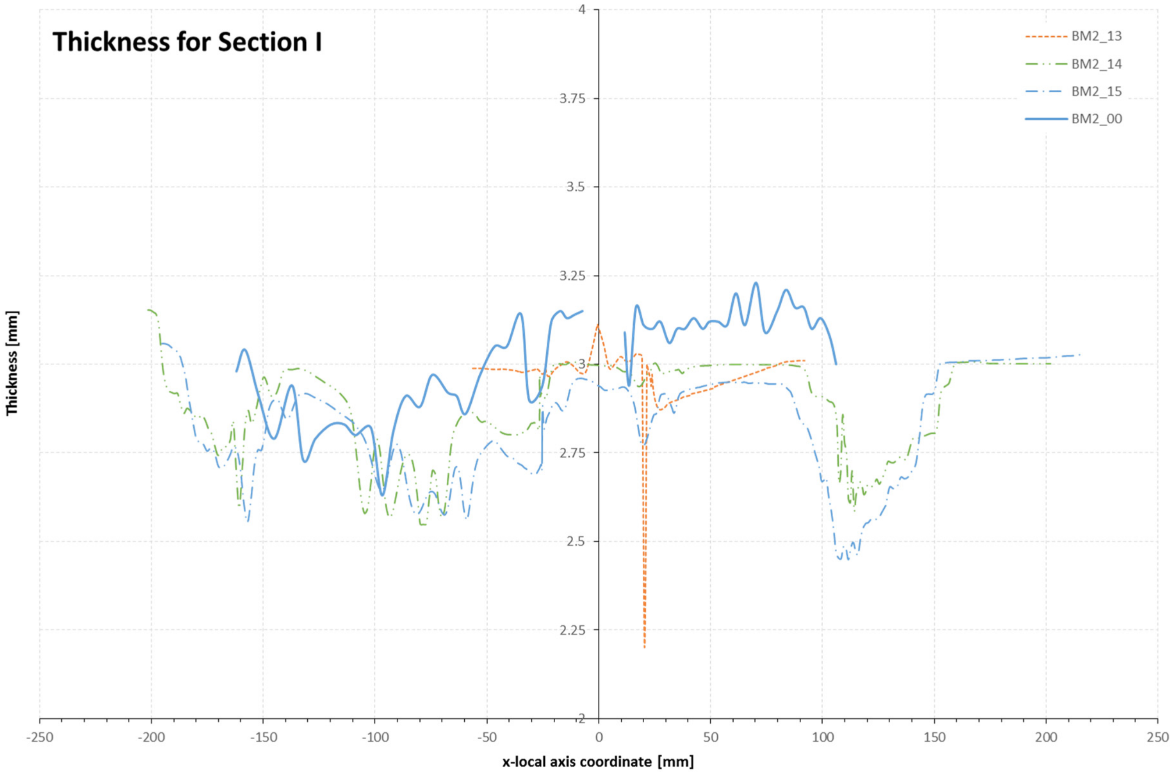


Figure 6.23. Thickness for Section I: BM2_13, BM2_14, BM2_15.

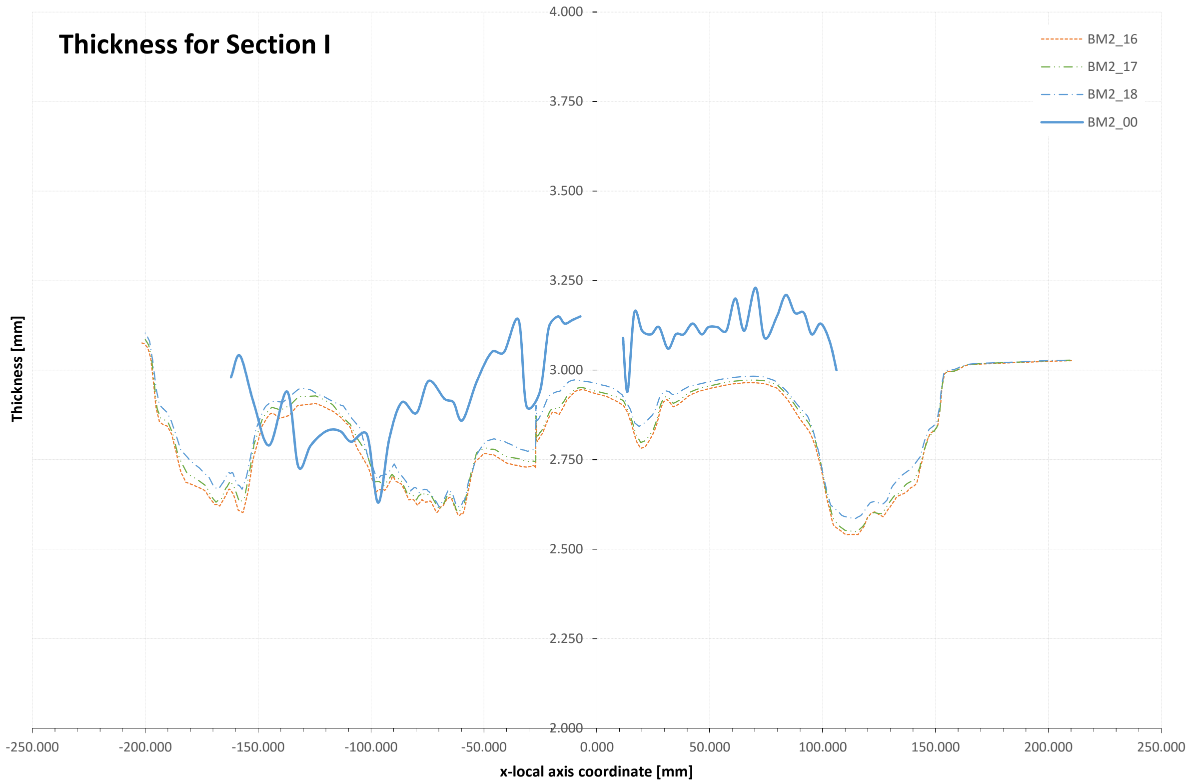


Figure 6.24. Thickness for Section I: BM2_16, BM2_17, BM2_18.

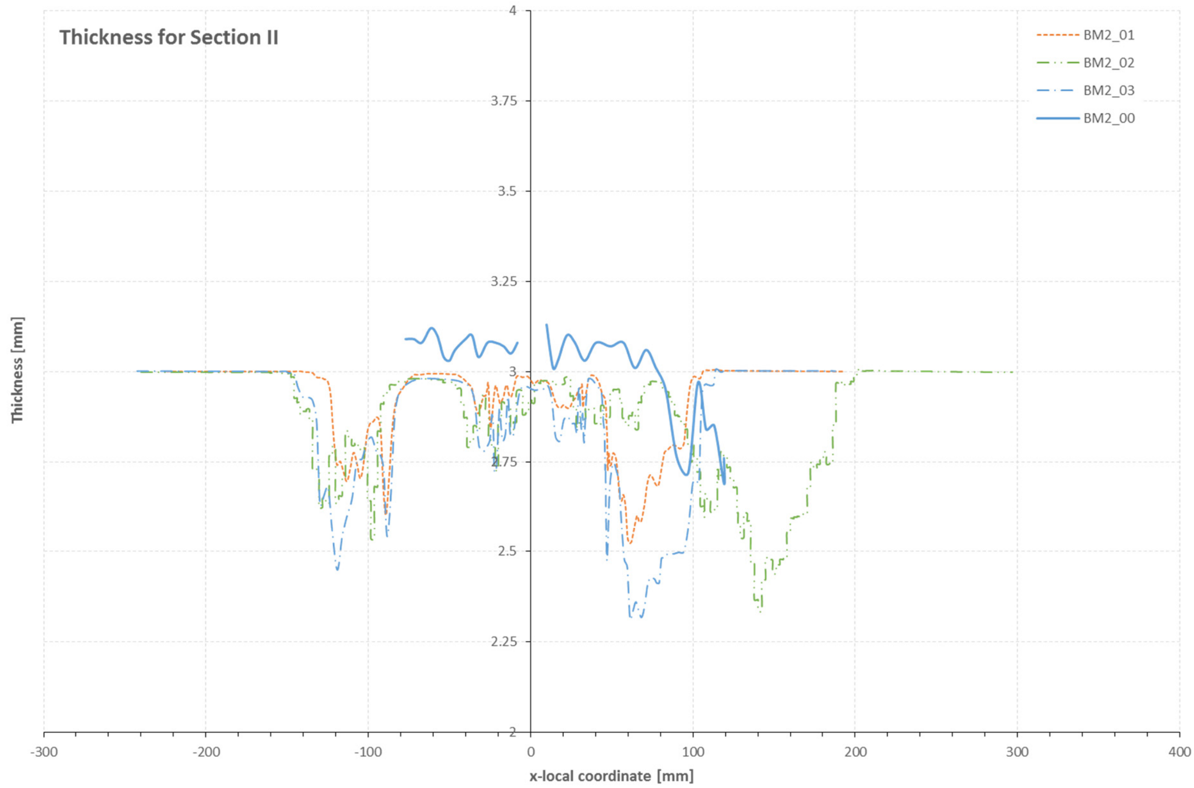


Figure 6.25. Thickness for Section II: BM2_01, BM2_02, BM2_03.

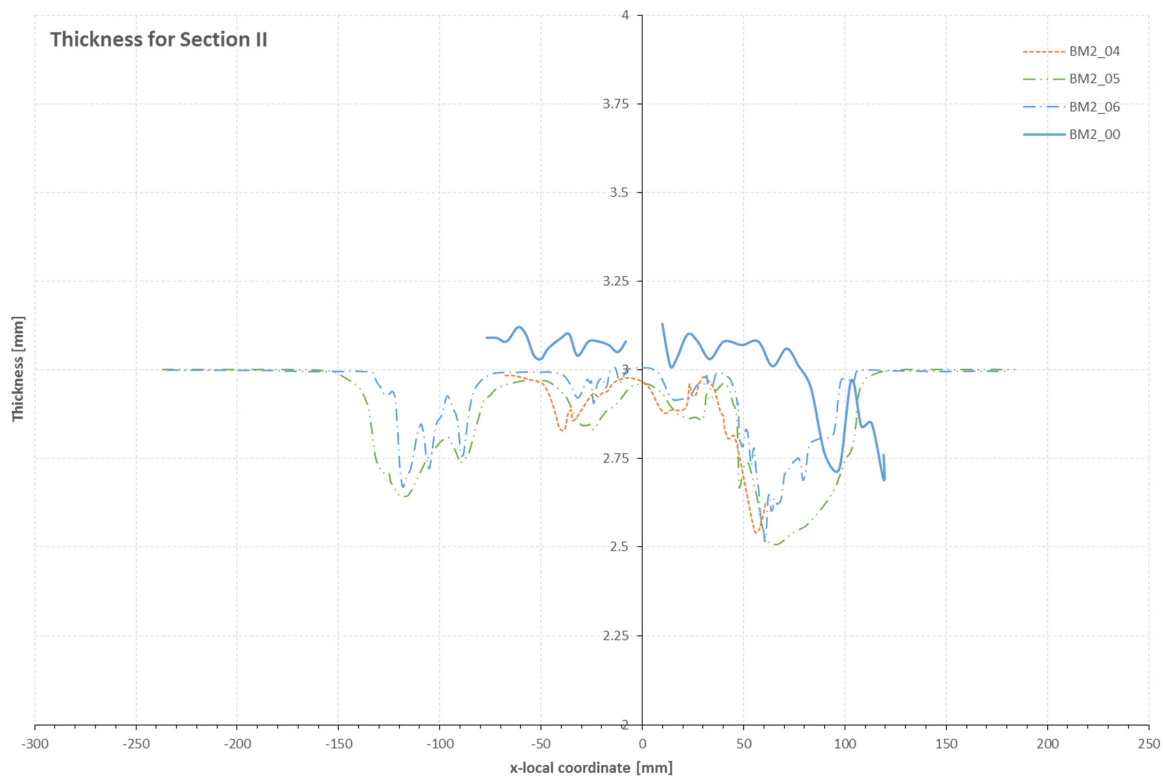


Figure 6.26. Thickness for Section II: BM2_04, BM2_05, BM2_06.

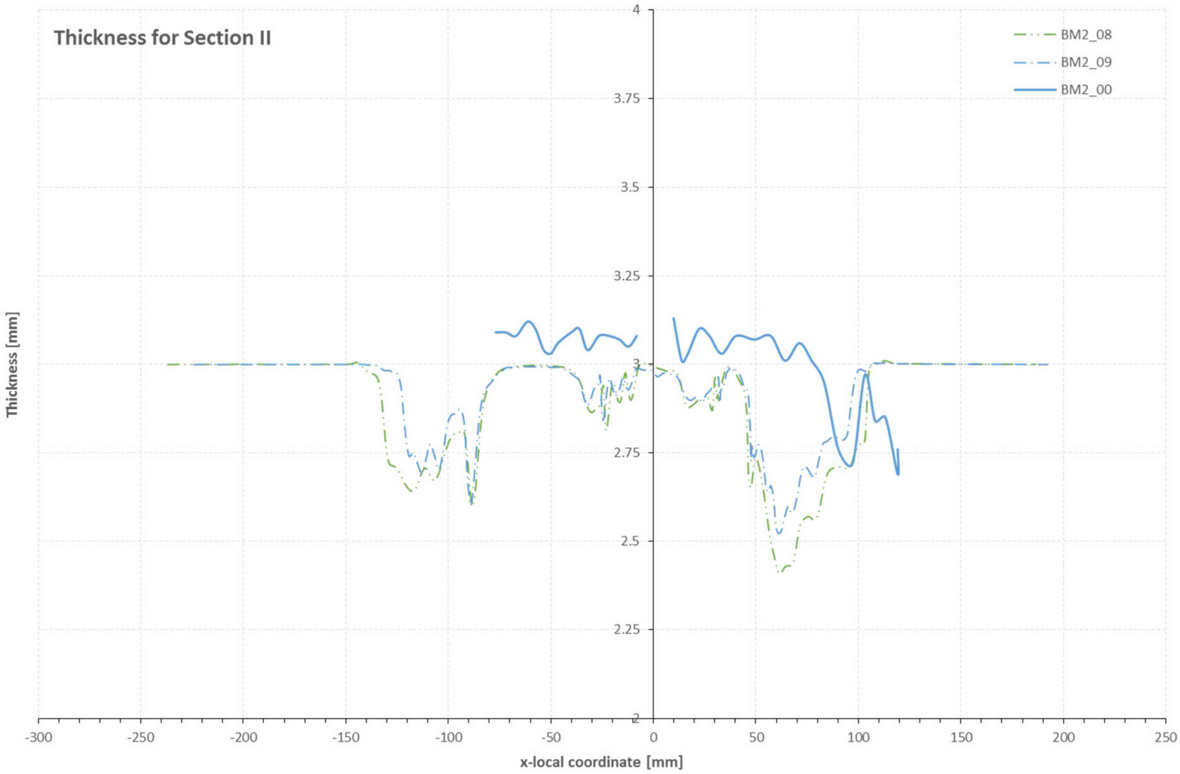


Figure 6.27. Thickness for Section II: BM2_08, BM2_09.

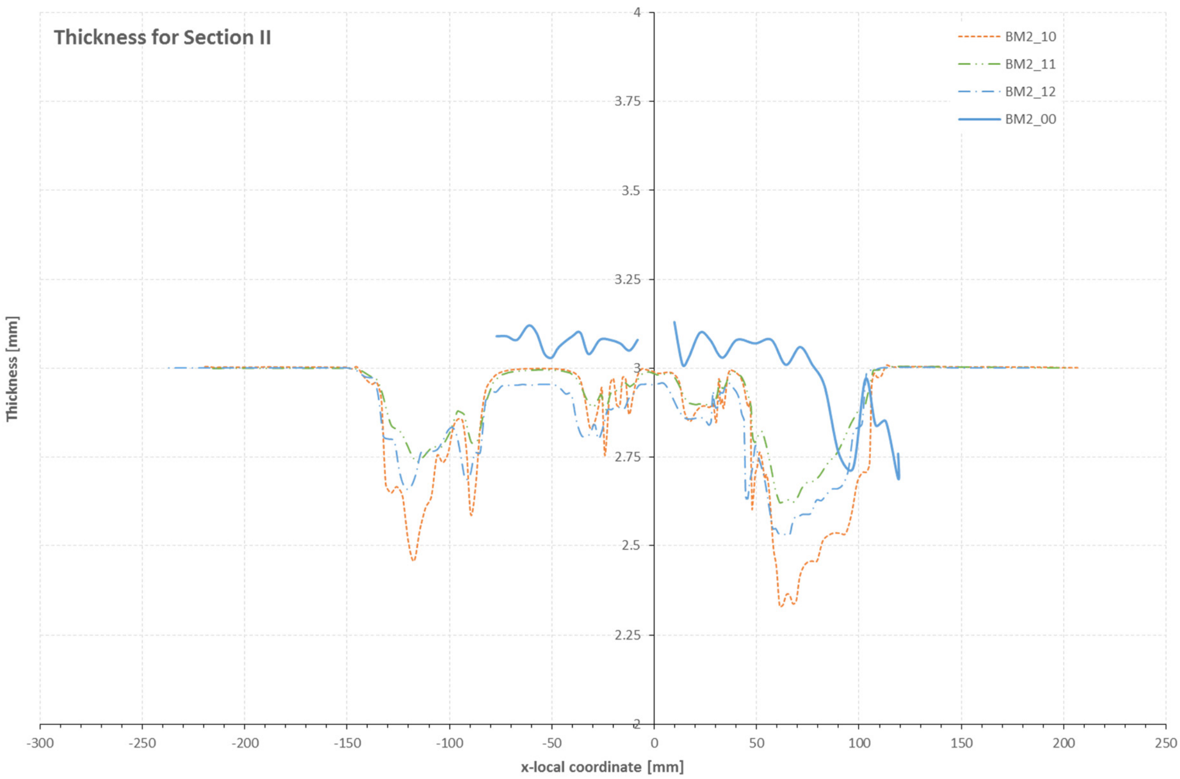


Figure 6.28. Thickness for Section II: BM2_10, BM2_11, BM2_12.

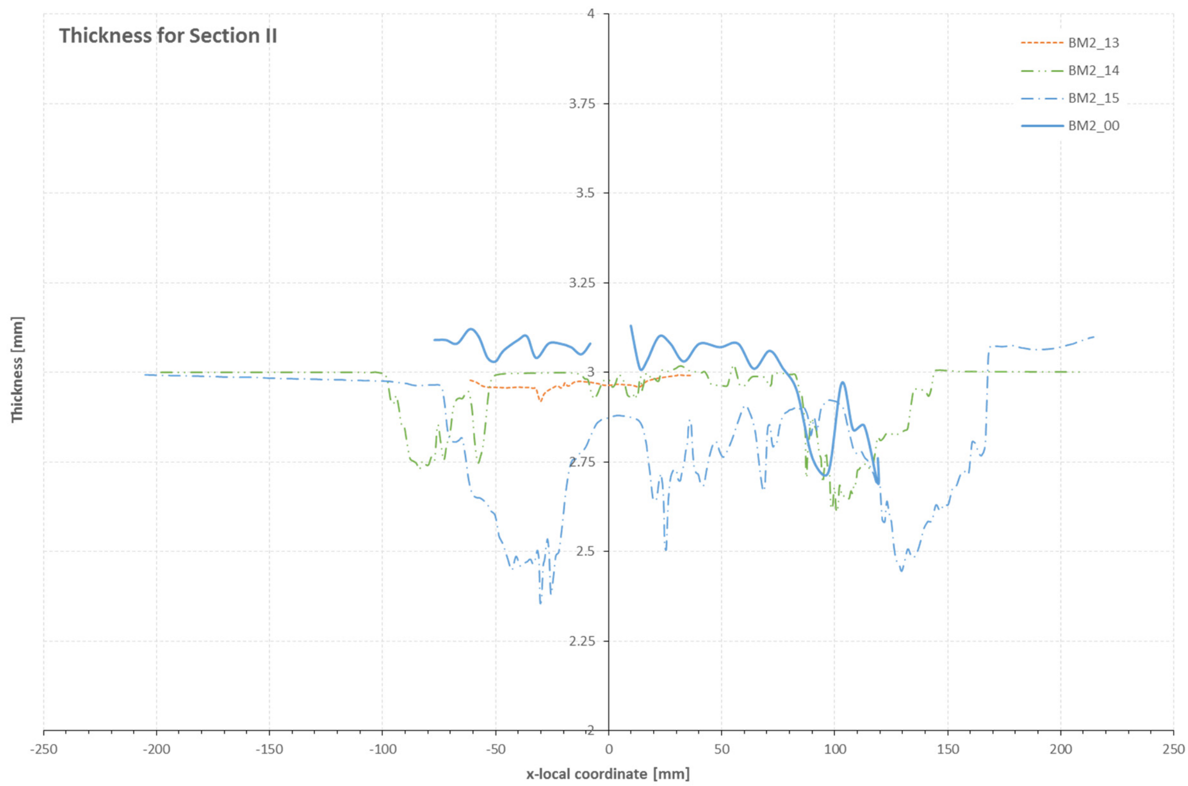


Figure 6.29. Thickness for Section II: BM2_13, BM2_14, BM2_15.

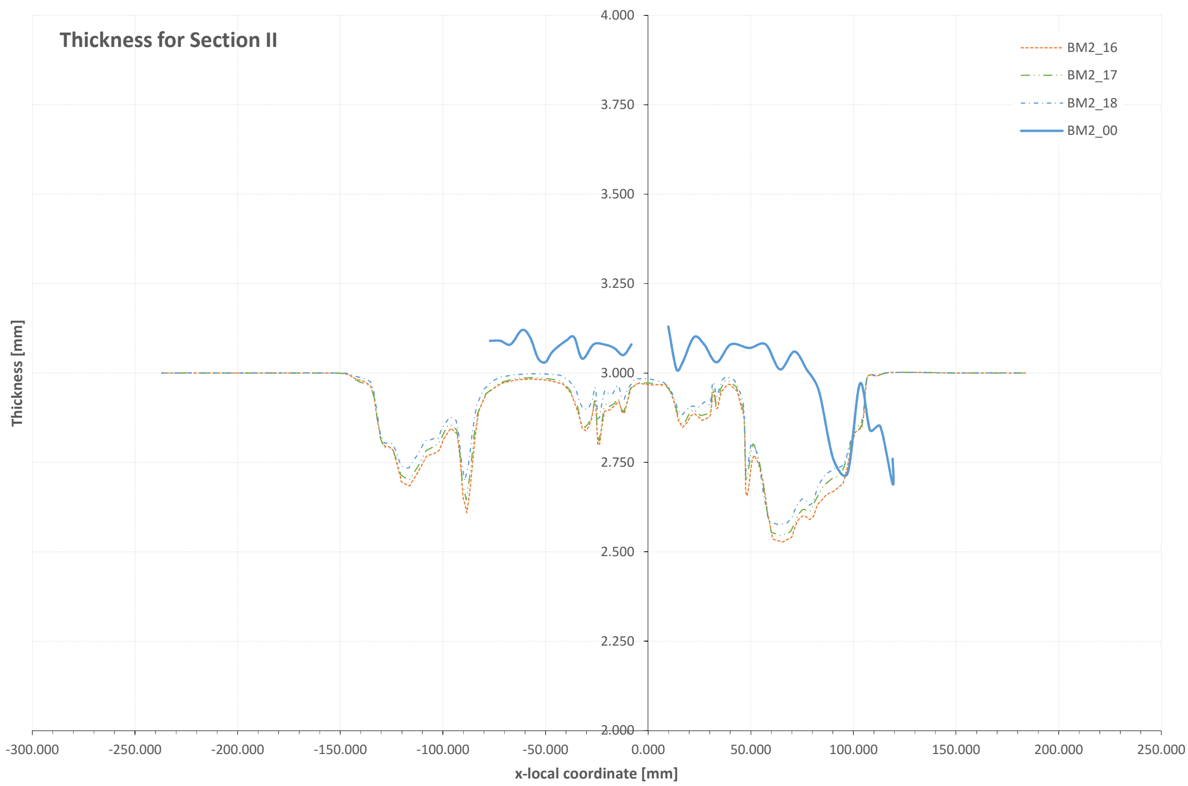


Figure 6.30. Thickness for Section II: BM2_16, BM2_17, BM2_18.

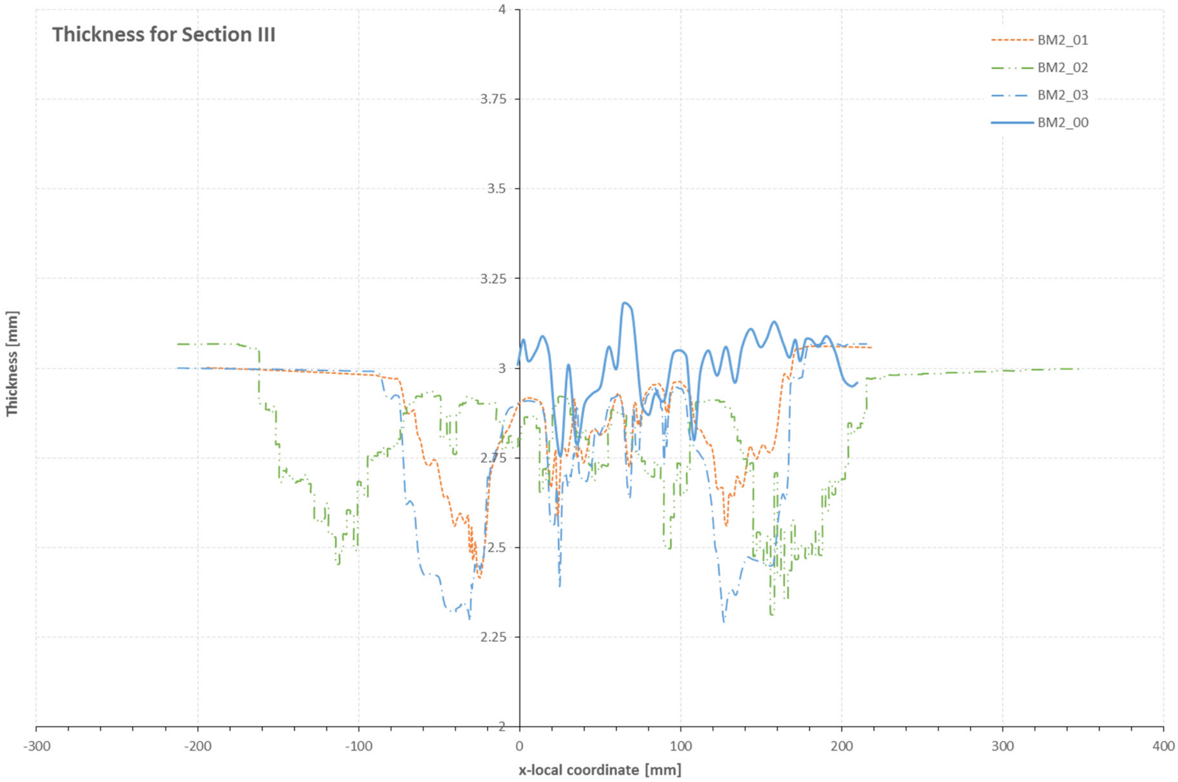


Figure 6.31. Thickness for Section III: BM2_01, BM2_02, BM2_03.

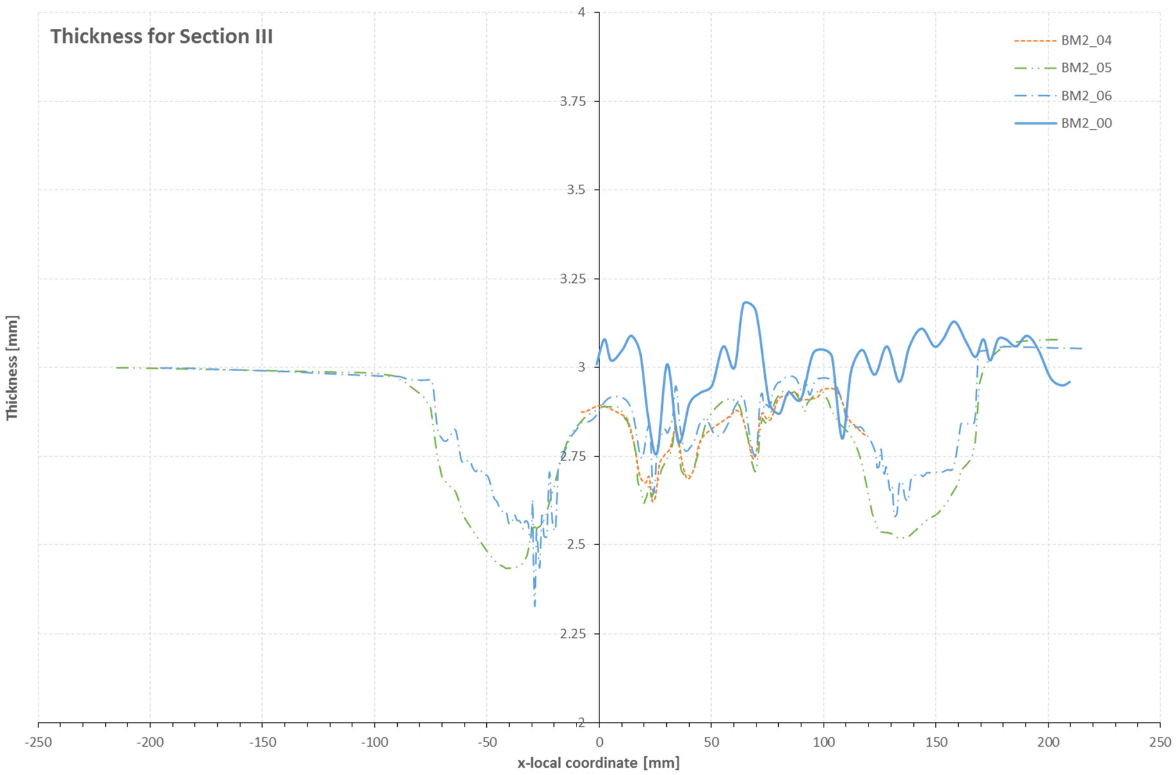


Figure 6.32. Thickness for Section III: BM2_04, BM2_05, BM2_06.

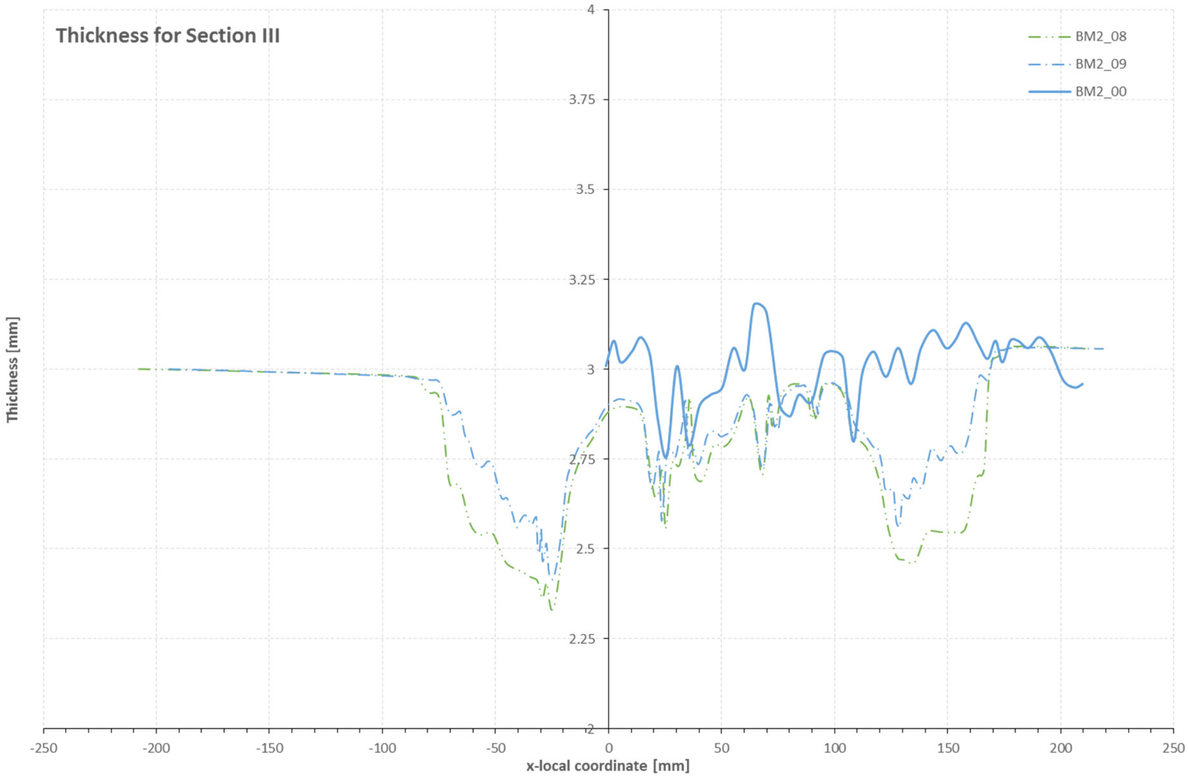


Figure 6.33. Thickness for Section III: BM2_08, BM2_09.

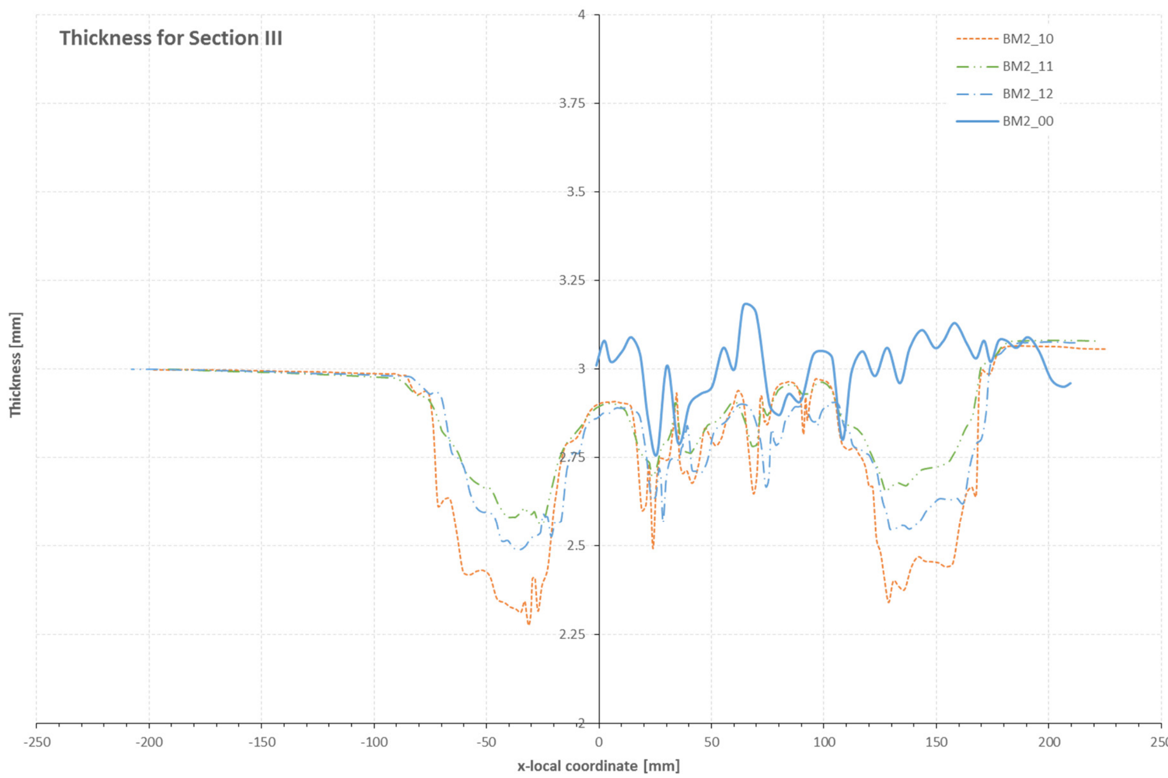


Figure 6.34. Thickness for Section III: BM2_10, BM2_11, BM2_12.

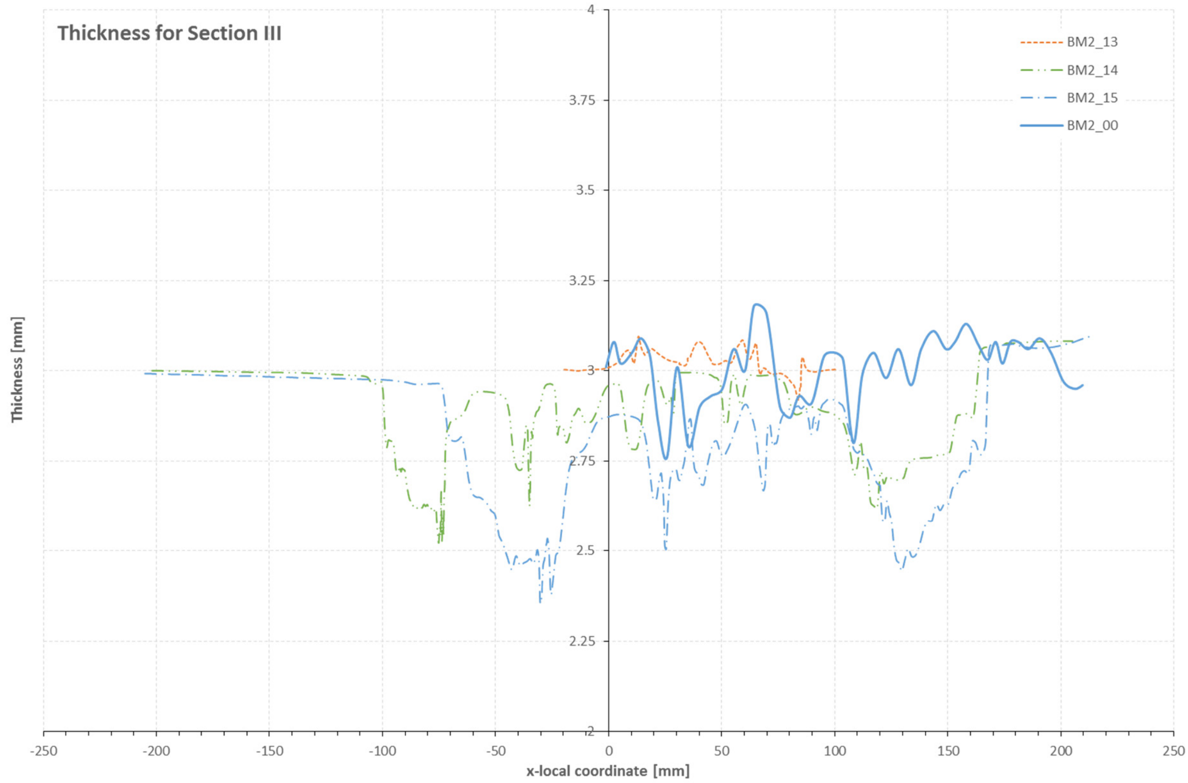


Figure 6.35. Thickness for Section III: BM2_13, BM2_14, BM2_15.

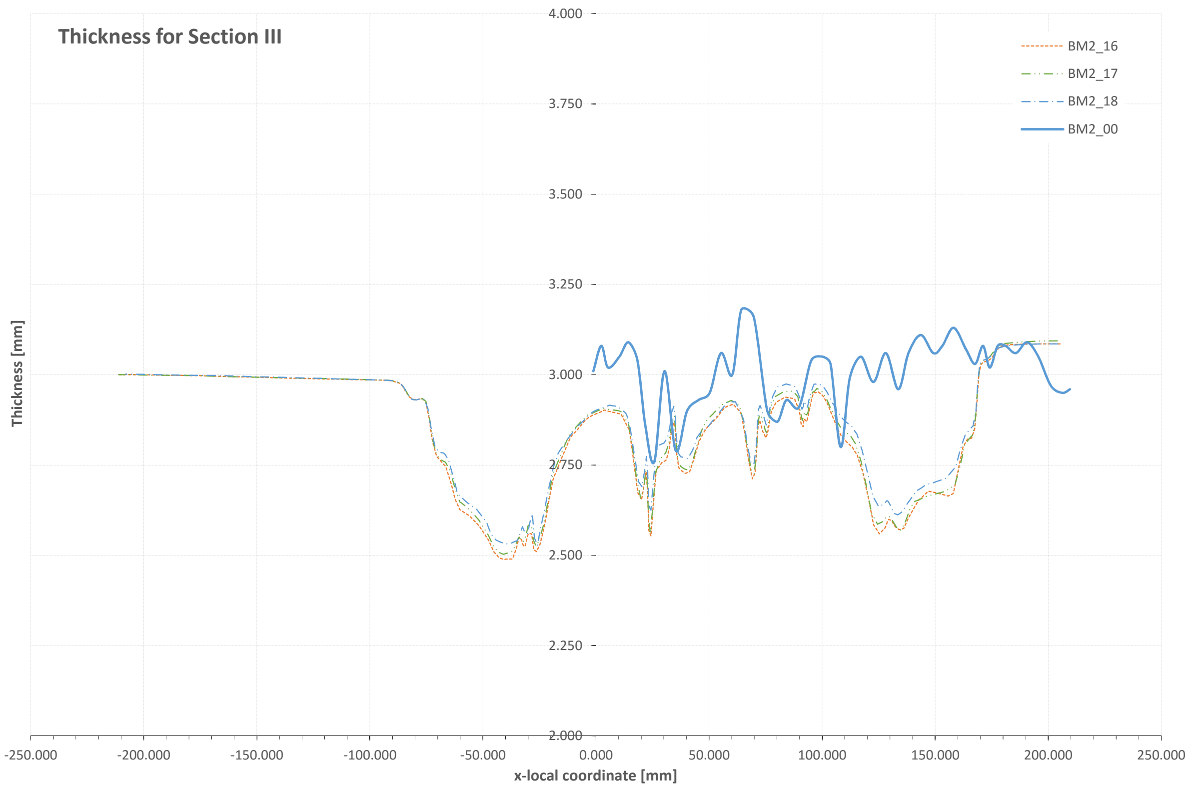


Figure 6.36. Thickness for Section III: BM2_16, BM2_17, BM2_18.

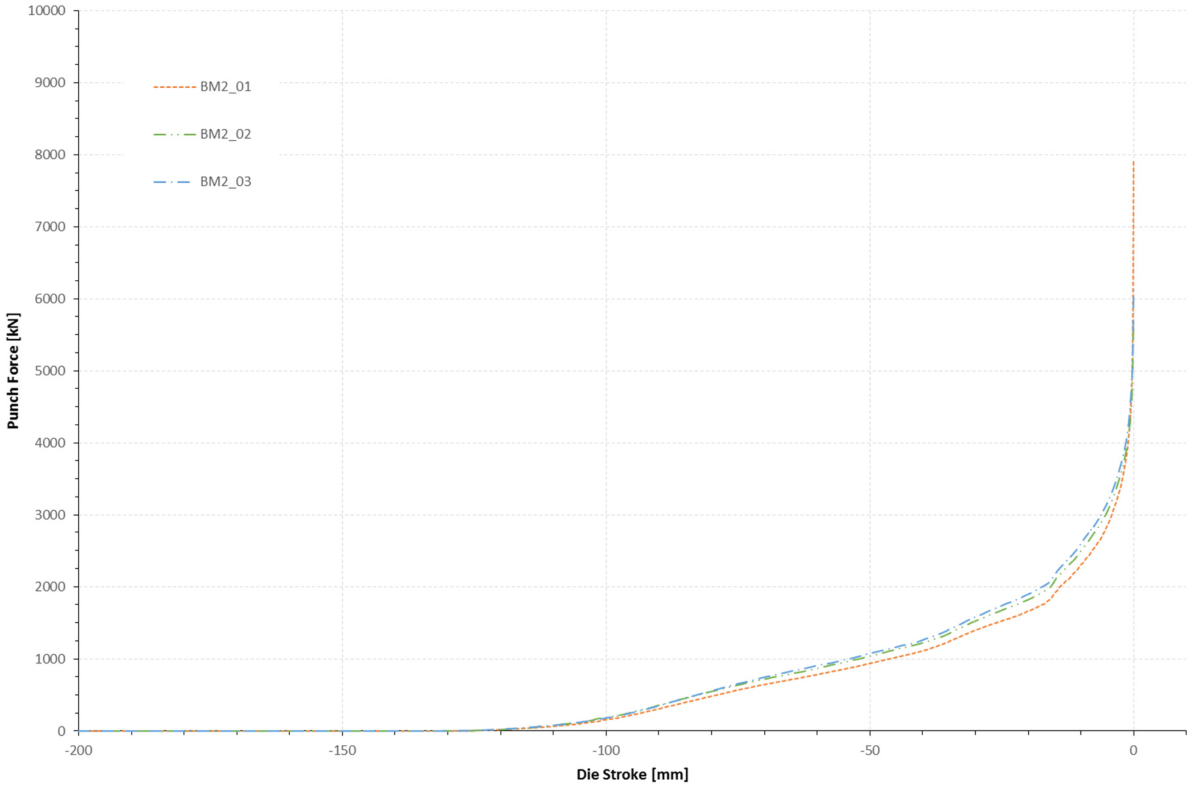


Figure 6.37. Punch Force: BM2_01, BM2_02, BM2_03.

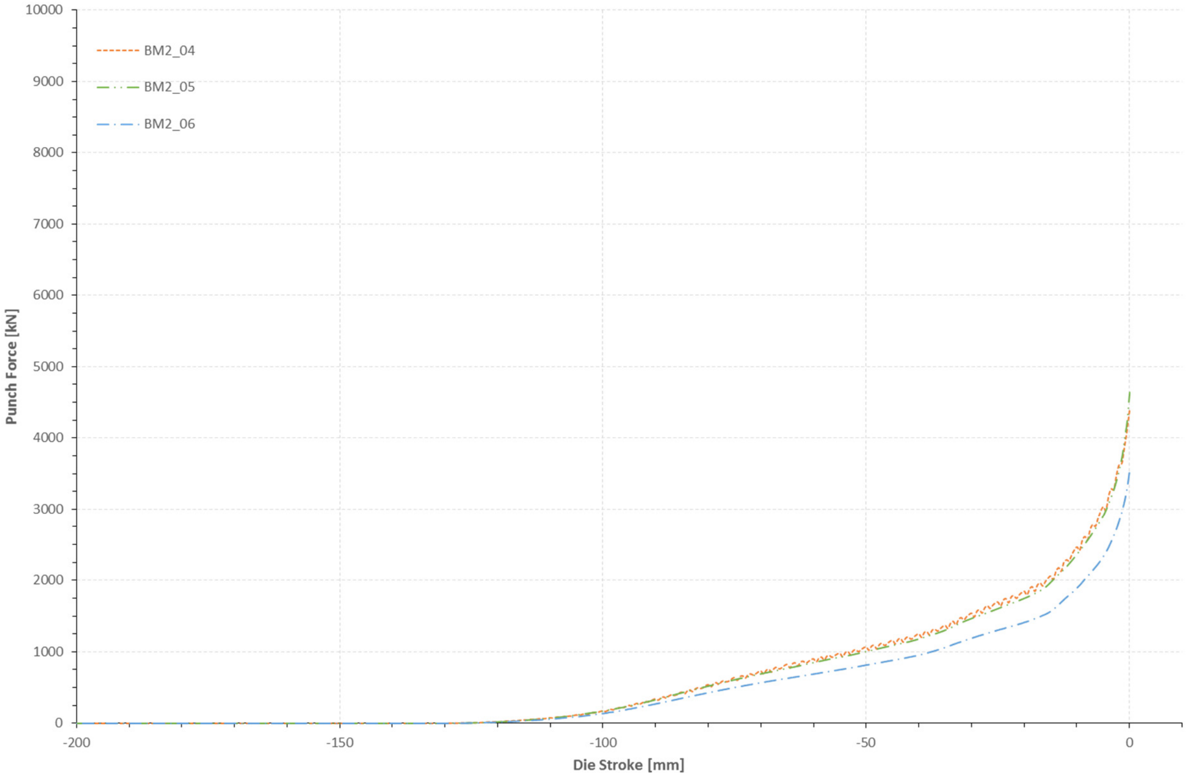


Figure 6.38. Punch Force: BM2_04, BM2_05, BM2_06.

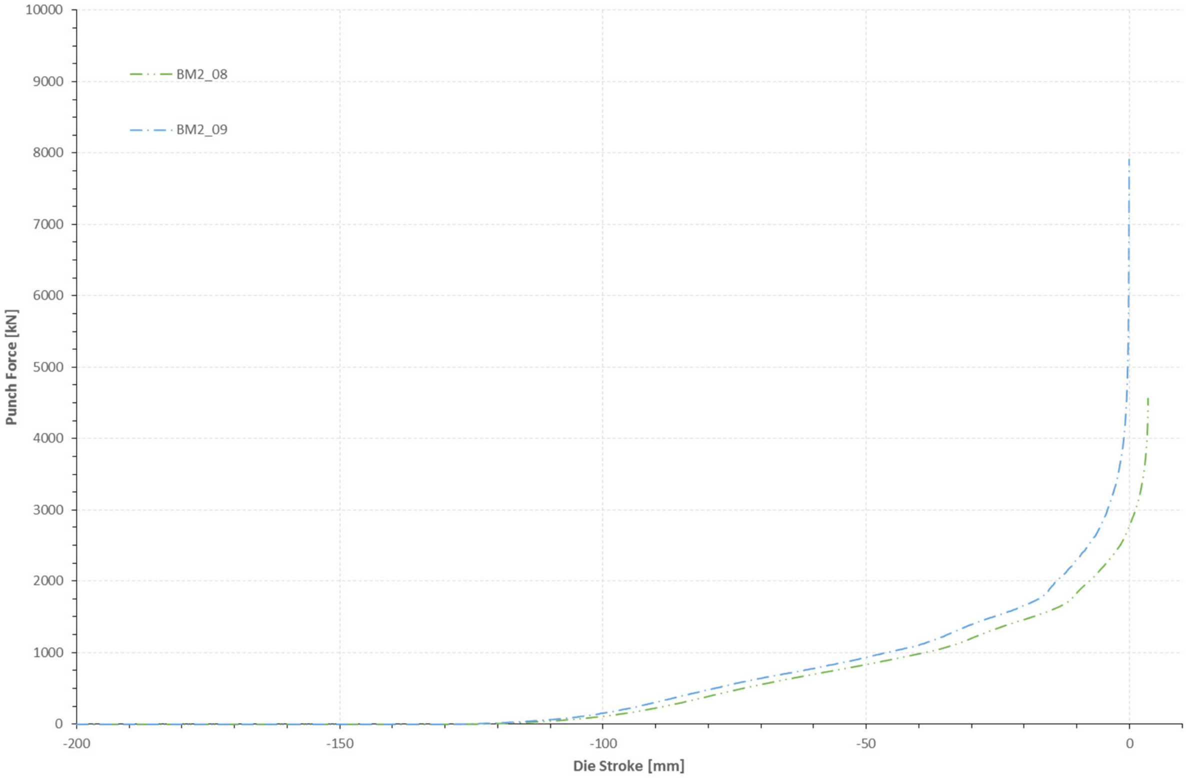


Figure 6.39. Punch Force: BM2_08, BM2_09.

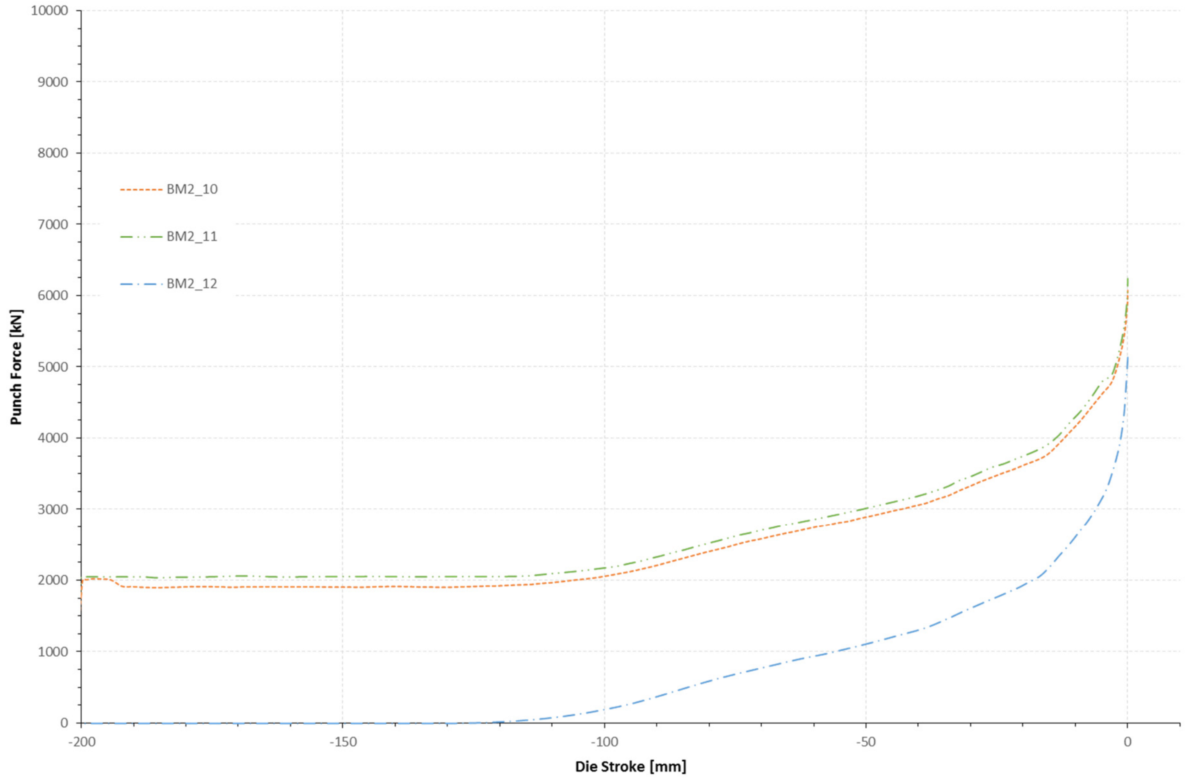


Figure 6.40. Punch Force: BM2_10, BM2_11, BM2_12.

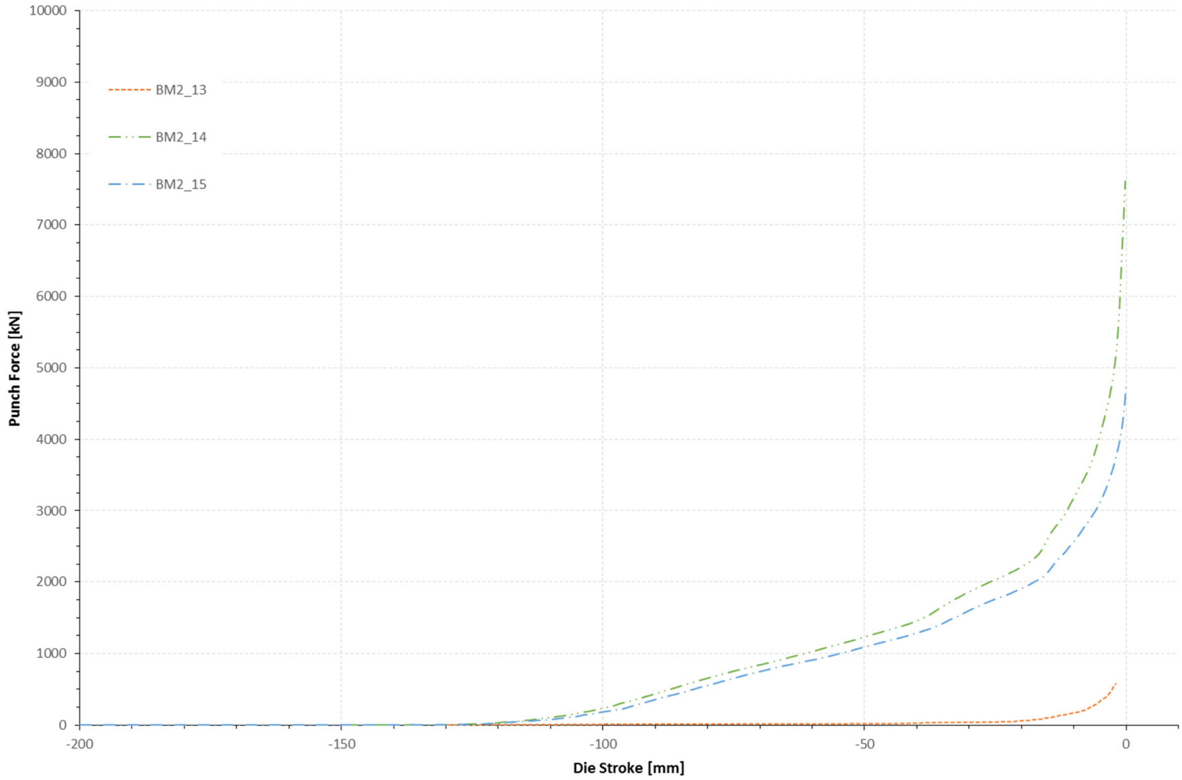


Figure 6.41. Punch Force: BM2_13, BM2_14, BM2_15.

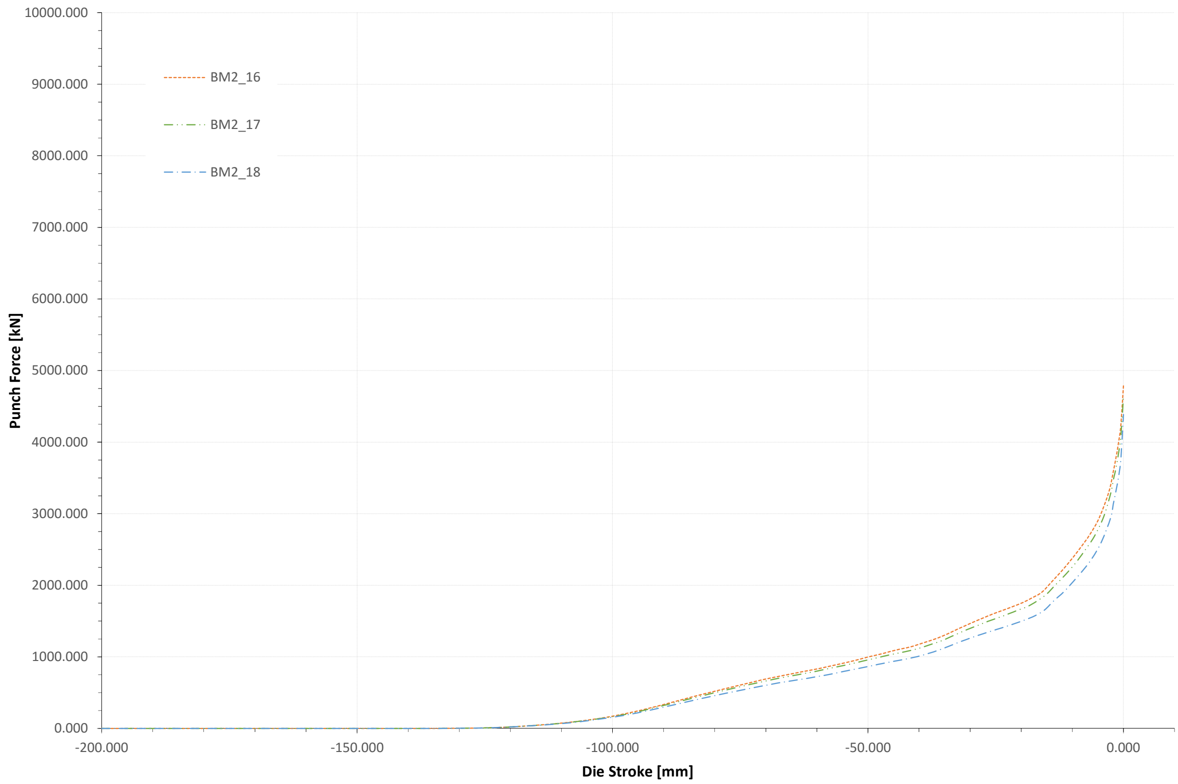


Figure 6.42. Punch Force: BM2_16, BM2_17, BM2_18.