SIMULATION OF SPHERICAL SHAPED SURFACES, PRODUCED BY PEEN FORMING WITH POINTED BALL SHOOTING AT LOWER COVERAGES

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ABSTRACT

The effect of compressive residual stresses in the surface layers of a workpiece induced by shot peening is used to create a definite shape of workpiece by the process of peen forming. Informations about all parameter concerning the forming process are a supposition of reproducable manufacturing.

The shape of workpiece especially depends on the input value of workpiece-parameters (like size and material characteristics) and peening-parameters (like number, sequence and shape of indentations). Based on the investigations by CLAUSEN and MARTIN [5, 6] first new formulas has been developed, characterizing relations between depth and diameter of indentations (h_E, d_E) and the process-parameters.

Using the results mentioned above, a mathematical model to predestinate the shape of sheet metal workpieces with constant thickness and coverages (< 20 %), dependent on peening- and workpiece-parameters, has been built up. It is based on a set of equations using the statement of quadric surfaces.

KEYWORDS

peen forming, ball shot forming, shape of indentations, mathematical model.

INTRODUCTION

Within the aircraft industries the use of peen forming is well-known because of its advantages at the production of curvatures on sheet metals for wings and cells. Thereby the process of manufacturing is controlled according to the different shapes, thicknesses, recesses and stringers.

In the past more than once has been reported about the possibilities to produce definite shapes of workpieces /e.g. 1 to 8/. This also was the subject at the earlier International Conferences on Shot Peening. It is known, that for a reproducable fabrication of curvatures especially the peening intensity and the guide of shot flow are of great importance.

The peening intensity of a peen forming process using balls as shot medium can be influenced by the ball velocity, the ball diameter, the ball material and hardness, as well as the coverage (processing time, shot flow). Above all, the guide of shot flow influences, the momentary shape of workpiece with its influence on the resulting final shape. Remarkable is the possible relation between the guide of shot flow and the peening intensity by partial or total overlay of peened traces (enlargement of coverage).

That means, that for automatically working machines, apart from the guide of shot flow the peening intensity has to be determined before beginning the peen forming process as well.

PEEN FORMING BY POINTED BALL SHOOTING (BALL SHOT FORMING)

As for the usual technique of air blast peen forming, the shot medium (balls) is continually distributed on the surface of the workpiece by a nozzle. The workpiece is hit at each moment by several balls, whereby the resulting indentations in the spread due to the nozzle are statistically distributed. The dephts of indentations are of different size because of different kinetic energies of balls.

As for minor coverages (e.g. less than 50 %) there will be, apart from single indentations, still indentations at the surface of the workpiece which touch and thereby influence each other. That means, that these multiple indentations generate other local residual stresses and thereby other lokal strains than several single indentations, which don't touch each other.

The manufacturing of only low curved workpiece demands very low coverages. In these cases it seems to be convenient to leave the conventional peening process for choosing a technology without the disadvantages mentioned above. Such a technique has been developed, which allows to place balls of low tolerances in shape and diameter with defined energy pointed at the surfaces of the workpieces.

At the 3rd ICSP in Germany the authors presented a paper about "Peen Forming by pointed Ball Shooting" (we call it:"Ball-Shot Forming" and discussed the advantages of this process /8/.
The main advantages of this peen forming process are:

- In respect to the exact positioning of indentations can be produced any patterns, adapted to material, thickness, stringers and required curvature of workpiece. For example figure 1 illustrates the surface of a peen formed workpiece by pointed ball shooting.

- There are no collisions between balls before touching the surface of the workpiece. Due to this fact, there is no loss of energy. The ball speed of single balls is measurable and variable. So the kinetic energy of single balls can be varied too.

- Especially there are better conditions for basic research. The influence of the different peening parameters, particularly the coverage can be investigated in detail, so that the possibility of creating mathematical models to predestinate the shape of sheet metal workpiece increases.

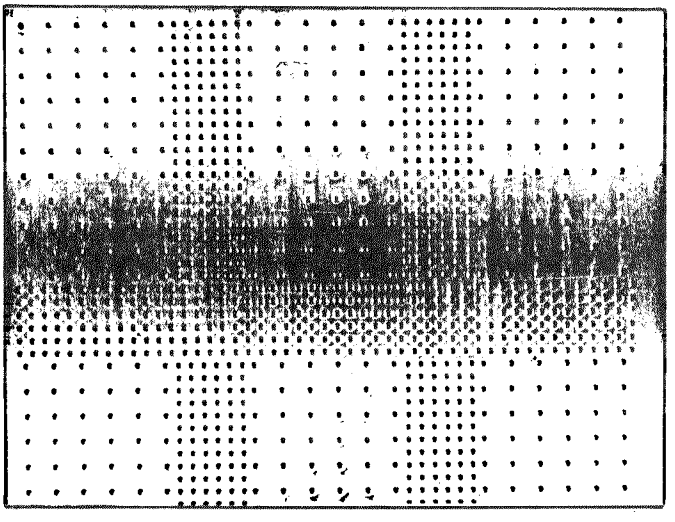


Fig. 1:

An example for exact positioning of balls (about ± 0,2 mm) at the surface of a workpiece by pointed ball shooting.

TEST RESULTS RELATING TO THE SHAPE OF THE BALL INDENTATION

Whereas the guide of shot flow has a considerable influence on the final shape of the workpiece at higher shot coverages (roughly > 30 %), the influence of the guide of shot flow is negligible with lower coverages [8]. From this it follows that for the production of slightly bent workpieces only the peening intensity is of importance. The latter is determined by the shape, the number, and the position of the ball indentation.

Therefore extensive investigations to determine the shape of the ball indentations in dependence on the different peening parameters were carried out first. When the difference in hardness between the ball and the workpiece material (for example steel balls and aluminium sheet metals) is very large, the shape of the indentation is sufficiently described by the depth h_E and the diameter d_E . In case of shooting flat sheet metals with balls the following influencing variables result:

- ball energy (ball velocity v_K , ball diameter d_K)
- ball material (hardness KH, density ρ)
- sheet metal material (hardness WH, structure)
- sheet metal workpiece (thickness s, surface roughness)
- state of the surface (dry, oily)
- way of coupling the workpiece

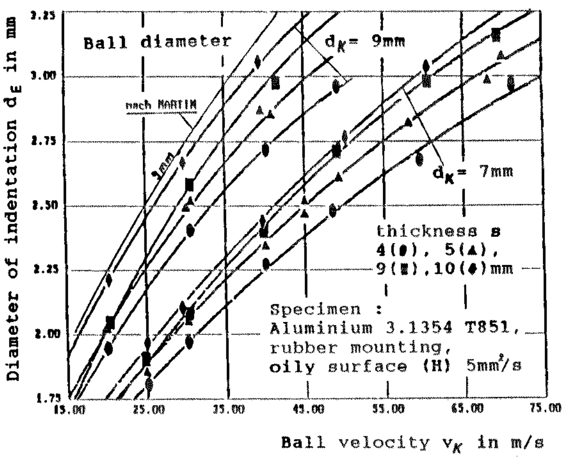


Fig. 2: Diameter of indentation in dependance on ball velocity and thickness of sheet metal specimen at different ball diameters

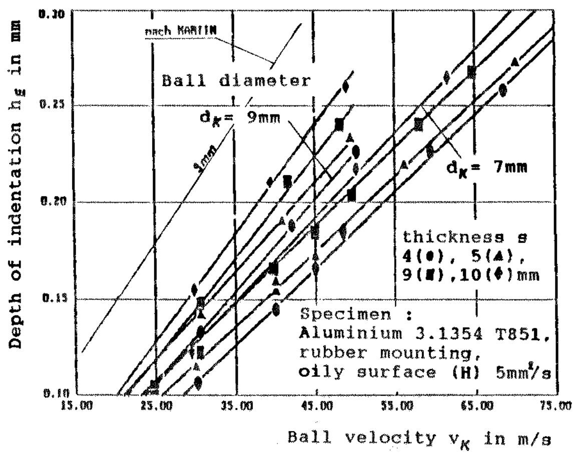


Fig. 3: Depth of indentation in dependence on ball velocity and thickness of sheet metal specimen at different ball diameters

The figures 2 to 5 represent several examples of the test results each in dependence of the ball velocity. Figure 2 clearly evidences the dependence of the indentation diameter on the thickness of the sheet metal by different ball diameters; figure 3 shows the respective results for the depth of the indentation. In figure 4 the influence of oily surfaces on the diameter of indentation becomes visible and figure 5 conveys the considerable dependence of the ball material on the dephts of indentation.
The figures 2 to 4 additionally show the course of the curves resulting from the mathematical equations established by Martin [5] in 1980. It becomes quite obvious that these mathematical models which only take into consideration the influence of the ball velocity, the ball diameter, and the hardness both of the ball and the material, do not offer any sufficient evidence to predestinate the shape of sheet metal workpieces. The reasons for this are mainly to be sought in the fact that the existing softness of the process system during ball shooting was not taken into consideration.

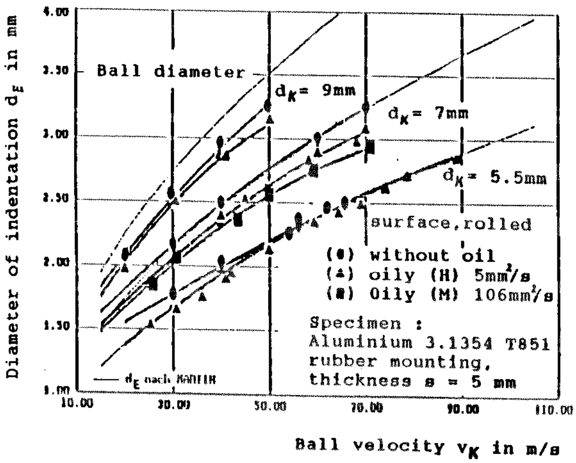


Fig. 4: Diameter of indentation in dependence on ball velocity and state of surface at different ball diameters

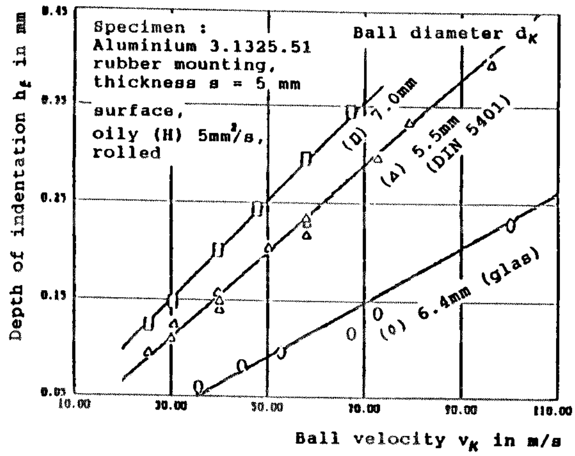


Fig. 5: Depth of indentation in dependence on ball velocity and the ball material

PREDETERMINATION ABOUT THE SHAPE OF BALL INDENTATION

The calculation of depth (h_E) and diameter (d_E) of indentation is based on the following common mathematical setup regarding to ball-velocities lower than 100 m/s and Aluminium wrought alloys as material of sheet metal:

$$h_E = H_1 * v_K + H_o \qquad\qquad d_E = D_1 * \sqrt{v_K} + D_o$$

The coefficients H_i and D_i consist of a combination between the peening parameters - hardness of balls (KH), hardness of sheet metal (WH), diameter of balls (d_K) (see MARTIN [5]) and additional

- density of balls (ϱ_K)
- thickness of sheet metal (s)
- state of the surface: dry, oily (ϑ)
  rolled (MSS=0) or milled (MSS=1)

(see section above).

The predetermination of the shape of indentation (by h_E, d_E) in dependence on the mainly influencing peening parameters mentioned above is realized using the following setup :

$$h_E = d_K * \sqrt[3]{\varrho_K^2} * f_{hs} * f_{h\vartheta} * f_{ho} * 0.002675 * KH/((KH+WH * f_{hw}) * \sqrt{WH * f_{hw}}) * v_K + 0.01296 * f_{hso} \quad [mm]$$

$$d_E = d_K * \varrho_K^{0.25} * f_{ds} * f_{d\vartheta} * (\sqrt{KH/WH * f_{dw}} * 0.005244 + 0.01935) * \sqrt{v_K} + 0.03832 \quad [mm]$$

The factors f... are built up empirically by linear, quadratic and cubic combinations with the influencing variables, for example:

$$f_{hs} = (-0.013175 * d_K^2 + 0.237215 * d_K - 0.765807) * (s-3.9)^{0.125} + (0.033748 * d_K^2 - 0.595002 * d_K + 3.043701)$$

$$f_{ds} = (0.002693 * d_K^3 - 0.07033 * d_K^2 + 0.615369 * d_K - 1.665163) * (s-3.95)^{0.1667} + (0.00955 * d_K^2 - 0.19187 * d_K + 1.71762)$$

By using statistical methods (correlation coefficient

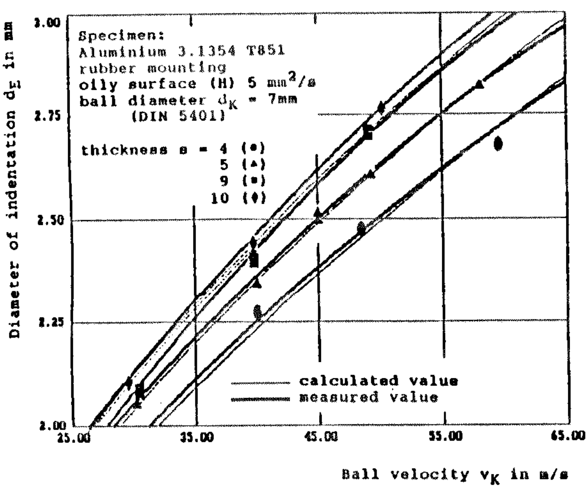
$$R = \sqrt{1 - \Sigma(y_i - \hat{y}_i)^2 / \Sigma(y_i - \bar{y})^2}$$

(one independent variable)
with y_i = measured values
$\hat{y}_i$ = calculated values
$\bar{y}$ = average of meas. value

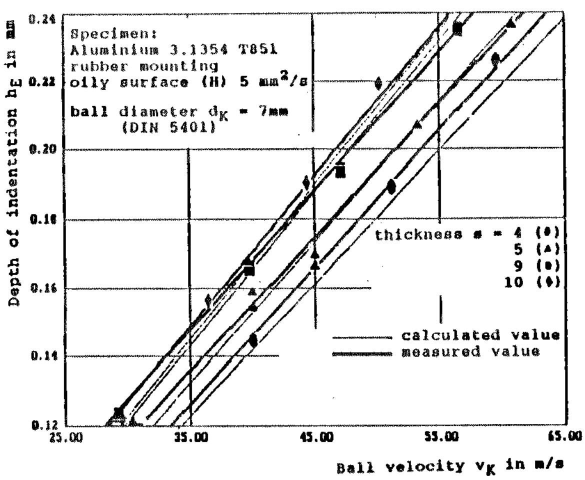
and multiple correlation coefficient (more independent variables)) relations were built up considering the requirement of confirmity $0.95 < R < 1$.

For example, some results of calculated values (d_E, h_E in dependence on ball-velocity) will be presented in Fig. 6 to 10.

Fig. 6 presents the dependence of indentation diameters on the thickness of sheet metal. Fig. 7 shows the respective results for the depth of indentation. In Fig. 8 the influence of oily surfaces on the diameter of indentation by different ball diameters becomes visible. Fig. 9 shows the dependence of indentation diameters on different ball diameters by various materials of sheet metal and fig. 10 presents the respective results for the depth of indentation.



<u>Fig. 6:</u> Influence of ball-velocity and thickness of sheet metal on indentation diameter



<u>Fig. 7:</u> Influence of ball-velocity and thickness of sheet metal on the depth of indentation

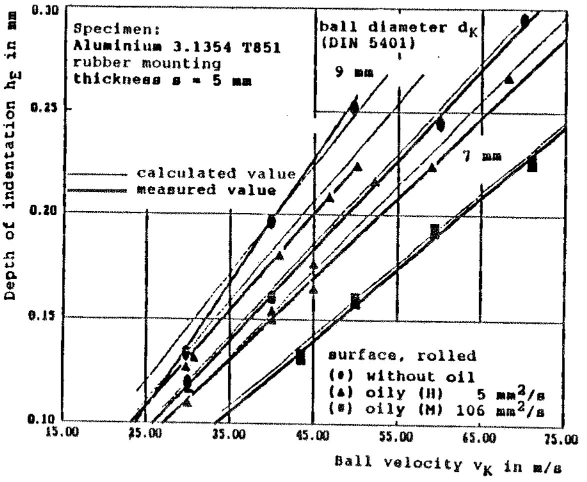


Fig. 8: Influence of ball-velocity, oily surfaces and different ball diameters on the depth of indentation

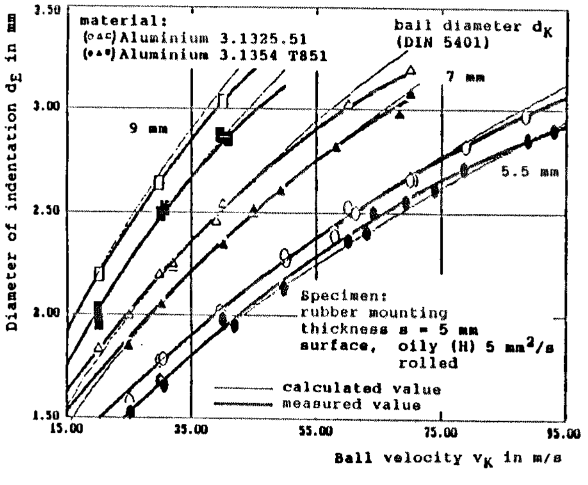


Fig. 9: Influence of ball-velocity, ball diameters and sheet metal material on the diameter of indentation

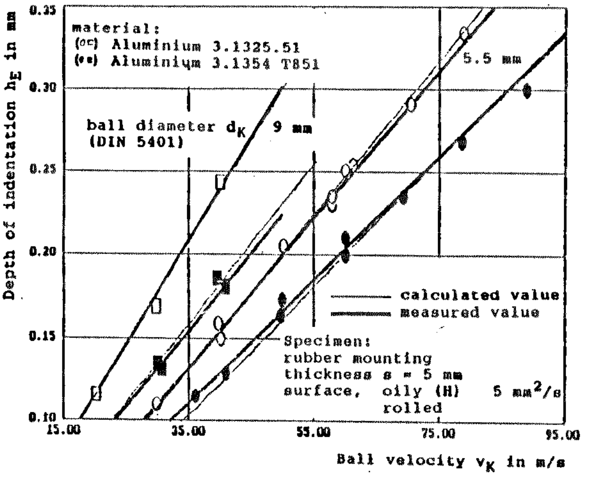


Fig. 10: Influence of ball-velocity, ball diameters and sheet metal material on the depth of indentation

PREDETERMINATION OF SPHERICAL FORMING IN PEENING SHEET METAL

During the investigations regarding the shape of indentations mentioned above, the final shape of every specimen was measured in dependence on several peening parameters. Therefore a database of nearly 80.000 measurement points was available.

Before starting analyzation, a common base layer for all specimens has been generated by calibrating distance data regarding to the theoretical mounting surface of each peened specimen.

Then, a mathematical setup of approximation has to be found on the premises of a practical and useful number of coefficients, like a setup out of the group of quadratic surfaces. The setup of "elliptic-parabolic surfaces" within eight coefficients (shape and location) offered best results.

By the use of the "method of least sqares" an absolute error rate lower than 3% due to the "elliptic-parabolic" approximation of measured data could be obtained for all specimens with coverages lower than 20 %.

The relations between the coefficients of each approximated specimen an the accompanying peening parameters like:

- depth of indentation (h_E)
- diameter of indentation (d_E)
- peened surface (A')
- difference of not-peened area and peened area (NPA)
- distance between indentations (l_x, l_z)
- sheet metal material (MAT)
- thickness of workpiece (s)
- mechanical state of surface (rolled, milled) (MSS)

have to be investigated in use of the methods of "multiple regression". The corresponding setup equations are based on linear, quadratic and cubic types.

Hence, the following system of equations was developped for symmetrical peened sheet metal out of Aluminium wrought alloys:

$$
\begin{aligned}
a &= F_1 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
b &= F_2 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
x_o &= F_3 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
y_o &= F_4 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
z_o &= F_5 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
w_1 &= F_6 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
w_2 &= F_7 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)\\
w_3 &= F_8 (h_E, d_E, A', NPA, [lx, lz], MAT, s, MSS)
\end{aligned}
$$

a,b = coefficients of shape

$x_o, y_o, z_o, w_1, w_2, w_3$ = coefficients of location

Fig. 11 presents the comparison between the measured surface of a peened specimen (choosen example) and the corresponding calculated surface. The important peening parameters are shown in the following list:

- sheet metal material:	Aluminium 3.1354 T851
- thickness of workpiece s:	5 mm
- mechanical state of surface MSS:	rolled
- Hardness of workpiece WH:	147 HV
- peened area A':	240*240 mm
- difference of not-peened area and peened area:	(280*280) - (240*240) mm
- distance between indentations l_x, l_z:	10*10 mm
- rubber mounted	
- depth of indentation h_E:	0.30 mm
- diameter of indentation d_E:	2.75 mm
- ball velocity v_K:	80 m/s
- ball diameter d_K:	5.5 mm (DIN 5401)
- ball hardness KH:	900 HV

Fig. 12 graphically shows the difference between calculated and measured surfaces out of Fig. 11. (Total flat layers represent an absolute error of zero).

Fig. 13 shows an abstract out of a listing, discribing the distance between the common base layer (origin rectangular) and the real peened specimen surface (Zmeas.) as well as the distance of the calculated surface (Zcalc) in each measurement point (Measpt.). The shown numerical data are corresponding to Fig. 11 and 12. The averaging relative error in this example is < 1.8 %. Furthermore the coefficients of the approximation are presented.

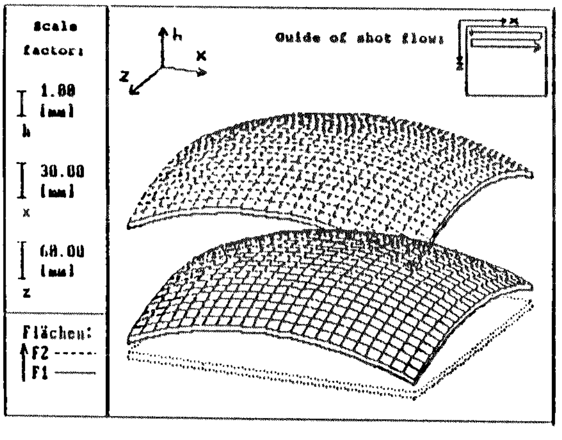


Fig. 11: Comparison between calculated and measured surfaces.

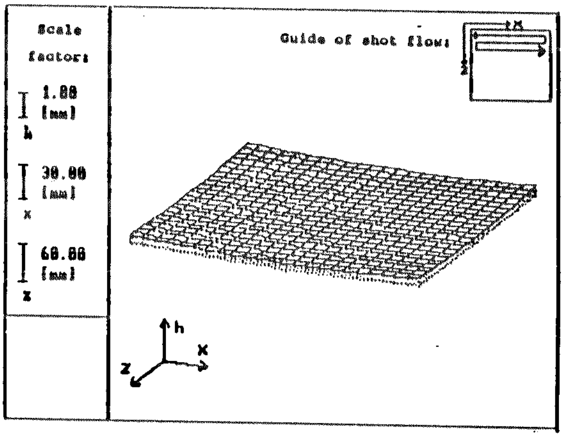


Fig. 12: Graphical difference between calc. and meas. surfaces out of Fig. 11.

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Measpt.= 17,19   Zcalc= 2.593   Zmeas.= 2.534   Zdiff= -0.059 [mm]
Measpt.= 17,20   Zcalc= 2.439   Zmeas.= 2.394   Zdiff= -0.045 [mm]
Measpt.= 17,21   Zcalc= 2.263   Zmeas.= 2.229   Zdiff= -0.034 [mm]
Measpt.= 17,22   Zcalc= 2.066   Zmeas.= 2.047   Zdiff= -0.019 [mm]
Measpt.= 17,23   Zcalc= 1.846   Zmeas.= 1.838   Zdiff= -0.008 [mm]
Measpt.= 17,24   Zcalc= 1.604   Zmeas.= 1.605   Zdiff= 0.001 [mm]
Measpt.= 18, 1   Zcalc= 1.505   Zmeas.= 1.503   Zdiff= -0.003 [mm]
Measpt.= 18, 2   Zcalc= 1.747   Zmeas.= 1.741   Zdiff= -0.006 [mm]
Measpt.= 18, 3   Zcalc= 1.967   Zmeas.= 1.940   Zdiff= -0.027 [mm]
Measpt.= 18, 4   Zcalc= 2.164   Zmeas.= 2.129   Zdiff= -0.036 [mm]
Measpt.= 18, 5   Zcalc= 2.340   Zmeas.= 2.289   Zdiff= -0.051 [mm]

de = 2.750        he = 0.300   [mm]

COEFFICIENTS:

a  = 95.419          b = 101.000                            [mm]
Zo = 3.2600          Xo = 115.0000     Yo = 115.0000        [mm]
w1 = -0.00010000     w2 = 0.00000011   w3 = 0.00000001      [rad]

Averaging absolute Error = 0.0581  [mm]

Identification of specimen:  S487-0-1
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Fig. 13: Partly numerical listing of corresponding distance data (Fig.11).

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