A New Procedure for the Determination of the Main Technology Parameters of Rolling Mills

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A. Öchsner et al. (eds.), *Design and Analysis of Materials and Engineering Structures*,
Advanced Structured Materials 32, DOI: 10.1007/978-3-642-32295-2_2,

Abstract Nowadays, approximately 90–95 % of metals are processed by cold rolling. There has been a substantial increase in demand for utility properties as well as for reducing production costs. These objectives cannot be achieved without a high degree of automation, control and monitoring throughout the manufacturing process. These qualitative changes require rather deep and comprehensive theoretical and metallurgical–technological knowledge of operators in the field of design, research and production of rolled steel sheets, which is needed for further development in rolling steel. A continuous quality control of material and surface during the rolling process is a part of these tasks and is associated with providing the full automation of rolling mills. Starting from theoretical foundations, we have developed a new procedure for the determination of main technology parameters of a rolling mill. The main difference between our proposal and current methods of calculation is as follows. Our proposal is based on the knowledge of deformation properties of materials and continuous processes of stress-deformation state and on the knowledge of reductions in different stages of rolling. Current procedures are on the contrary based on static calculations using the geometry of the system—working roll and instantaneous sheet metal thickness in a gap between the rollers. In doing so, the calculations almost ignore the real stress—deformation properties of rolled metal sheets, optimal transmission rate of deformation in the material at the given speeds of rollers and the given main rolling force. We are concerned with the optimum balanced system: main rolling force—rolling speeds, or transmission rate of deformation in the material. This procedure allows us to achieve a significant increase in operational performance as well as in rolling process quality.

1 Introduction

Rolling means a continuous process in the course of which the material being formed deforms between the working rolls under conditions of prevailing all-around pressure. The material being rolled deforms between the rolls, the height decreases, the material elongates and simultaneously widens, and also the speed at which the material being rolled leaves the rolling mill changes [5].

Continuous cold rolling is an important process in the metallurgical industry. Its performance influences directly the quality of a final product. This process is a very complicated system, including many multidisciplines, such as: computing technique, automatic control, mechanics, material engineering, and others. Any correctly designed recovery of the system may bring a large financial gain, consisting in an increase in performance, quality and overall business competitiveness, to a company [1, 2, 3, 4].

The goal of metal cold rolling process is to manufacture very high quality flat rolled products from metals, where the high quality means that the final product has the required geometry, including sheet flatness [6, 7, 8]. The issue of longitudinal cold rolling and its influence on the topography of surface of rolled sheets

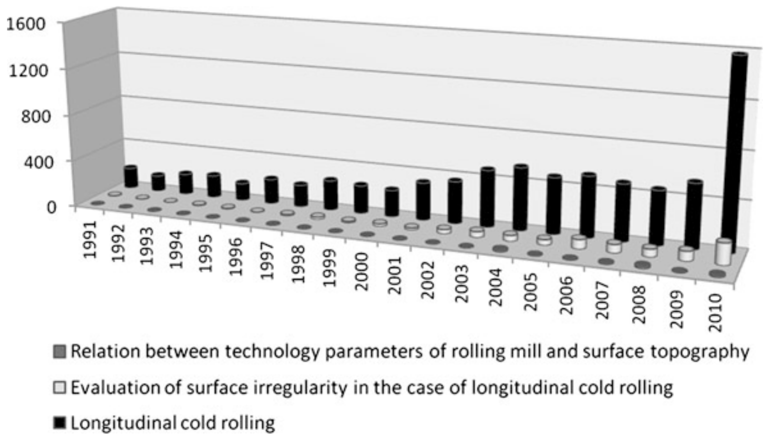

Fig. 1 Overview of world literature in the SCIRUS database

is graphically represented in Fig. 1. It shows this issue dealt with in the world literature in the course of last 20 years with a view to presenting the numbers of publications in individual study areas. Research into the area of relations between technology parameters of the rolling mill and the topography is done very rarely owing to comprehensive complexity of solving.

2 Experimental Procedure

Low carbon steel of type PN EN 10263-2:2004 with the Young's modulus $E_{mat} = 126$ GPa and the yield strength of 310 MPa was chosen as an initial material for the realization of experiments. The chemical composition is given in Table 1. Deep drawing quality steel of U.S.Steel Košice, Ltd. production of type KOHAL 697 with the Young's modulus $E_{mat} = 186.7$ GPa and the yield strength of 390 MPa was chosen as the second material being used in experiments. Its chemical composition is given in Table 2.

Chemical analysis was performed by a glow discharge optical emission spectrometer LECO GDS 750.

The material investigation consisted of the metallographic analysis. The metallographic analysis of the samples were done perpendicularly to the longitudinal axis of the samples. For a visual observation of the samples there was used the inverted microscope for transmitted light GX51 with the maximum magnification of 1000x. Figure 2 shows an example of the microstructure of low carbon steel of type PN EN 10263-2:2004.

The analysis of micro purity does not show any significant contamination by non-metallic additives. There were observed globular-oxide-type inclusions. The microstructure of deep-drawing steel consists of ferrite, pearlite and cementite

Table 1 Chemical composition of the used low carbon steel PN EN 10263-2:2004

Fe	C	Mn	Si
99.620	0.0228	0.1928	0.0117
P	S	Cr	V
0.0081	0.0053	0.0209	0.0018
Cu	Al	Co	As
0.0275	0.0562	0.0075	0.0047

Table 2 Chemical composition of the used deep-drawing steel of type KOHAL 697

Fe	C	Mn	Si
99.5327	0.037	0.251	0.007
P	S	Al	N_2
0.007	0.007	0.051	0.0031
Cu	Ni	Cr	As
0.021	0.009	0.014	0.001
Ti	V	Nb	Mo
0.001	0.001	0.002	0.002

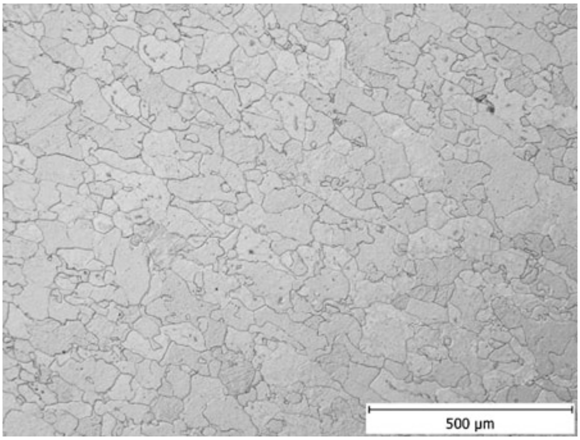

Fig. 2 Microstructure of low carbon steel

(Fig. 3). A ferritic grain is polyedric, equally distributed in cross-sectional area of the investigated material.

In contrast to the existing methods, the final condition of rolled sheet surface topography was taken as an initial input parameter for solving. It is above all the final roughness of sheet surface in relation to the main technology parameters, namely the rolling force F_{roll}, rolling speed v_{roll}, reduction Δh and in relation to sheet materials. Low carbon steel sheets and deep-drawing steel sheets produced by longitudinal cold rolling were measured using an optical profilometer Micro-Prof FRT. Samples were placed on a scanning table and an area of about 5×5 mm^2 size (Fig. 4) was scanned by a fixed sensor at a step of 3 μm and a frequency of 1 kHz. In this way, data on the studied surface topography were

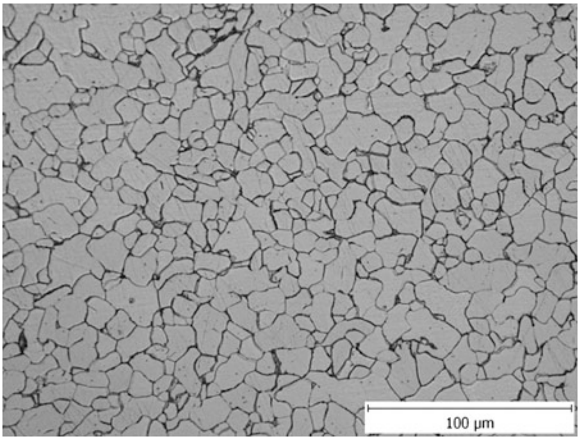

Fig. 3 Microstructure of deep-drawing steel

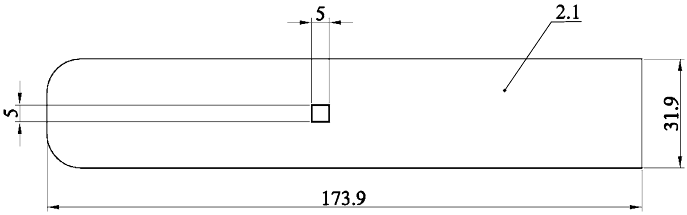

Fig. 4 Diagram of sample 1C with 0.4 mm reduction and delimited 5 × 5 mm^2 measured area

acquired. By the optical profilometer, the 3D topography of surface of measured areas was obtained.

Information on surface irregularities produced by longitudinal cold rolling for individual reductions Δh, i.e. the mean arithmetic deviation of surface profile Ra, root mean square deviation of profile Rq and the maximum height of profile irregularity Rz, is given in Table 3.

On the basis of data acquired from low carbon steel and deep-drawing steel, a graph in Fig. 5 was constructed. It shows that the quality of surface of low carbon steel sheets is higher (lower values of mean arithmetic deviation of surface profile Ra) than that of surface of deep-drawing steel sheets.

Surface roughness is expressed implicitly as follows: $Ra = \mathrm{f}\,(F_{roll}, Q_{Froll}, v_{roll}, n_{roll})$. It is necessary to look for relations between technology, material and resultant surface quality.

Using the program Gwyddion, measured areas of individual samples were analysed. Gwyddion is a modular program for analyzing scanning probe microscopy (SPM) data files. Gwyddion is free and open source software, covered by GNU General Public License. In the measured areas of 5 × 5 mm^2, ten equidistant measuring lines at a step 0.5 mm were there. The measuring lines were perpendicular to the direction of rolling. From each measuring line, a signal

Table 3 Relevant standardized parameters of surface texture evaluation for individual low carbon steel and deep-drawing steel samples

Samples from	Sheet designation	*Δh* (mm)	*Ra* (μm)	*Rq* (μm)	*Rz* (μm)
Low carbon steel	0A	–	0.71	0.97	7.42
	1A	0.4	0.37	0.52	3.39
	2A	0.5	0.43	0.56	3.77
	3A	0.6	0.21	0.28	2.05
	4A	0.8	0.12	0.17	1.60
Deep-drawing steel	0C	0	1.07	1.38	6.94
	1C	0.38	0.76	0.97	4.66
	2C	0.96	0.73	0.94	5.12
	3C	1.27	0.43	0.55	3.02
	4C	1.56	0.61	0.81	4.74
	5C	1.73	0.48	0.61	3.16

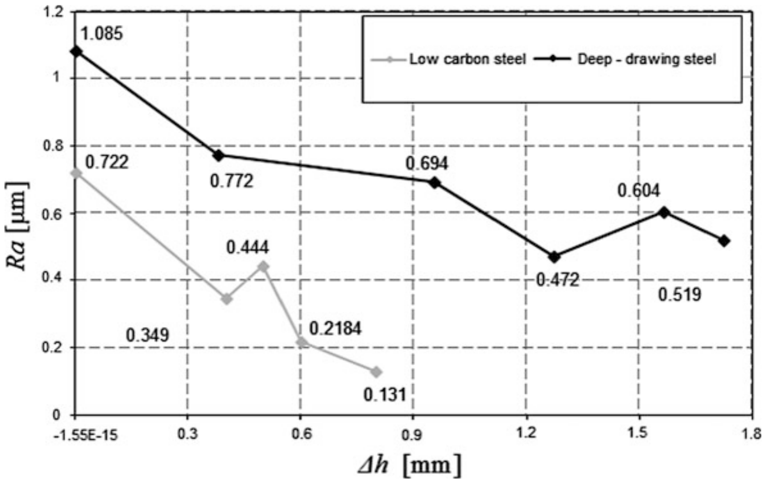

Fig. 5 Graphical representation of dependence of mean arithmetic deviation of surface profile on absolute reduction

carrying the information on the distribution of surface height fluctuations (*RMS*) was obtained (Fig. 6).

The rolling force of a rolling mill DUO 210Sva (testing stand) was already in the case of deep-drawing steel measured by metallic resistance tensometers (see Fig. 7) mounted on this mill in the course of rolling our sheets.

The rolling force was measured at a rolling speed of 0.7 m s^{-1} (see Fig. 8a) in the case of all deep-drawing steel sheets; the rolling force ranged from 67.9 to 145.1 kN. The greater is the used reduction, the higher is the rolling force and also the smoother is the surface of the given rolled product, as graphically represented in Fig. 8b.

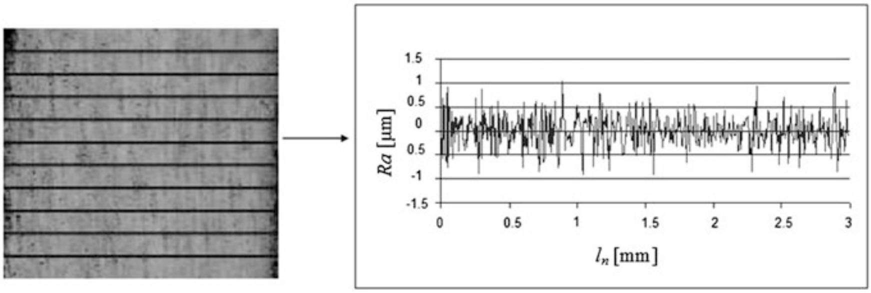

Fig. 6 Measured areas of sample with 0.6 mm reduction in ten equidistant lines (0.5 mm distance) from which signals representing surface irregularities were obtained

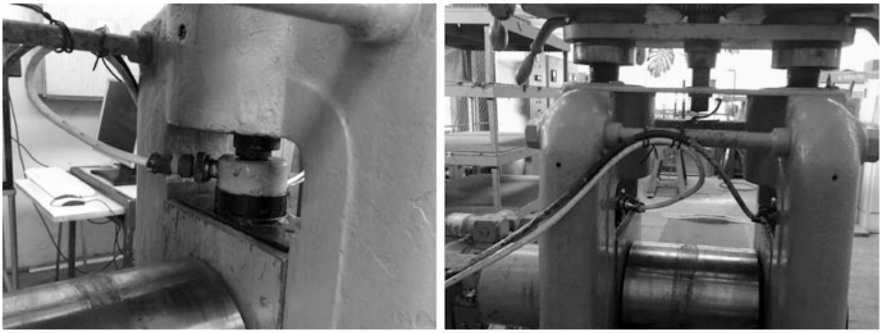

Fig. 7 Detail showing the location of tensometers on the rolling mill

In Fig. 8b a difference between the curve representing the dependence of rolling force on reduction for low carbon steel and the curve for deep-drawing steel is clear. This difference is given by different numbers of reductions and reduction values that were not identical for the low carbon and deep-drawing steels (see Table 4).

3 Analytical Processing

For a purpose of analytical processing and generalization, the authors have chosen the concept of regression and correlation analysis. In order to determine the main functions of rolling process there was measured a number of metallic materials with different mechanical parameters. As a reference parameter was chosen the modulus of elasticity and the material constant of plasticity K_{plmat} (1) used in previous works of the authors.

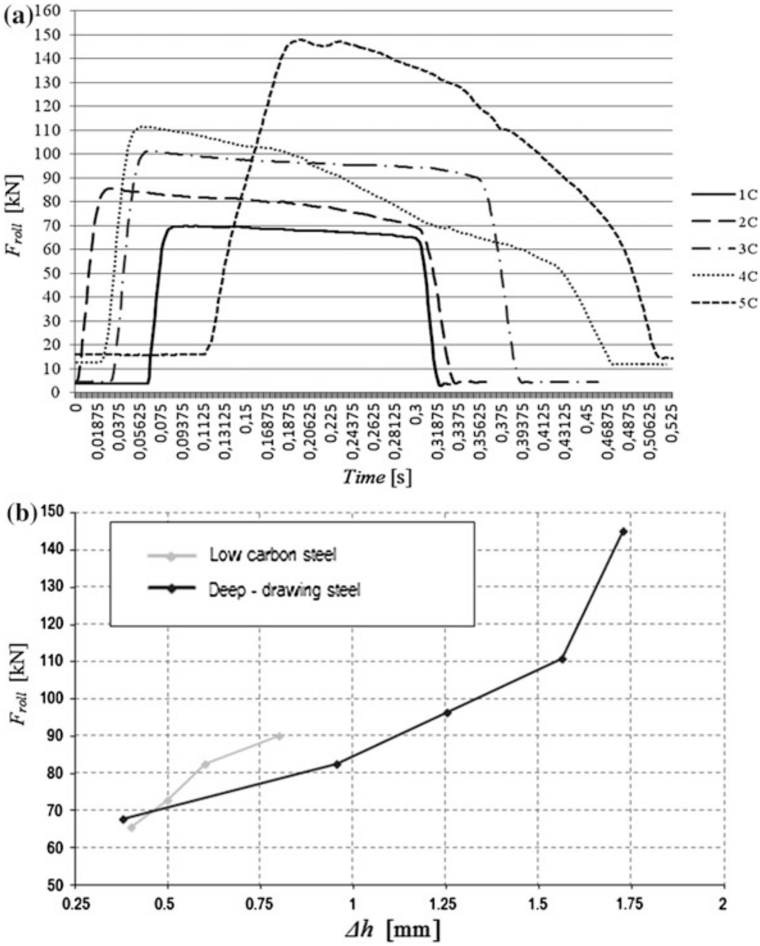

Fig. 8 **a** Graphical representation of rolling force variation in time at 0.7 m s^{-1} rolling speed. **b** Relation between the reduction Δh and the rolling force F_{roll}

$$K_{plmat} = \frac{10^{12}}{E_{mat}^2}\left[\mathrm{MPa}^{-2}\right] \quad (1)$$

It was found that using the index ratio (2) that is incorporated into the regression relations for reduction in thickness, it is possible to distinguish different materials in the process of rolling.

$$I_{kpl} = \sqrt{\frac{K_{plmat0}}{K_{plmat}}}[-] \quad (2)$$

Table 4 Dependence of mean arithmetic deviation of surface profile on rolling force

Samples from	Sheet designation	Δh (mm)	Ra (μm)	F_{roll} (kN)
Low carbon steel	0A	–	0.71	0
	1A	0.4	0.37	65.55479
	2A	0.5	0.43	72.90912
	3A	0.6	0.21	82.71223
	4A	0.8	0.12	90.06656
Deep-drawing steel	0C	0	1.07	0
	1C	0.38	0.76	67.8861
	2C	0.96	0.73	82.5948
	3C	1.27	0.43	96.3955
	4C	1.56	0.61	110.9628
	5C	1.73	0.48	145.1399

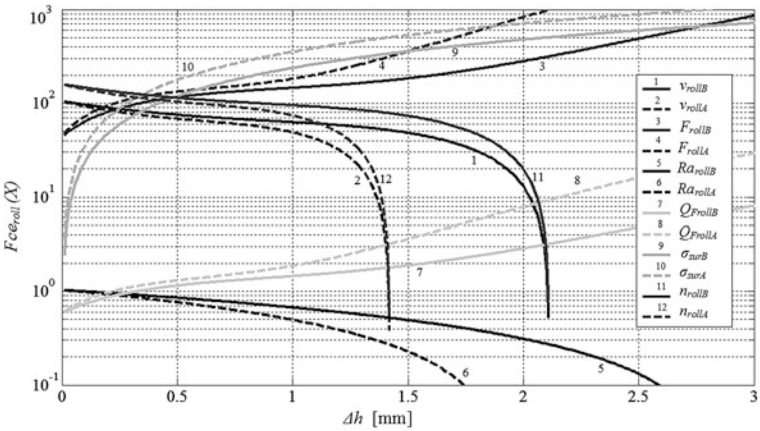

Fig. 9 Mathematical model illustrating the course of the main rolling parameters for the used materials deep-drawing steel (material A, *Ementry* = 186.7 GPa) and low carbon steel (material B, *Ementry* = 126 GPa)

Based on this finding, an algorithm for mathematical modeling in MATLAB has been developed. An example of the course of basic parameters for rolling of the material marked as "A" (low carbon steel) and material "B" (deep-drawing steel) is shown in Fig. 9.

A set of equations for the algorithm (3) and Fig. 9 contains the following variables for material "A" and "B":

σ_{sA}, σ_{sB}	Surface tension (MPa),
F_{rollA}, F_{rollB}	Rolling force (kN),
n_{rollA}, n_{rollB}	Rotations of the rolls (rot min^{-1}),
v_{rollA}, v_{rollB}	Rolling speed (m min^{-1}),
Q_{FrollA}, Q_{FrollB}	Forming factor (–),
Ra_A, Ra_B	Measured and predicted surface roughness (μm),
Δh	Reduction in thickness (mm),

D_{gr}	Grain size (mm),
S_h	Horizontal projection of the contact surface between the rolled metal and the roll (mm^2),
l_d	Length of deformation (mm),
h_s	Average value of reduction in thickness (mm),
Δh_{maxA}, Δh_{maxB}	Maximum reduction in thickness for material A and B (mm),
D_{roll}	Roll diameter,
b_s	Average width of rolled sheet [8, 6].

The input equations to the algorithm and their exact record (3) are given below:

Droll = 0.210; delh = 0.01:0.01:8;
EmentryA = 186700; Kplmato = 28.68873;
EmentryB = 125580; Kplmat = 10.^12/1./Ementry.^2;
Ikpl = (Kplmato/ Kplmat) ^0.5
Vroll = 148.0662 − 132.41266.*(delh* Ikpl) + 160.17705.*(delh* Ikpl).^2 − 83.55556.*(delh* Ikpl).^3;
Froll = 43.63183 + 329.16274.*(delh* Ikpl) − 413.33298.*(delh* Ikpl).^2 + 222.8675.*(delh* Ikpl).^3;
Ra = 1.47963 − 0.534 .* (delh* Ikpl);
QFroll = 0.57873 + 2.50374.*(delh*Ikpl) − 3.00062.*(delh*Ikpl).^2 + 1.78554.*(delh* Ikpl).^3;
SIGsur = 4.66667E – 5 + 354.26751 .* (delh* Ikpl);
nroll = vroll /1./(3.14.*Droll);
Dgrc = 0.05*(0.34843 + 3.30751 .* Rarollm);
Sh = 1000*Froll/1./(Emat^0.5.*QFroll);
ld = Sh/1./bs;
hs = ld/1./QFroll;
MATactual = 1001.

The curves of these parameters D_{gr}, S_h, L_d and h_s are not plotted in Fig. 9 to make a clear interpretation.

Figure 9 illustrates the course of rolling functions, showing a high degree of comformity with the measured values given in Tables 1 and 4 and in Figs. 5 and 8 according to individual reductions in thickness of both materials. Using the algorithm (3) that contains the regression equations, it is possible to get the high degree of conformity between the measured and predicted values. The closeness of the resulting values does not exceed 10 %. The model calculation requires to control the rolling speed v_{roll} and to control the rotations of the rolls n_{roll} depending on the increase in these parameters: thickness reduction Δh_i, rolling force F_{roll}, surface strengthening σ_{sur} and forming factor Q_{Froll} while the surface roughness values are decreasing. The surface tension curve σ_{sur} can be considered as a function of strengthening.

4 Conclusion

The theoretical treatment and the basic project concerning the operational application of optical check of mechanical parameters, especially the yield strength of a material of cold rolled sheets, rest conceptually on basic documents and specific operating conditions at a workplace of a specific company. Values of trace roughness *Ra* are input data for worked-out algorithms. Interpretation procedures and their results are conceived to provide not only the check values, i.e. in principle values obtained by defectoscopy, but also to model-predict the instantaneous mechanical condition of the material, capacity-deformation data, and others in the whole rolling process so that they can be used in designer's work both in the stage of project designing the rolling parameters and in the stages of check and control of sheet cold rolling process. Thus the algorithm, which after putting input material data will automatically provide a comprehensive mathematical model of the process in numeral as well as graphic form, is available for theory and practice. The main goal of the presented solutions was to derive the equations for the algorithm (3) according to experimental works. Looking further ahead, the authors will make some adjustments of the algorithm for industrial multistage cold rolling mills, what shall be followed by verification in real operating conditions. Next step is to propose a way to use the algorithm for on-line control and automatization.

Acknowledgments The contribution was supported by the projects RMTVC No. CZ.1.05/2.1.00/01.0040. Thanks also belong to the Moravian-Silesian Region project RRC/04/2010/36 for financial support and IT4 Innovations Centre of Excellence project, reg. no. CZ.1.05/1.1.00/02.0070.

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Design and Analysis of Materials and Engineering Structures
Öchsner, A.; da Silva, L.F.M.; Altenbach, H. (Eds.)
2013, VIII, 180 p., Hardcover
ISBN: 978-3-642-32294-5