ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 18 (2018) 227–234

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

An empirical examination of the thickness profile formation of twin-roll-cast magnesium strips

Claudia Kawalla [a,*], *Michael Höck* [a], *Madlen Ullmann* [b], *Christian M. Ringle* [c,d]

[a] *TU Bergakademie Freiberg, Institute of Industrial Management, Operations and Logistics, Freiberg, Germany*
[b] *TU Bergakademie Freiberg, Institute of Metal Forming, Freiberg, Germany*
[c] *Hamburg University of Technology (TUHH), Institute of Human Resource Management and Organizations, Hamburg, Germany*
[d] *The University of Newcastle, Faculty of Business and Law, Newcastle, Australia*

ARTICLE INFO

Article history:
Received 13 March 2017
Accepted 26 June 2017
Available online 24 July 2017

Keywords:
Twin-roll casting process
Quality assurance
Thickness profile
Structural equation modeling
Partial least squares

ABSTRACT

The recently developed technology of twin-roll-cast (TRC) magnesium strips permits an efficient production of magnesium sheets, primarily for the automotive industry. The focus of the paper is to develop a structural equation model explaining the variance of the thickness profile formation. Hence, the complex and partially unknown relationships between twin-roll casting process parameters and the thickness profile formation are analyzed using latent variables, e.g. the deformation resistance, length of contact arc, etc., which consist of several observed parameters. The fundamental process variables and their effect on the thickness profile formation during twin-roll casting are investigated and evaluated by partial least squares structural equation modeling (PLS-SEM) – a statistical method that fits networks of constructs to empirical data. The results of the predictive modeling technique allow an approximation of the existing interrelationships between thickness profiles, rolling force as well as processes in the roll gap which are typically difficult to measure directly using sensors. In this context, it was identified that the thickness profile variation is primarily caused by the forming force, which is mainly driven by the length of contact arc. Moreover, implications for the control of the thickness profile are derived.

1. Introduction

Magnesium has a high application potential due to its low density of 1.74 g/cm^3 and beneficial properties such as high specific strength [1–3]. These advantageous characteristics of magnesium as a lightweight construction material are especially in the automotive industry of interest [4,5]. Yet, most magnesium construction parts in the automotive industry are cast products, such as engine blocks. Only few components are nowadays made from semi-finished products such as strips or sheets. A main barrier to a wider-ranging use is the cost-intensive conventional forming method of magnesium strips, which consists of slab casting

---

[*] *Corresponding author.*
E-mail address: claudia.kawalla@bwl.tu-freiberg.de (C. Kawalla).

http://dx.doi.org/10.1016/j.acme.2017.06.006
1644-9665/

with subsequent hot rolling including several reheating steps in between.

As an alternative approach the Institute of Metal Forming (IMF) at the Technical University Bergakademie Freiberg, in collaboration with MgF Magnesium Flachprodukte GmbH, a subsidiary of the ThyssenKrupp Steel Europe AG, developed a new cost-efficient technology for magnesium strip production, based on twin-roll casting and hot strip rolling [6]. The intended industrial application of this technology requires a quality assurance ensuring reproducible production runs under the influence of unavoidable process related deviations. In an initial step to develop such a quality assurance system the processes and their interrelations need to be captured and analyzed, whereby twin-roll casting combines multi-stage forming processes and parameter settings. In addition several of the theoretical induced parameters which influence the quality of the thickness profile, like the deformation resistance and length of contact arc, are often difficult to measure directly using sensors, but can be approximated indirectly using a set of observed variables. Hence, structural equation modeling – a statistical method that fits networks of latent variables, i.e. indirectly measured parameters, to empirical data – is applied to quantify the interdependences between different process parameters and quality characteristics. The paper proposes a predictive modeling approach to approximate the interdependences of selected quality characteristics, such as the camber and wedge shape of TRC strip. Hereunto, the twin-roll casting process is analyzed regarding the causes, which lead to different characteristics of the thickness profile.

The aim of this paper is to establish a process model of the thickness profile formation of magnesium strips. The results of the PLS-SEM analysis show that variations in the thickness profile are to a large extend determined by the forming force, which in return is driven by the length of the contact arc, i.e. length of the solidification zone, as main control parameter of the deformation process. Furthermore, this paper serves as an example for quality assurance in developing innovative production technologies. The systematic procedure of preventing defects in manufactured products requires a flexible, predictive modeling technique, such as the proposed PLS-SEM approach, to analyze roughly the complex and to some extend unknown effects of various control parameter settings.

2. Magnesium strip production

The first step of the magnesium strip production is the twin-roll casting, which starts with melting magnesium alloy ingots in a furnace. Subsequently, the melted magnesium alloy is led through the casting channel to the nozzle. The melt is fed from the nozzle into the roll gap of two horizontally positioned rolls counter-rotating at the same peripheral speed. As soon as the melt gets in touch with the cooled work rolls, a meniscus-shaped solidification zone is formed. In total, two solidifying shells build up in the contact areas on both roll surfaces, which grow into each other during the process in the roll gap. They are merged together and deformed by the roll pressure [7–9]. Therefore, the deformation process already starts in the area of the heterogeneous phase (l_m) and extends to the solid phase of the material (l_s), which makes modeling and simulation of the twin-roll casting process so complex. l_s and l_m can also be summarized as length of contact arc l_{ca}.

The result of twin-roll casting is TRC strip, which can be refined in a following production step. During hot strip rolling the TRC strip is reheated and homogenized in an air circulated furnace. Afterwards magnesium strip is rolled out by a quarto-reversing mill to the required thickness and final annealed. The technology enables the production of hot rolled strips up to a thickness of 0.8 mm.

One of the most important quality criteria of TRC strips is the thickness profile for hot strip rolling. The thickness profile can be classified into symmetric and asymmetric profiles, which have different effects on the flatness of hot rolled strips. Fig. 2 shows the effects of the thickness profile on the flatness of 1.5 mm of a certain hot rolled magnesium alloy (AZ31) strip. On the left side, a symmetric thickness profile (a) is shown, whereas on the right side an asymmetric thickness profile (b) is illustrated, which causes so-called flatness errors. The flatness errors are illustrated as red areas. Local deviation of thickness in the thickness profile leads to flatness errors due to difference of local yield stresses. In case of extreme differences [7], the thickness deviation cannot be compensated by the shape control of the rolling mill. It is also not possible to eliminate these deviations completely by subsequent straightening of rolled strip.

In order to release symmetric and asymmetric profiles of TRC strips for further processing, a quality standard including tolerance limits has been established (Table 1). The camber profile, the maximum thickness difference between the neighboring measured points and the wedge shape belong to these criteria, whereby the tolerance limits depend on the subsequent rolling strategy. The tolerances are defined based on the guidelines of Pechiney SA – a major aluminum conglomerate based in France (PAE), in accordance to EN DIN 485 and individual experiences of the IMF.

3. Process model of the formation of the thickness profile

A first process model, which describes the formation of the thickness profile of TRC magnesium strips, has been

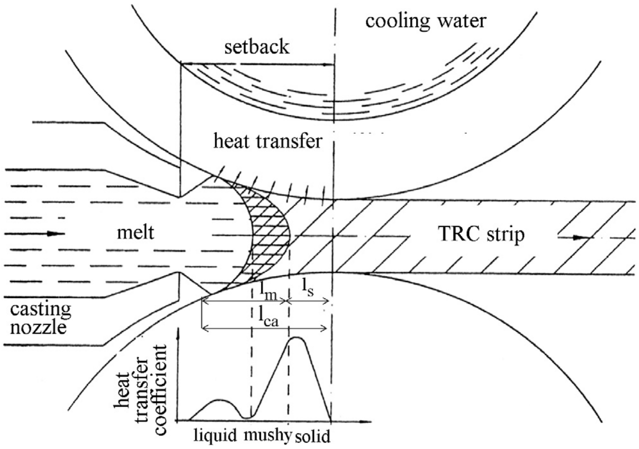
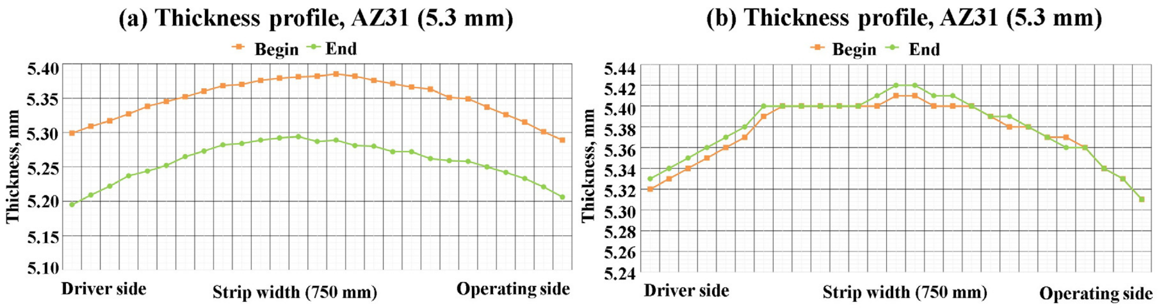


Fig. 1 – Schematic illustration of the twin-roll casting process (cf. [10,11]).



(a) Flatness, AZ31 (1.5 mm) (b) Flatness, AZ31 (1.5 mm)

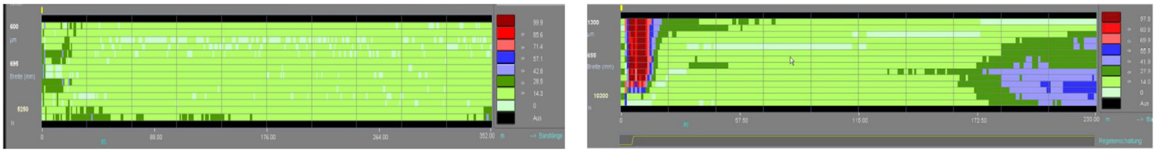


Fig. 2 – Impact of thickness profile of TRC strip on flatness of 1.5 mm thick hot rolled strip [7].

established. In a preliminary step solidification kinetics and shaping basics are described to derive hypotheses for the experimental investigation. Afterwards the data collection and preparation is specified before the model estimation and evaluation can be performed.

3.1. *Solidification kinetic and shaping process*

In general, the shaping of the thickness profile of the TRC strip is affected by the solidification process as well as by the roll gap profile of the local thermal expanded and the force-loaded work rolls [12]. This is principally valid for twin-roll casting processes of both steel and non-ferrous metals. Considering the roll gap, the entire length of the contact arc l_{ca} during twin-roll casting consists of the length of the area, where the solidified shells grow into each other l_m and the longitudinal section l_s, in which the shaping process of the completely solidified material happens (see Fig. 1). The roll gap profile is a consequence of the elastic deformation of the work rolls, which is caused by the rolling force cf. [13]. The rolling force F_{TRC} during twin-roll casting is defined as the sum of all acting rolling forces cf. [14], which are required for merging the solidified strip shells and for the subsequent deformation of the solidified area. Even the thermal expansion of the work rolls does not compensate the mechanical work roll bending [12]. Therefore, it leads to the first hypothesis:

- *Hypothesis* 1: Rolling force is positively related to the variation of the thickness profile.

From a theoretical point of view, the rolling force is defined as the product of the total contact area ($w * l_{ca}$) and deformation resistance k_{TRC} cf. [15,16].

$$F_{TRC} = w * l_{ca} * k_{TRC} \tag{1}$$

Within this context, the following hypotheses can be derived:

- *Hypothesis* 2–3: Width – w (1), length of contact arc – l_{ca} (2) and deformation resistance k_{TRC} (3) are positively related to rolling force.

The hypothesized relationships between the thickness profile, rolling force, width (w), length of contact arc (l_{ca}), deformation resistance (k_{TRC}) and its indicators, which are described in the following section are illustrated in Fig. 3. In practice, however, quality constructs, such as the goodness of fit of the thickness profile, as well as other determining factors,

Table 1 – Quality features of the thickness profile of TRC strips determined by the IMF.

Target thickness hot rolled strip [mm]	Camber profile[a] [mm]	Maximum thickness deviation between measuring points[b] [mm]	Wedge shape [mm]
2.00	0.05–0.15	0.030	0.050
1.50	0.05–0.15	0.020	0.040
1.25	0.06–0.13	0.015	0.030
1.00	0.06–0.10	0.010	0.020

[a] Camber profile depends on crown of the rolls in the twin-roll casting plant and the specific rolling force during twin-roll casting (targeted minimum of 10 kN/mm).

[b] Measuring point distance: in the TRC strip = 24 mm.

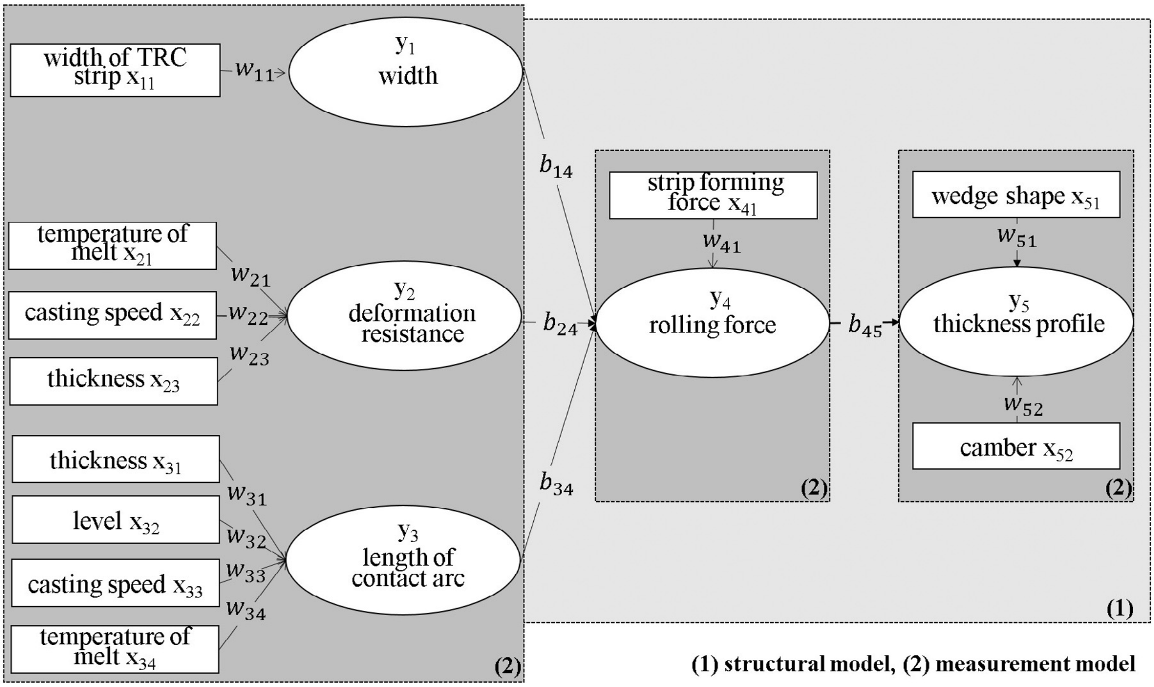


Fig. 3 – Structural equation model for the thickness profile formation of TRC magnesium strips.

like the length of contact arc and deformation resistance, cannot be measured directly, but need to be approximated based on the available data.

3.2. Data

The analysis of the twin-roll casting parameters was carried out systematically by deliberately induced and documented fluctuations at the pilot plant of the Institute of Metal Forming. For the empirical investigation of the thickness profile, 61 data sets from 7 casting campaigns of the magnesium alloy AZ31 have been selected from the data pool. The data sets have been examined for their completeness and plausibility [7]. For missing data, the mean values of the parameters of the casting campaign were calculated. Moreover, the Taguchi loss function approach has been used for the process parameters and quality characteristics to get quality-oriented metrics. Taguchi's quality understanding considers any deviations from the target value respectively nominal value as a loss, whereby there are three types of loss functions [17]. The following quadratic loss function was selected for the empirical investigation:

$$L(y) = k(y - m)^2 \tag{2}$$

$L(y)$ is the quality loss, which results from the value of the characteristic feature y, the target value m and the loss coefficient k [18]. The target values in matters of the quality characteristics and process parameters depend on both the sought hot rolling strategy for the TRC strip and the applied twin-roll casting strategy.

Based on the previous research and experimental data from the pilot plant fundamental indicators (measurable proxy variables) for the above-mentioned latent variables (k_{TRC}, l_{ca}, etc.) have been identified. Their measurements will be explained hereafter.

(1) *Thickness profiles*: Corresponding to Fig. 2, symmetric and asymmetric thickness profiles can be distinguished. The symmetric thickness profile is characterized by a camber. Based on the definition of [19], the camber can be calculated using following equation:

$$\mathrm{Camber} = \mathrm{Thickness}_{\mathrm{M}} - \frac{(\mathrm{Thickness}_{\mathrm{OS}} + \mathrm{Thickness}_{\mathrm{DS}})}{2} \tag{3}$$

where M = middle, OS = operating side, DS = driver side of the TRC process.

The camber is the mean value of three measured thickness values in the middle of the TRC strip minus the mean value of the two outer strip thicknesses. The values of the thickness on the operating side (OS) and driver side (DS) are the mean values of three measured points at the edge area of OS and DS. These values do not include boundary values. In the examination thickness profiles with symmetrical decreasing values are considered.

Contrary to symmetric profiles, asymmetric profiles are defined by the wedge shape. The computation of the wedge shape is carried out according to the following equation cf. [20]:

$$\mathrm{Wedge\ shape} = \mathrm{Thickness}_{\mathrm{OS}} - \mathrm{Thickness}_{\mathrm{DS}} \tag{4}$$

where OS = operating side, DS = driver side of the TRC process.

$\mathrm{Thickness}_{\mathrm{OS}}$ and $\mathrm{Thickness}_{\mathrm{DS}}$ are mean values of three measured points of the respective strip side. The strip wedge is the difference between the mean thicknesses of the TRC strip on the OS and DS. If these two points are connected an imaginary wedge arises. Extreme waviness in asymmetric profiles is excluded of the empirical investigations.

(2) *Rolling force*: The rolling force is measured by means of dynamometers at the TRC staging. It consists of the measured values of the force on the OS and DS. Corresponding to the definition of the rolling force the sum of the rolling force of the OS and DS is used.

(3) *Width*: The spread of the material in the roll gap of the twin-roll casting plant (spreading of the melt immediately after leaving the casting nozzle) cannot be measured due to technological reasons. Therefore, the width of the TRC strip is measured at several sections.

(4) *Length of contact arc*: The total length of the contact arc l_{ca} cannot directly be determined in the roll gap but it can be defined by the target thickness of the TRC strip, pressure of melt, temperature of melt and casting speed. The pressure of the melt equals indirectly the melting bath (level) in the casting channel. Afterwards, the melt lies on the work roll surfaces depending on the mass flow. Hence, it leads to changes in the heat flux into the cooled work rolls. Changes in the heat flux occur alongside with changes in the formed strip shells and simultaneously in the length of the contact arc. A further indicator which affects the total length of the contact arc is the temperature of melt. Depending on the temperature of melt both, the length of the area, where the shells are merged (l_m) as well as the length of the solidified area (l_s), which will be deformed, vary.

(5) *Deformation resistance*: The deformation resistance depends on the melt temperature and casting speed, which are also indicators of the length of contact arc. In the following we will consider them only in case of the deformation resistance.

In all cases, the indicators cause the latent variables, so that a formative measurement model is applied.

3.3. *Model estimation and evaluation*

Within the scope of structural equation modeling, the covariance-based method (CB-SEM) [21–23] and the variance-based PLS-SEM approach are available for the estimation of cause–effect relations [24]. The PLS-SEM approach, a multivariate analysis method has been chosen according to predefined quality criteria for an empirical investigation [25,26]. It is more suitable than CB-SEM due to the special research objective to predict structural relationships [25]. Especially for the magnesium strip production, where no model exists, the formation of the distinctive thickness profile characteristics should be predicted and explained. Moreover, the data was generated at a pilot plant where research oriented casting campaigns are carried out. Therefore, the data set is relatively small due to cost-intensive experiments. In addition, the data is non-normal distributed. In contrast to CB-SEM, PLS-SEM relaxes the demands regarding sample size and assumption of multivariate normality [25–27] which accommodate the special conditions. Despite small sample size, non-normal data PLS-SEM achieves high levels of statistical power [25–27].

The software SmartPLS 3.2.6 [28] has been used to estimate the structural equation model with the PLS-algorithm and the production data. Fig. 4 shows the model estimation results (i.e. standardized regression coefficients and R^2 values).

Before interpreting the results displayed in Fig. 4, we address their evolution. For this purpose, we follow the procedures and criteria suggested by Hair and co-authors [29]. The latent variables are measured by a formative measurement model. The variance inflation factor (VIF) values allow assessing if the indicators have critical collinearity levels. The

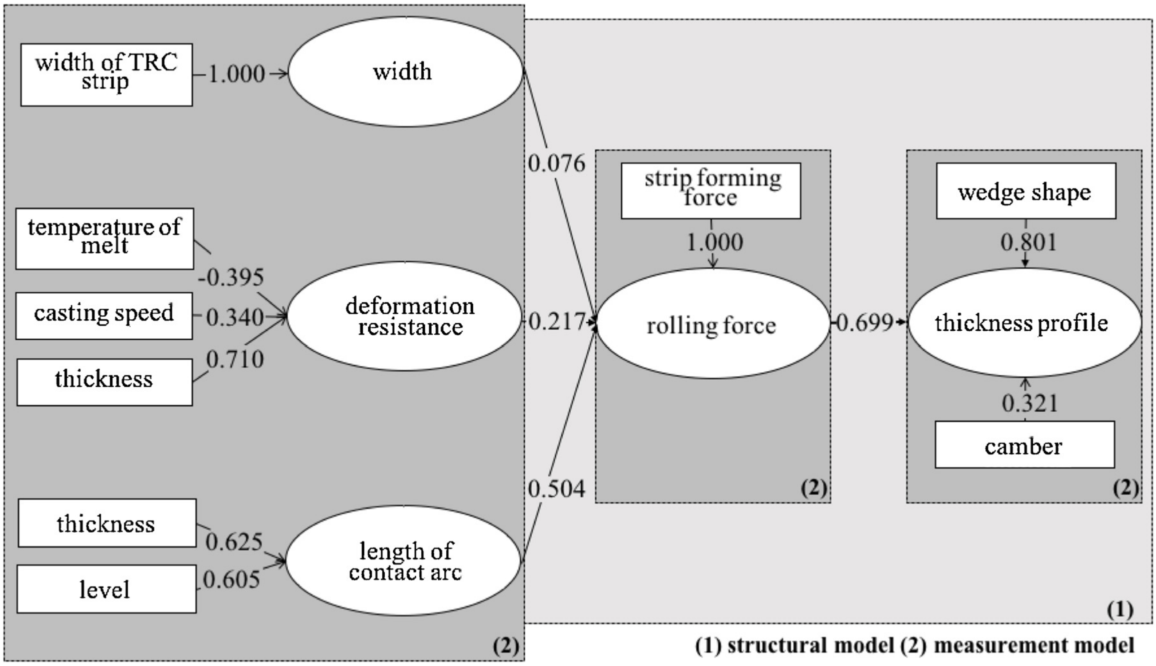


Fig. 4 – Structural equation model for the thickness profile formation of TRC magnesium strips.

Table 2 – Evaluation results of formative measurement model.

Latent variable[a]	Indicator	Outer weight	VIF	90% bias-corrected bootstrap confidence interval[b]	Significant?
Deformation resistance	Temperature of melt	−0.395	1.167	[−0.511; −0.318]	Yes
	Casting speed	0.340	1.062	[0.104; 0.590]	Yes
	Thickness	0.710	1.107	[0.571; 0.808]	Yes
Length of contact arc	Thickness	0.625	1.116	[0.444; 0.822]	Yes
	Level	0.605	1.116	[0.468; 0.728]	Yes
Thickness profile	Wedge shape	0.801	1.327	[0.626; 0.996]	Yes
	Camber	0.321	1.327	[0.072; 0.455]	Yes

[a] The single-item constructs width and strip forming force (F_{TRC}) are not included in this table (i.e., their outer relationship is 1.0).

[b] *Note*: Bias-accelerated and corrected bootstrapping (BCa) procedure; 5000 bootstrapping subsamples; individual sign change option.

highest VIF values not exceed 1.327 (Table 1), which clearly is below the critical value of 5 [30]. The results of the bias-corrected and accelerated bootstrapping procedure (i.e., 5000 samples and the individual sign change option) allow assessing the significance of indicators per measurement models (Table 2). All outer weights are significant ($p < 0.1$), whereby p illustrates the probability of erroneously denying a true null hypothesis [29]. Also, the coefficients show the expected signs. The indicators level (0.605) and the thickness (0.625) have nearly the same outer weight and, thus, an almost equal relevance for the length of contact arc (l_{ca}) construct. In contrast, thickness (0.710), the temperature of melt (−0.395), and casting speed (0.340) have different relevance, as indicated by their standardized outer weights, for forming the construct deformation resistance (k_{TRC}). The lower the temperature of melt and the higher the casting speed the higher is the deformation resistance. The thicker the material in the roll gap, which has the largest impact on the deformation resistance, the higher the deformation resistance. For the construct thickness profile the wedge shape plays a particularly important role (0.801), whereas the influence of cambers (0.321) is less pronounced. In summary, the analysis meet the relevant evaluation criteria of formative measurement models [29].

When assessing the results of the structural model [29], the coefficient of determination of the endogenous latent variables (i.e., their R^2 values) are of primary interest. The R^2 values of the thickness profile (0.488) and rolling force (0.454) have relatively high level (Table 3); the model almost explains 50% of their variance. Moreover, the Stone–Geisser's Q^2 values [31,32] have been obtained by using the blindfolding procedure [33] and an omission distance of six. All Q^2 values are above zero, which substantiates the predictive relevance of the path model.

Table 3 also shows the size and significance of the coefficients in the structural model. The strongest (and significant) relationship (0.699) exists between rolling force (F_{TRC}) and the thickness profile. For the target construct rolling force (F_{TRC}), the length of contact arc (l_{ca}) construct (0.504) has the highest (significant) coefficients, followed by the (significant) relationships of the deformation resistance (k_{TRC}) construct (0.217) and the rolling force (F_{TRC}) construct (0.076). The latter low relationship (i.e., width → rolling force) results from the small variations of the width at the pilot plant (650–750 mm). In case of an industrial plant, however the impact on the rolling force should be higher considering the larger differences in width, which can be produced. The f^2 effect size values further substantiate the relevance of the significant path coefficients. In conformity with the assessment of the relevant criteria for the structural model [29], this analysis supports and further substantiates underlying hypothesis.

4. Results and discussion

A basic quality assurance model has been developed analyzing the thickness profile formation of TRC strip at a pilot plant despite the fact that not all potential factors (like thermal transmittance) have been be captured. In total 48.8% of the variance of the thickness profiles, i.e. cambers and wedge shapes, can be explained by the above stated model. The

Table 3 – Structural model evaluation results.

Endogenous latent variable		R^2 value		Q^2 value
Rolling force		0.454		0.402
Thickness profile		0.488		0.213
Relation	**Path coefficient**	**90% bias-corrected bootstrap confidence interval***	**Significant?**	**f^2 value**
Width → rolling force	0.076	[0.017; 0.138]	Yes	0.010
Deformation resistance → rolling force	0.217	[0.050; 0.408]	Yes	0.038
Length of contact arc → rolling force	0.504	[0.290; 0.914]	Yes	0.197
Rolling force → thickness profile	0.699	[0.467; 0.772]	Yes	0.955

* *Note*: Bias-accelerated and corrected bootstrapping (BCa) procedure; 5,000 bootstrapping subsamples; individual sign change option.

predictive modeling technique allows an approximation of the existing interrelationships among different thickness profiles, rolling forces and various processes in the roll gap and shows the control parameters that can be leveraged to improve the quality of the thickness profile. The key parameter to adjust the thickness profile is the rolling force, which is primarily influenced by the length of contact arc (0.504), deformation resistance (0.217), and with a lower weight the width (0.076). Consequently, the regulation of the length of contact arc l_{ca} and deformation resistance k_{TRC} should be given special attention. To improve the thickness profile of TRC magnesium strips, operators of the pilot plant should primarily focus on the correct melting bath level in the casting channel and the appropriate thickness of the material in the roll gap. Of secondary relevance for the quality of the TRC thickness profile is the deformation resistance, here measured by casting speed, melt temperature as well as the thickness of the material in the roll gap. A higher than aspired melt temperature has a negative impact on the thickness profile. In contrast to the deformation resistance (k_{TRC}) and length of contact arc (l_{ca}) the width is of minor importance for the rolling force. This can be explained by slight variations of the width at the investigated pilot plant (650–750 mm).

Regarding the TRC formation we can also conclude that if the length of contact arc l_{ca} and the deformation resistance k_{TRC} is higher it will be more difficult to control the solidification front and the evenly distributed rolling force. The identification of the interrelationship concerning the thickness profile formation is a first step in the development of a quality assurance system. Moreover, first findings can be used during the pilot production of TRC strips.

Future research will focus on expanding the basic model by additional quality characteristics. Due to the fact that the formation of the thickness profile is closely related to the formation of segregations, i.e. separation of impurities and alloying elements in different casting regions, the interrelations between important quality requirements can be investigated. In addition, on-line control chart pattern detection and discrimination using the PLS-SEM approach can be implemented to ensure a stable TRC process. All these measures need to be embedded in the stepwise pilot plant quality improvement process toward accreditation.

Ethical disclosures

Authors state that the research was conducted according to ethical standards.

Funding

European Union (European Social Fund) and Saxonian Government under grant 100270111.

Acknowledgements

This work was supported by the European Union (European Social Fund) and Saxonian Government under grant 100270111. This article uses the statistical software SmartPLS 3 (http://www.smartpls.com). Ringle acknowledges a financial interest in SmartPLS.

REFERENCES

[1] A. Nam, U. Prüfert, M. Eiermann, R. Kawalla, Modelling the temperature evolution during hot reversing strip rolling of magnesium alloys, Trans Tech Publications – Materials Science Forum 854 (2016) 140–145.

[2] A. Nam, U. Prüfert, R. Kawalla, Thermal modelling for production of hot strip of magnesium alloy, Journal of Machine Engineering 14 (2014) 29–38.

[3] C. Kammer, D. Aluminium-Zentrale, Magnesium Taschenbuch, Aluminium-Verlag, Düsseldorf, 2000.

[4] M.K. Kulekci, Magnesium and its alloys applications in automotive industry, The International Journal of Advanced Manufacturing Technology 39 (2008) 851–865.

[5] H. Friedrich, S. Schumann, Research for a ‘‘new age of magnesium’’ in the automotive industry, Journal of Materials Processing Technology 117 (2001) 276–281.

[6] R. Kawalla, M. Oswald, C. Schmidt, M. Ullmann, H.-P. Vogt, N. D. Cuong, New technology for the production of magnesium strips and sheets, Metalurgija 47 (2008) 195–198.

[7] C. Kawalla, M. Hoeck, Quality assurance system for hot rolled TRC magnesium strips, Scientific Papers of Silesian University of Technology. Organization and Management Series 100 (2017) 171–179.

[8] A. Miehe, U. Gross, Modelling of heat transfer and solidification processes in horizontal twin-roll casting of magnesium AZ31, IOP Publishing – IOP Conference Series 33 (2012) 1–8.

[9] A. Miehe, Numerical Investigation of Horizontal Twin-Roll Casting of the Magnesium Alloy AZ31, 2014.

[10] B. Frischknecht, G. Thun, Bandgießtechnologien – Stand der Technik und Trends, Aluminium 77 (2001) 746–751.

[11] J. Strid, Twin roll casting, a technological over view, Proceedings of the 3rd International 3 (1992) 321–356.

[12] U. Albrecht-Früh, Prozeßdatengestützte Modellbildung des Banddickenprofils beim Dünnbandgießen nach dem Zweirollenverfahren, Shaker Verlag, 1997.

[13] H. Beyer-Steinhauer, Thermische Walzenbombierung beim Zwei-Rollen-Gießwalzverfahren, Verlag Stahleisen, 1993.

[14] H. Hoffmann, R. Neugebauer, G. Spur (Eds.), Handbuch umformen, Carl Hanser Verlag GmbH & Co. KG, 2012.

[15] S. Bernhard, Zur Regelung und Steuerung von Bandgiessanlagen nach dem Zwei-Rollen-Verfahren, VDI-Verlag, 1993.

[16] M. Enning, Beitrag zur Dickenregelung beim Gießwalzen von Bändern, VDI-Verlag, 1990.

[17] P.J. Ross (Ed.), Taguchi Techniques for Quality Engineering: Loss Function, Orthogonal Experiments, Parameter and Tolerance Design, 2nd edn., McGraw-Hill, New York, 1988.

[18] W.-N. Pi, C. Low, Supplier evaluation and selection via Taguchi loss functions and an AHP, The International Journal of Advanced Manufacturing Technology 27 (2006) 625–630.

[19] W. Tautz, EP 0 575 636 AI (10.06.92).

[20] M. Degner, E. Neuschütz, Walzen von gleichmäßigem (keilfreiem) Warmbanddickenprofil: Europäische Kommission, Generaldirektion Forschung und Innovation, EUR, Luxembourg, 1998.

[21] K.G. Jöreskog, Structural analysis of covariance and correlation matrices, Psychometrika 43 (1978) 443–477.

[22] K.G. Jöreskog, The LISREL Approach to Causal Model-Building in the Social Sciences, Systems Under Indirect Observation. Part I, 1982, 81–100.

[23] K.G. Jöreskog, A.S. Goldberger, Estimation of a model with multiple indicators and multiple causes of a single latent variable, Journal of the American Statistical Association 70 (1975) 631–639.

[24] D.X. Peng, F. Lai, Using partial least squares in operations management research: a practical guideline and summary of past research, Journal of Operations Management 30 (2012) 467–480.

[25] J.F. Hair, C.M. Ringle, M. Sarstedt, PLS-SEM: indeed a silver bullet, Journal of Marketing theory and Practice 19 (2011) 139–152.

[26] J.F. Hair, M. Sarstedt, C.M. Ringle, J.A. Mena, An assessment of the use of partial least squares structural equation modeling in marketing research, Journal of the Academy of Marketing Science 40 (2012) 414–433.

[27] J.F. Hair, M. Sarstedt, T.M. Pieper, C.M. Ringle, The use of partial least squares structural equation modeling in strategic management research: a review of past practices and recommendations for future applications, Long Range Planning 45 (2012) 320–340.

[28] C.M. Ringle, S. Wende, J.-M. Becker, SmartPLS 3, Boenningstedt: SmartPLS GmbH, 2015 http://www.smartpls.com.

[29] J.F. Hair, G.T.M. Hult, C.M. Ringle, M. Sarstedt, A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM), 2nd ed., Sage Publications, Thousand Oaks, 2017.

[30] A. Diamantopoulos, P. Riefler, Formative Indikatoren: Einige Anmerkungen zu ihrer Art, Validität und Multikollinearität, Zeitschrift für Betriebswirtschaft 78 (2008) 1183–1196.

[31] S. Geisser, A predictive approach to the random effect model, Biometrika (1974) 101–107.

[32] M. Stone, Cross-validatory choice and assessment of statistical predictions, Journal of the royal statistical society: Series B (Methodological) (1974) 111–147.

[33] M. Tenenhaus, V.E. Vinzi, Y.-M. Chatelin, C. Lauro, PLS path modeling, Computational Statistics & Data Analysis 48 (2005) 159–205.