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QUALITY ASSURANCE SYSTEM FOR HOT ROLLED TRC MAGNESIUM STRIPS

Abstract. Challenging environmental regulations concerning carbon dioxide emissions force the automotive industry to reduce the vehicle weight dramatically. One solution to achieve huge weight savings is the application of automotive components using magnesium sheets produced by means of the innovative Twin-Roll-Casting (TRC) technology. The TRC technology, which was developed at the Institute of Metal Forming of the TU Bergakademie Freiberg, has already reached industrial level. Furthermore, the successful application of prototypes by well-known automotive manufacturers such as BMW, Porsche, and VW shows huge potential. To advance the application of magnesium sheets in serial production a quality assurance system is required by the automotive industry. We propose a concept of a quality assurance system for the special conditions of the magnesium strip production and explain the complexity of its construction. The procedure of preparation will be explained in the first step.

Keywords: Twin-Roll-Casting, quality assurance system, thickness profile, partial least squares structural equation modeling (PLS-SEM)

SYSTEM ZAPEWNIENIA JAKOŚCI DLA GORĄCOWALCOWANYCH LISTEW MAGNEZOWYCH TRC

Streszczenie. Nowe regulacje środowiskowe dotyczące emisji dwutlenku węgla powodują, że przemysł samochodowy stara się w znacznym stopniu zredukować wagę pojazdu. Jednym z rozwiązań, które można w tym celu zastosować, jest użycie komponentów wytworzonych z gorącowalcowanych innowacyjnych listew wykonanych w technologii TRC. Technologia TRC została opracowana w Instytucie Formowania Metali TU Bergakademie Freiberg i obecnie jest gotowa do przemysłowego wykorzystania. Dodatkowo sukcesy wdrożenia technologii w zakresie prototypowego wykorzystania u producentów, takich jak BMW, Porsche i VW, pokazują jej duży potencjał. Aby jednak wykorzystać gorącowalcowane listwy w produkcji seryjnej, niezbędne są odpowiednie systemy zapewnienia jakości w przemyśle motoryzacyjnym. W artykule przedstawiono propozycję systemu zapewnienia jakości, który można zastosować w tym przypadku.

Słowa kluczowe: Podwójna kabina natryskowa, system zapewnienia jakości, grubość profilu, modelowanie równań strukturalnych metodą najmniejszych kwadratów (PLS-SEM)

1. Introduction

Stricter environmental regulations force the automotive industry to reduce the carbon dioxide emissions sharply. To achieve the required emission targets the vehicle weight has a key role[1]. 100 kg saved on the mass of a car can save about 9 grams of CO2 per kilometer[2]. However, the vehicle weight has increased in the last decades due to higher requirements concerning safety, comfort, etc.[3]. The fulfillment of the higher requirements is interrelated to each other. For example, higher safety standards led to the adjustment of the body, which causes additional weight. Adjustments of the body go along with a heavier chassis. Not to lose dynamic performance, better engines with bigger tanks are necessary. This phenomenon, called weight spiral principal, is shown in Fig. 1[4].

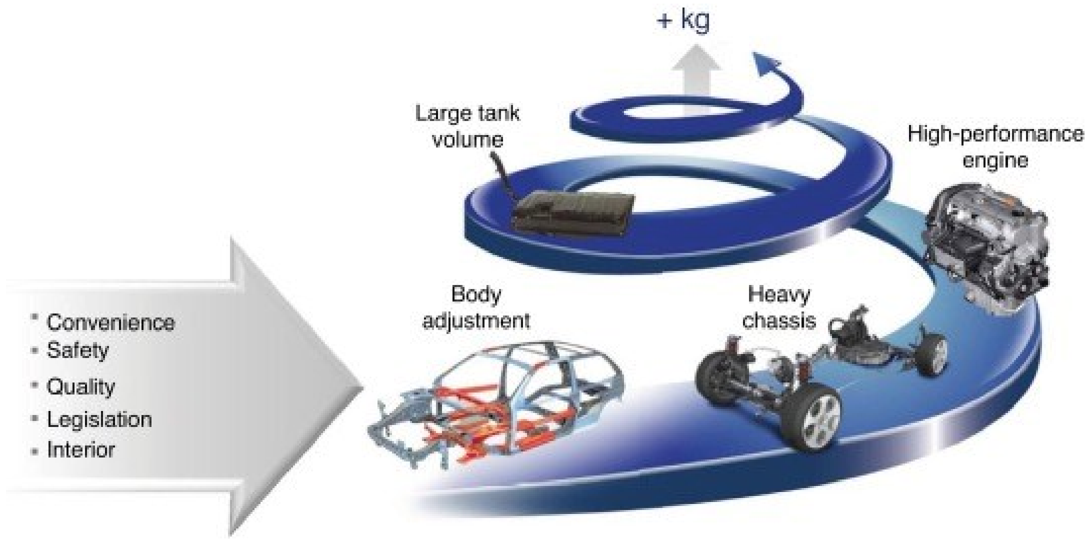

Fig. 1. Weight spiral Source: Mainka et al. (2013), p. 2.

[1] Cf. Hirsch (2011), p. 818; Mainka et al. (2015), p. 284.
[2] See Hirsch (2011), p. 818.
[3] Cf. Hirsch (2011), p. 818; Mainka et al. (2015), p. 284.
[4] Cf. Mainka et al. (2013); Mainka et al. (2015), p. 284.

A reversal of the weight spiral can only be managed by enormous weight savings of 50% or more in certain automotive components[5]. A material with high potential in this context is magnesium, which could substitute conventional materials like steel and aluminum. With a density of 1,74 g/cm^3 it is considerably lighter than aluminium (2,7 g/cm^3) and steel (7,8 g/cm^3)[6]. Nonetheless, the application of semi-finished magnesium sheets in the automotive industry is restricted by the high production costs of the conventional sheet production[7]. To bridge the gap, the TRC technology, which has already reached industrial level, has been developed at the Institute of Metal Forming of the TU Bergakademie Freiberg. Moreover, successful studies concerning prototypes using semi-finished magnesium-sheets demonstrate the high application potential in the automotive industry[8]. Notable examples are the roof of Porsche GT3[9], the automobile rear panel of the BMW 3 Series[10], and the instrument panel of the VW XL 1[11]. Due to the material substitution, Porsche has achieved a reduction of 69% of the weight dropping from 7.5 kg to 2.3 kg[12]. BMW obtained similar results with 11.5 kg to 5.74 kg (~ -50%)[13]. To move to serial production, a quality assurance system which ensures stable and reproducible processes is required by the automotive industry. The paper introduces a rough concept of a quality assurance system for the special conditions of the magnesium strip production using the TRC technology. For this, the production of hot rolled TRC strips and their quality standard is explained. Furthermore, the specific interrelationships between the properties of Twin-Roll-Cast and hot rolled TRC magnesium strips are considered, which is of particular importance for the process stability of the magnesium strip production in an industrial environment. Afterwards, the data acquisition, structure, and analysis are outlined, which is followed by the introduction of the quality assurance concept.

2. Production of hot rolled TRC strips and their quality features

Hot rolled TRC strips are produced in a two-stage procedure comprising the Twin-Roll-Casting and hot strip rolling process (Fig. 2).

[5] Cf. Mainka et al. (2015), p. 284.
[6] Cf. Kammer (2000), p. 81.
[7] Cf. Neh et al. (2015), p. 219.
[8] Cf. Kawalla et al. (2016), p. 25.
[9] Cf. Vogt (2014).
[10] Cf. Ullmann SFU (2014).
[11] Cf. Grigoleit (2015).
[12] Vogt (2014).
[13] Grigoleit (2015).

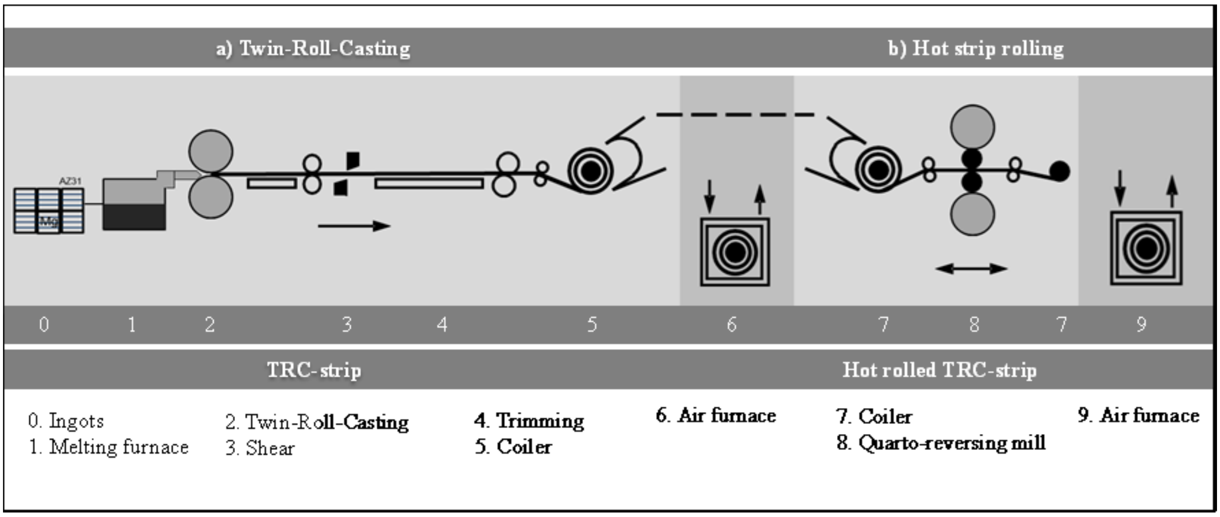

Fig. 2. Technological chain of the magnesium strip production
Source: In accordance to Nam (2015), p. 23.

The first process step is Twin-Roll-Casting. In this process magnesium ingots are melted in a furnace under protective gas. The molten magnesium alloy is fed from the melting furnace into the heated casting channel. From the casting channel the melt is routed to the heated casting nozzle, which casts the melt into the roll gap. By contacting the melt with the water-cooled rolls, the material solidifies and two strip shells build up. They grow into each other during the process till they are joined together. Simultaneously, the deformation is carried out within the roll gap. The produced strip is finally trimmed and coiled. All in all, TRC strips with a thickness of 3.0 to 7.0 mm can be produced using the technology. During hot strip rolling, the TRC strip is reheated in an air circulated furnace up to the required rolling temperature and held at this temperature until homogenization is reached. Subsequently, the TRC strip is transported to the rolling line of the four high quarto-reversing mill, where it is hot rolled up to the required target thickness in a single stage or two stages. The hot rolled strip is afterwards finished annealed. The quality characteristics of hot rolled TRC strips were summarized in a quality standard (Table 1). The standard has been developed based on the technical feasability of the technological process and the requirements of the automotive industry.

Table 1

Quality features of hot rolled AZ31 strip

Chemical composition	Alloy grade AZ31 according to ASTM B90/90M-93					
Shape	Available shape tolerances in mm				Strip crown Max. 2-5% of nominal thickness	Flatness ≤ 25 IU
	Thickness	Thickness tolerance	Width			
			Trimmed	Untrimmed		
	1,0	+/- 0,07	630	670-690		
	1,5	+/- 0,07	630-650	670-690		
	2,0	+/- 0,07	630-650	690		
	2,5	+/- 0,07	630-650	690		
	3,0	+/- 0,07	630-650	690		

cont. tab. 1

Surface	Roughness $R_a = 0{,}1\text{-}0{,}4$ µm	Scar-, groove-, crack free surface					
Mechanical properties	Thickness in mm	Longitudinal value			Transverse value		
		$R_{p0,2}$	R_m	A_{80}	$R_{p0,2}$	R_m	A_{80}
	1,0	≥170	≥240	≥20	≥170	≥240	≥17%
	1,5	≥170	≥240	≥20	≥170	≥240	≥17%
	2,0	≥170	≥240	≥20	≥160	≥240	≥17%
	2,5	≥170	≥240	≥20	≥150	≥240	≥12%
	3,0	≥170	≥240	≥20	≥150	≥240	≥12%
Internal defects	Pitting-, blow hole free			Inclusion ≤ 5 µm			
Micro-structure, texture	Precipitation size ~1 µm				Grain size ≤ 20 µm (up to 7 µm for 1,0 mm)		

3. Interrelationship between properties of TRC strips and hot rolled TRC strips

During the construction of the quality assurance system for the magnesium strip production, the exploration and comprehension of the interrelationships between the quality of TRC strips and the properties of hot rolled TRC strips are of great significance. An illustrative example which demonstrates the extremely sophisticated interrelationships is the thickness profile of TRC strips and the flatness of hot rolled strips (Fig. 3). The thickness profile can be divided into symmetric (a) and asymmetric profiles (b). The desirable symmetric profile does not lead to flatness errors, whereas the asymmetric profile causes shape problems due to different of local yield stresses.

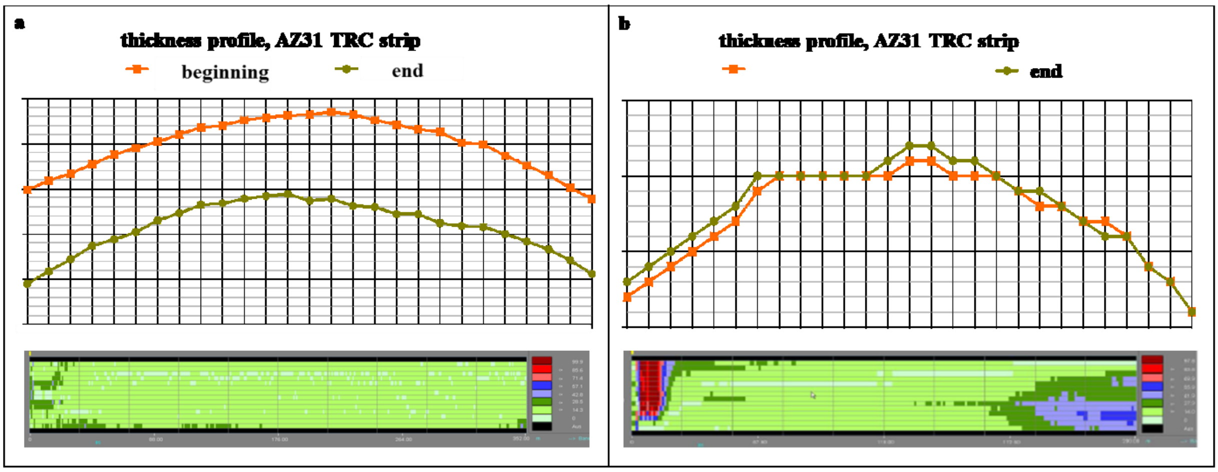

Fig. 3. Effects of thickness profile on flatness of 1.5 mm thick AZ31 hot rolled strip

4. Data acquistion, data structure and data analysis

As part of the preparation for the development of this quality assurance system the interrelationships between the properties of TRC strips and hot rolled TRC strips, as well as the formation of the individual quality characteristics, must be analyzed. For this purpose, data of 400 casting campaigns of the Institute of Metal Forming has been collected and filed. To obtain a better overview, the data was divided into quality characteristics, process parameters, and manipulated variables according to its casting campaign. Moreover, it was assigned to the respective units of the technological chain. Within this context, it should be mentioned that not all process parameters have been or can be captured in experiments due to missing sensor technology.

The individual data sets of the collected and filed data were checked for completeness and plausibility. In case of incorrect measurements, data sets were excluded from the investigations. For missing data, the sequential hot deck imputation method was applied.

A fundamental problem during the construction of the quality assurance system for the new TRC technology is that no general theoretical model exists, which includes all relationships between the stated parameters. Consequentially, in a first step for each process stage the presumed relationships for the formation of the individual quality features must be estimated and validated based on existing models and the empirical data of the experiments provided by the Institute of Metal Forming. In some cases, the analysis must refer to other materials, such as aluminum or other technologies like the vertical Twin-Roll-Casting, if no model exists.

The interrelationships for the formation of the specific quality characteristics will be modeled by means of structural equation modeling. To estimate the cause-effect relations in structural equation models, two approaches can be applied, the covariance-based (CB-SEM)[14] or the variance-based partial least squares structural equation modeling method (PLS-SEM)[15]. Based on the key arguments for the selection of an adequate method[16], PLS-SEM was chosen for the estimation. Especially for the analysis of the formation of the individual quality characteristics it is a useful method due to the fact that PLS-SEM is a prediction-oriented approach, which is mainly applied for the development of theories (exploratory research)[17]. Moreover, medium and complex model set ups, such as in the case of the TRC process, are handled reliably with fewer restrictions in comparison to CB-SEM. Despite a database consisting of 400 casting campaigns, the analysis must be carried out according to the different magnesium alloys which were explored at the Institute of Metal Forming. The different magnesium alloys possess distinct properties and therefore different complex behaviors in the

[14] Cf. Jöreskog (1978), p. 443-477; Jöreskog (1982), p. 81-100; Jöreskog/Goldberger, p. 631-638.
[15] Cf. Hair et al. (2017); Lohmöller (1989).
[16] Cf. Hair et al. (2011), p. 144; Ringle et al. (2012), p. 4-7.
[17] Cf. Hair et al.(2017), p. 4; Sarstedt et al. (2014), p. 106; Dijkstra (2010), p. 44.

TRC process. For this reason PLS-SEM is suitable because it is not sensitive to small sample sizes and it requires no normal distribution.

5. Concept of the quality assurance system for hot rolled TRC strips

The data analysis forms the prerequisite for the construction of the quality assurance system. With the implementation of the quality assurance system for the special requirements of the TRC technology, a robust and adaptive process which leads to increasing efficiency and capacity while the costs and system complexity are reduced, should be achieved.

The individual process steps of the entire magnesium strip production should be monitored and controlled by control units in the online and offline mode. In order to respond quickly to quality deviations, the online mode is necessary. The measured values must be automatically fed into a closed control loop based on control engineering to meet the quality-determining target requirements. For technical reasons, not all relevant parameters for the creation of control loops in the online mode can currently be generated. Thus, certain properties are examined through destructive and non-destructive tests on additional machines. Corrective actions are taken by re/setting manipulated variables. The individual process steps of the magnesium strip production should be connected with each other in cyber-physical systems. The received data must be processed smartly to use it for process adaption.

6. Conclusion

Magnesium strip production according to the Twin-Roll-Casting technology has reached industrial level. Moreover, the automotive industry has already tested prototypes of magnesium sheets successfully. To advance the application of magnesium sheets in serial production a quality assurance system which ensures a stable quality of hot rolled TRC magnesium strips is necessary. The concept of the quality assurance system for the magnesium strip production has been introduced. In this context the complexity of the development task has been described by the interrelationships between the properties of the TRC and hot rolled TRC strip. Moreover, the procedure for the preparation of the development of the quality assurance system has been explained.

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