DOI: https://doi.org/10.24425/amm.2025.153512

C. JASIŃSKI[1*], Ł. MORAWIŃSKI[1], A. KOCHAŃSKI[1]

ASSESSMENT OF THE ALUMINIUM PROFILES SURFACE CONDITION DURING THE EXTRUSION PROCESS

Correct production of aluminium profiles requires optimising many parameters on the production line. Irregularities in the process cause, among others, unfavourable changes in the surface geometry structure (SGP) of the profile, including roughness. Therefore, assessing surface roughness makes it possible to identify abnormalities in the production process. An original vision system was proposed to analyse changes in the profile surface roughness during the extrusion process. The constructed system, placed on the production line, consists of a monochromatic camera and prototype illumination that enable recording profiles of various shapes. The system allows for quick detection of changes in the quality of the profile surface based on the analysis of reflected light distribution. The work presents, among others, a comparison of vision measurement results obtained during extrusion with the process parameters recorded on the production line.

Keywords: Aluminium profiles; extrusion; vision system; surface roughness; support decision system

1. Introduction

The value of the market for aluminium alloy products was estimated at approximately $150 billion at the beginning of the 2020s. It is expected to almost double in the coming years and reach $260 billion in the early 2030s [1]. The development of industry segments such as transport and construction significantly contributes to this increase. New industry segments (e-mobility and renewable energy sources) widely use aluminium profiles.

By the classification presented in [2], the process of extruding aluminium profiles can be carried out in six variants. The two main types of the process, direct extrusion and indirect extrusion, can be implemented in different ways depending on the design of the punch (with a mandrel, without a mandrel). The most frequently used method of producing aluminium profiles is direct extrusion. Aluminium alloy in the form of a heated ingot is pressed through a properly shaped die that gives it the desired shape. The obtained profile's accuracy, surface roughness, and possibility of defects depend on the process parameters and the condition of devices and tools, including the die. The geometry of the cross-section of the extruded profile is no less important. The degree of complexity significantly affects the difficulty of extrusion, but this phenomenon is not clearly explained. This fact is evidenced by numerous attempts, starting from the 1960s [3] to define the concept of extrudability and to build a classification [4] that allows for organizing the cross-section geometry in terms of increasing extrusion difficulty [5].

To examine defects occurring in the process of extruding aluminium profiles [6], vision systems based on traditional cameras supported by convolutional neural networks [7] or based on gradient-only co-occurrence matrices (GOCM) [8], thermal cameras [9] and a combination of a CCD camera with a thermal imaging camera [10] are increasingly used.

Assessment of the condition of the profile surface, including its roughness, enables the identification of disturbances in the production process. These disturbances may affect not only the visual aspects of the profile surfaces but also the features important for their further processing [11]. Hence, it was decided to use roughness measurements to monitor the extrusion process. There are two basic types of roughness measurements: contact and non-contact. Due to the need for ongoing measurement on the production line during the extrusion process, only non-contact measurements are possible. In the field of non-contact measurements [12] performed online [13], laser light scattering models [14] can be used. A measurement system consists of a laser, a screen and a light detector (camera). The laser beam falling on the tested surface is reflected and partially scattered towards the screen. On the screen recorded by the detector, an image of the scattering of laser light reflected from the surface is obtained. This image is created by two reflection components: specular

[1] WARSAW UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL AND INDUSTRIAL ENGINEERING, NARBUTTA ST. 85, 02-524 WARSAW, POLAND

* Corresponding author: cezary.jasinski@pw.edu.pl

reflection and diffuse reflection. The intensity of reflected light (called reflectivity) for specular reflection depends on the surface roughness [15]. The share of both reflection components also depends on the surface roughness. Analysis of the distribution of light falling on the screen allows to determine the roughness of the tested surface with high accuracy [16]. Such measurements are possible for the surface roughness in the range of small values (below Ra 1 μm), which is consistent with the system's requirements for monitoring the extruded profile surface, for which the roughness Ra usually does not exceed 1 μm.

2. Experimental setup – research method

A point laser light source allows, after prior calibration, the determination of the roughness of the tested surface with high precision. However, using such a light source has two main disadvantages in the discussed application. The first is health and safety requirements, which could limit the possibilities of using laser sources reflected from the surface of highly reflective profiles. The second disadvantage is related to the possibility of measurement only at one point, which limits the profile area that can be measured simultaneously. This is especially important when extruding more than one profile simultaneously. To eliminate problems related to the use of a laser source, it was decided to replace it with an LED illumination, which was preceded by an analysis using the prepared light reflection model (Fig. 1). At the same time, the configuration of the vision system was changed by getting rid of the screen. The setup, using a point LED light source (Fig. 2b), still allows the detection of roughness changes similarly to the use of a laser source (Fig. 2a). A point light source enables the assessment of surface roughness. Still, it limits the measurement to only one point. To monitor roughness changes simultaneously in many places of the aluminium profile during the direct extrusion process, it was decided to use line illumination consisting of many point LED sources. It allows for the recording of roughness across the entire profile as it moves under the optical system. In the solution used, the reflection of the line light source from the tested surface is recorded by a camera. A light reflection model was used to analyse the possibility of recording changes in surface roughness using a line illumination based on the combination of many point sources arranged in a line. The model used is based on, among others, the relationship presented in the publication [10], which allows for determining the value of the reflectivity of a metallic surface as a function of its roughness. The model considers the brightness distribution of the reflected point light source recorded by the camera in directions parallel and perpendicular to the direction of the surface texture. The model uses the combination of specular and diffuse reflection described by formula (1).

$$I_k(x) = S_1 * \exp\left(\frac{-(x-c)^2}{2\sigma_1^2}\right) + S_2 * \exp\left(\frac{-(x-c)^2}{2\sigma_2^2}\right) \quad (1)$$

where: I_k – light intensity in the k direction (perpendicular or parallel) at the point with coordinate x; c – location of the reflection centre in the image and S_1, S_2, σ_1, σ_2 – experimentally determined parameters depending on the surface roughness and the configuration of the vision system.

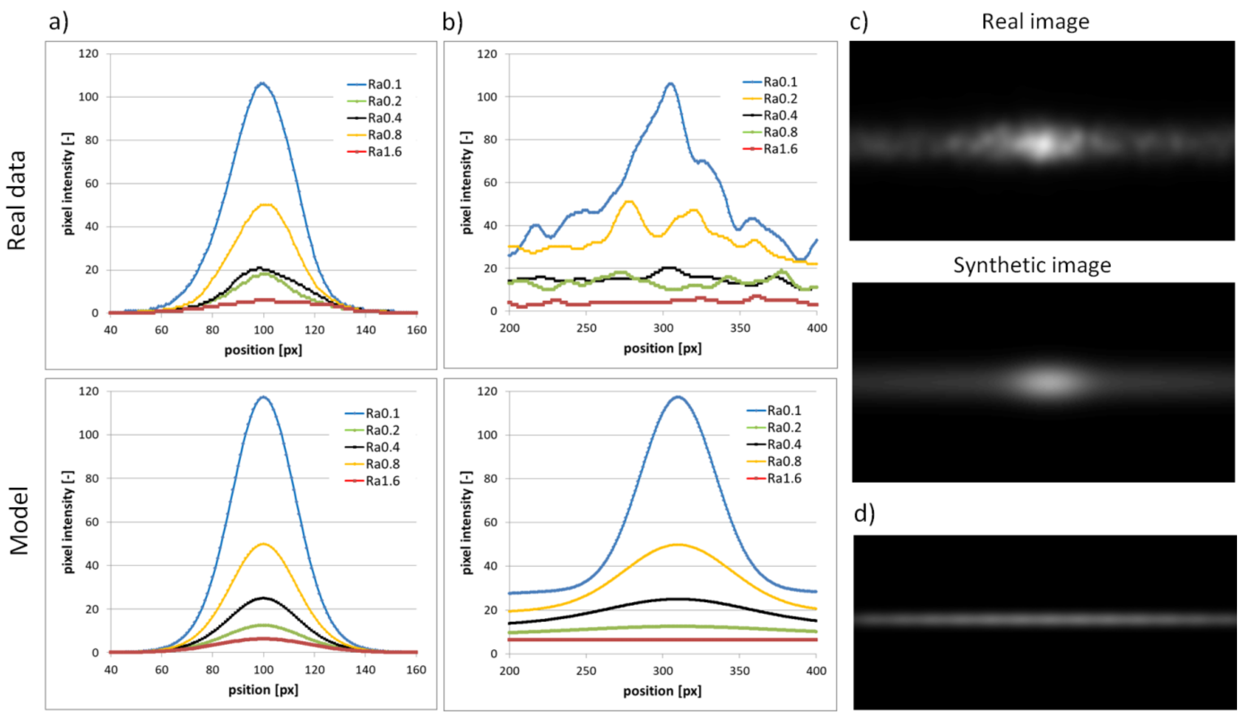

Fig. 1. Comparison of pixel brightness distributions for different roughnesses for experimental measurements and the model in the direction parallel to the surface texture (a) and perpendicular (b); comparison of the real and synthetic image for a point light source with a roughness of Ra 0.1 (c) and a synthetic image for a line illumination (d)

Comparison of pixel brightness distributions for experimental measurements (Fig. 1a,b upper graphs) and the model (Fig. 1a,b bottom graphs) indicate high compliance of the model with experimental data. Finally, based on the above model, synthetic images were generated for the point light source (Fig. 1c bottom image) and then for line illumination as a set of point light sources (Fig. 1d).

Line illumination causes changes in the characteristics of light reflected from the surface. Such illumination behaves like a set of point sources located close to each other, whose distributions overlap to create a complex reflected light system. This forced the creation of a new parameter called the Roughness Synthetic Parameter (RSP), which enables the analysis of reflected light for the line illuminator. Roughness assessment using the RSP parameter is based on the brightness distribution of reflected light in the direction perpendicular to the light line. The analysis can be performed along the entire length of the light line or at any point therein. Thanks to this, the RSP parameter can reflect in detail the changes occurring in the roughness in a specific place of the profile or average them over the entire currently examined surface. It should be noted that this parameter is also sensitive to other process conditions that affect the reflection, absorption and scattering of light. For this reason, during the process, changes cannot be made to the geometry of the vision system, the distance of the system from the examined surface, the geometry of the profile or the type of extruded aluminium alloy. These changes affect the parameters of reflected light and may cause incorrect results in assessing the roughness of a given profile. Due to its universality, resulting from the assumption of many point sources arranged in a line, the RSP parameter can also be used with point sources, as shown in Fig. 2, where the results for point and line illuminators are presented.

3. Industrial research

The analyses performed using synthetic images showed the possibility of estimating roughness using a line illuminator, confirmed by experimental tests (Fig. 2c). This enabled the construction of a vision system intended for installation on a production line. Therefore, it was decided to install the system in the production line of one of the Polish manufacturers. The line where the system was installed is equipped with a press that allows the extrusion of ingots with a diameter of 7” and the production of profiles weighing from several dozen grams to several kilograms per linear meter of the extruded profile. Profiles with a wide range of cross-sectional geometries were used in the tests, having both external surfaces flat (polygonal cross-sections) and convex (oval cross-sections). Three basic 6xxx series alloys were selected for testing, i.e. 6060, 6063 and 6082. The in-line extrusion speed, ranging from 2 to 50 [m/min], required adjusting vision system operating parameters, particulary exposure time and recording frequency. The prepared system is based mainly on an industrial camera and a prototype line illuminator in the shape of a semicircle. The illuminator works in strobe mode. A special controller was used to synchronize the camera with the illuminator. The camera is connected via the CoaXPress interface to a computer equipped with vision software prepared by the authors. The video recording parameters, i.e. exposure time, illuminator power, recording frequency, interface data throughput, etc., have been selected so that at maximum line speeds of up to 50 m/min it is possible to record the entire profile surface with a resolution of up to 0.2 mm/px. The short exposure time used (150 μs) allowed to minimize the impact of possible profile vibrations. After previously performed analyses, it was decided that the vision system would be placed behind

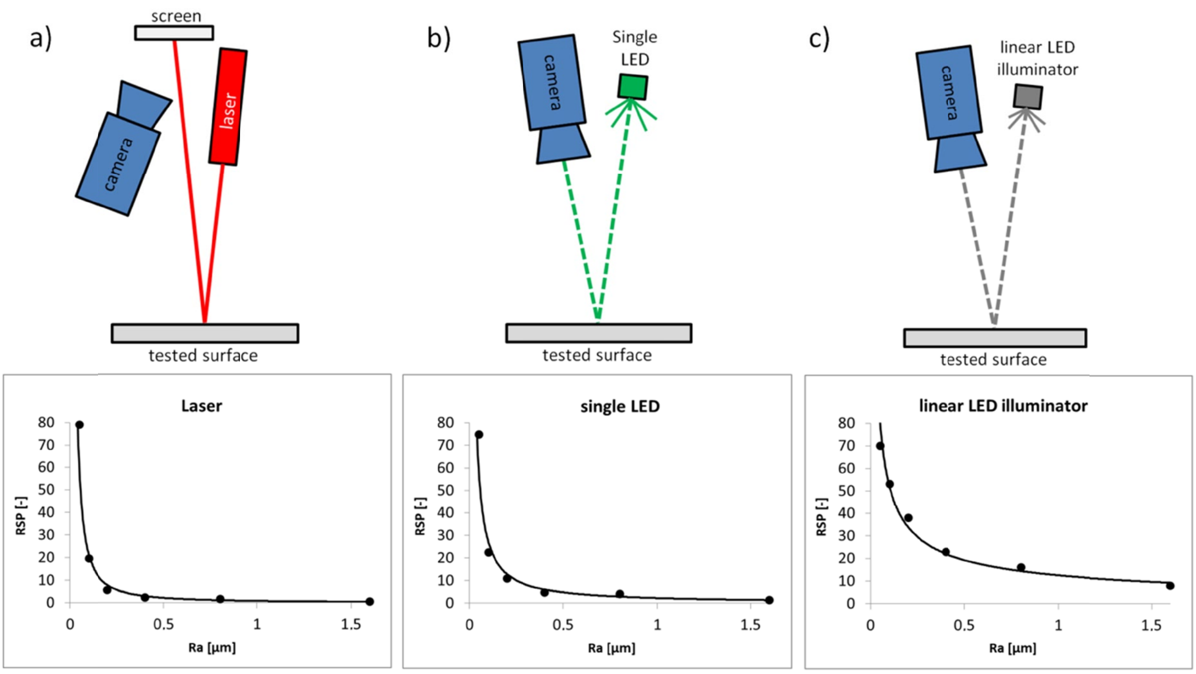

Fig. 2. Diagram of the experimental setup and the course of the RSP parameter as a function of roughness for laser light source (a), LED point light source (b) and line illumination (c)

the cooling system (Fig. 3), next to the cooling system housing (Fig 4a). The choice of such a location for the system resulted from several conditions:

- need to be install in a place with a limited temperature,
- acceptable delay in response to changes occurring during the extrusion process,
- high stability of the profile position on the transport rollers.

Placing the system directly behind the cooling system allowed for a reduction of the temperature, affecting the components of the vision system, including the illuminator. Depending on the extrusion speed, the profile at the registration area appears, with a delay of 30÷120 seconds after leaving the die. Placing the profile on rollers and guiding it through a puller makes the monitored element sufficiently stable.

The vision system for roughness assessment using the RSP parameter enables adaptive adjustment of the shape and size of one or several measurement areas to the extruded profiles. This allows to assess the roughness of any number of simultaneously extruded profiles of different widths and shapes. Due to the nature of the measurement, the measured surface must be visible through the vision system. Hence, measurements of internal surfaces are not possible using the proposed method. By default, the vision system provides an average RSP roughness assessment result from all active measurement areas. By observing this parameter, the line operator can quickly react to any anomalies occurring in its course, which may indicate changes in the roughness of the tested surface. Moreover, the system continuously records the images of the examined surfaces. This allows to compare the RSP results with a direct visual examination of the profile surface (Fig. 4b). Additionally, it is possible to set the limit values of the RSP parameter. When exceeded, an alarm appears, and photos of the surface are saved. This allows the operator to be informed about potentially critical surface quality and to see surface images captured during the alarm at any time. The RSP parameter and visual assessment combination should enable a detailed analysis of the anomaly and be used to prevent it.

Example images of defects on the surface of the profile recorded by the system after exceeding the limit RSP value during extrusion are shown in Fig. 5a. The examples were taken from profile (reference surface image – Fig. 5b) extruded with 12 m/min velocity.

4. Results and discussion

The vision system installed on the production line records the RSP value with a frequency of 2 Hz and 50 Hz in the event of an alarm, which is sufficient to detect even short-term changes. Fig. 6 shows an example of a five-hour RSP course. This course contains several characteristic elements. These include areas related to line downtime between die replacements, where RSP reaches zero.

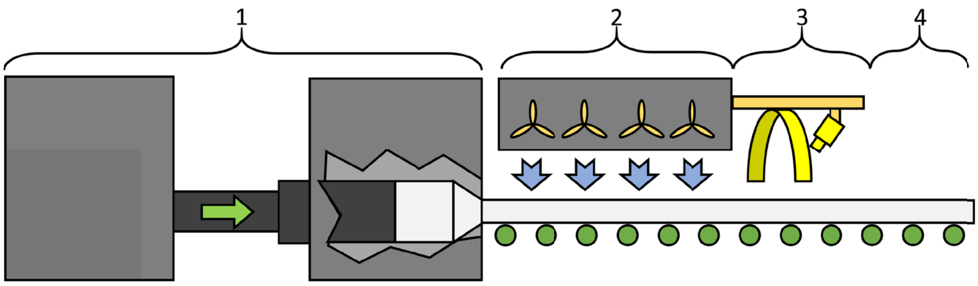

Fig. 3. Place of vision system installation on the production line: 1 – hydraulic press, 2 – cooling section, 3 – vision system, 4 – run-out table

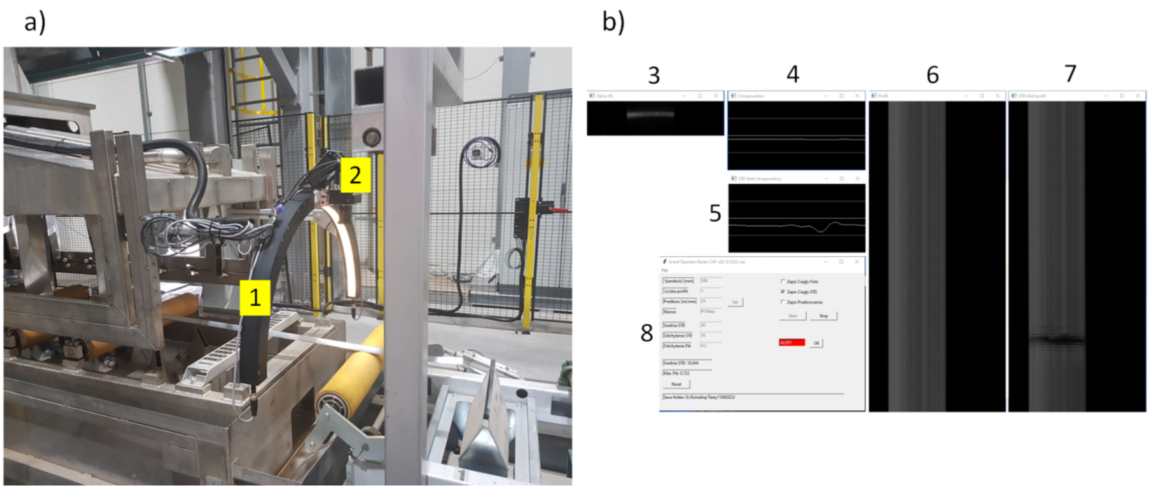

Fig. 4. Vision system mounted on the production line (a) and vision application windows (b): 1 – illuminator, 2 – camera, 3 – image recorded by the camera, 4 – current RSP waveform with marked alert limits, 5 – RPS waveform during the alert occurrence, 6 – current preview of the profile surface, 7 – preview of the profile surface during the alarm, 8 – control window

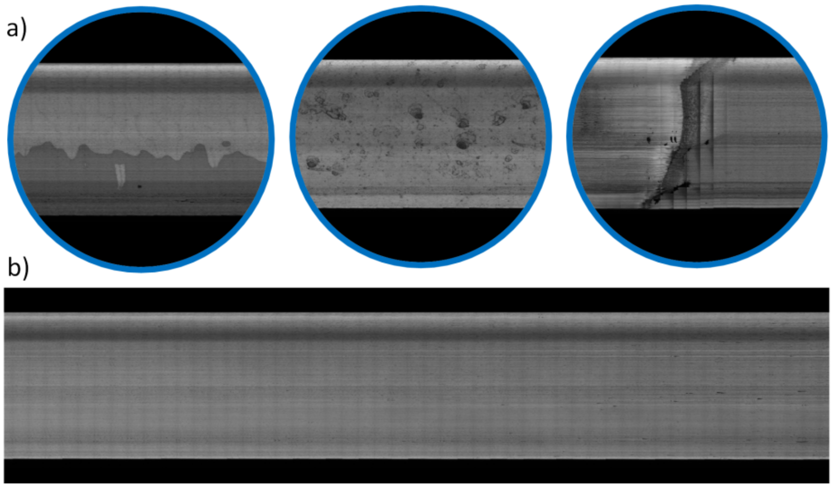

Fig. 5. Examples of anomalies recorded by the system on the profile surface (a) and the reference profile surface (b)

The waveform also shows regularly occurring short jumps in the RSP value (Fig. 7a), which appear when the connection zone of successive billets passes under the vision system. Observing the RSP course without exchanging the die, one can often notice a decrease in its value in the initial period of extrusion and then stabilization. Within a single billet (Fig. 7b), locating areas of disturbance resulting from the nature of the production line operation is also possible.

All the previously mentioned changes in the RSP value are related to the course of the production process and its parameters, which are manifested, among others, by changes occurring on the profile surface. Due to the configuration of the vision sys-

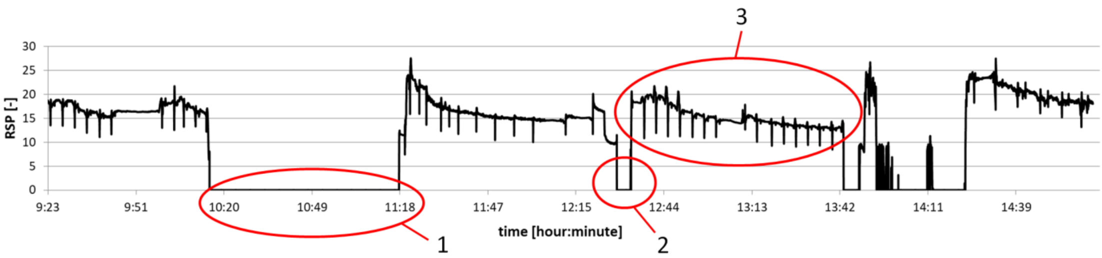

Fig. 6. Example of a five-hour course of the RSP value: 1 – production downtime, 2 – die replacement, 3 – course for a single die

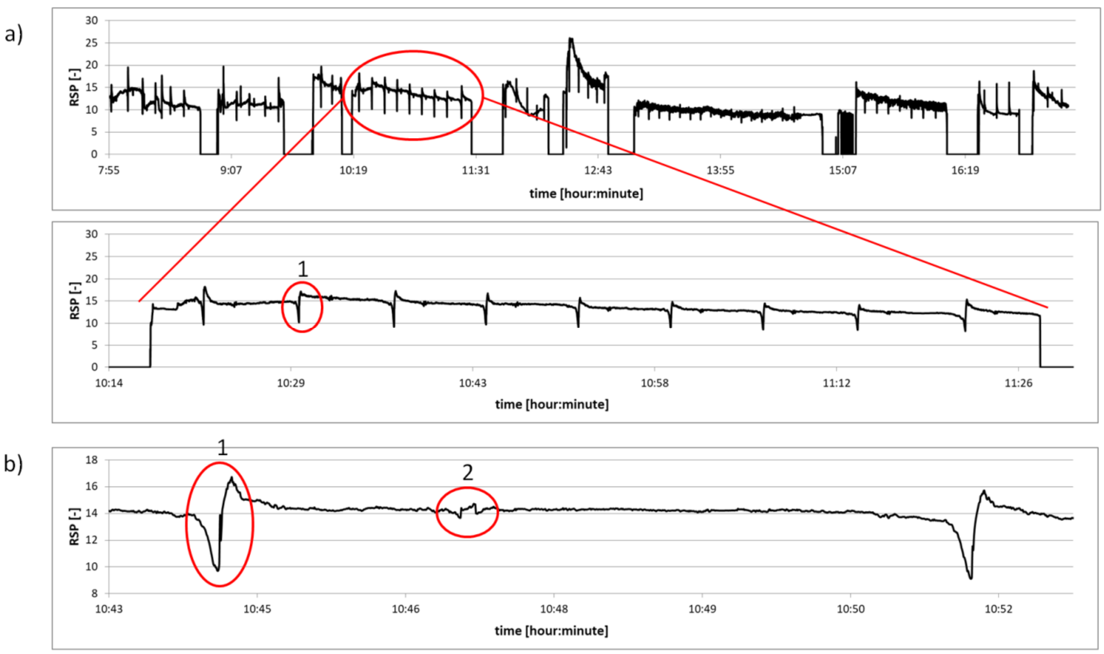

Fig. 7. Close-up of the RSP waveform for one matrix (a) and the waveform for a single billet (b): 1 – area of connecting billets, 2 – disturbance within a single billet

tem, the RSP value depends not only directly on the condition of the profile surface but also enables the detection of various types of disturbances, such as deflection of the profile causing a change in the orientation of the examined surface in relation to the vision system. During the research, a series of extrusion tests were performed. In addition to recording the RSP value, selected operating parameters of the production line were also recorded at a frequency of 2 Hz. These included punch speed, puller speed, profile temperature at the die exit and profile temperature after cooling (near the place of vision measurement). The recorded data were compared to the RSP waveform (Fig. 8), considering the time shift between the profile leaving the matrix and its appearance under the vision system.

Analyzing the compiled data allows observing certain dependencies between the recorded waveforms, such as the relationship between temperature and surface quality. However, not all relationships are clear and vary depending on the profile being extruded.

In turn, the observable disturbance in the RSP course for a single billet (Fig. 9a) could be perceived as a recording disturbance caused by possible vibrations during a sudden change in the puller speed. In fact, it is related to the change in the qual-

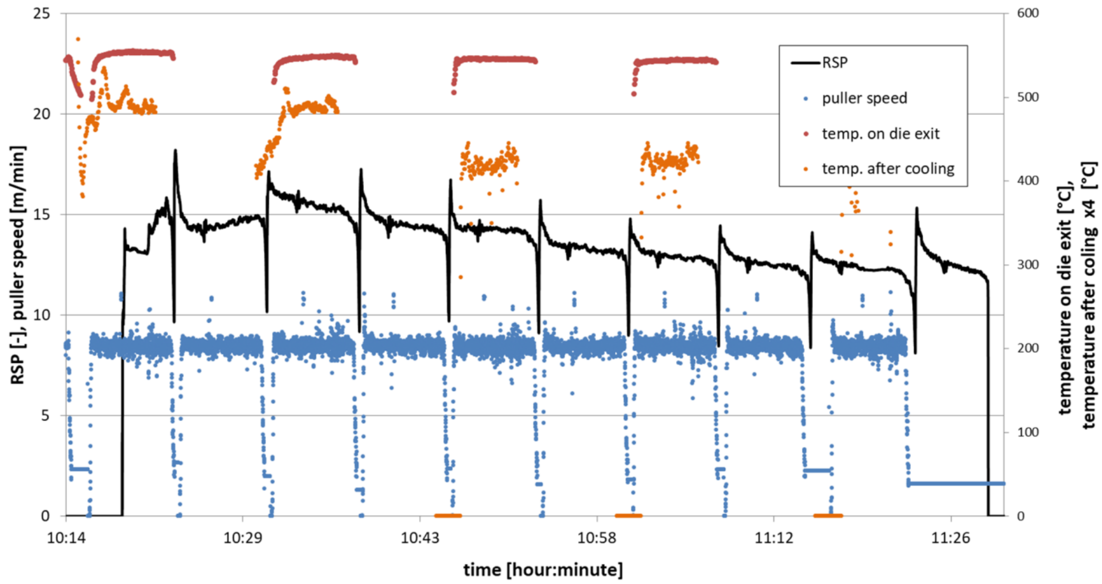

Fig. 8. Compilation of the RSP waveform with temperature and puller speed measurements

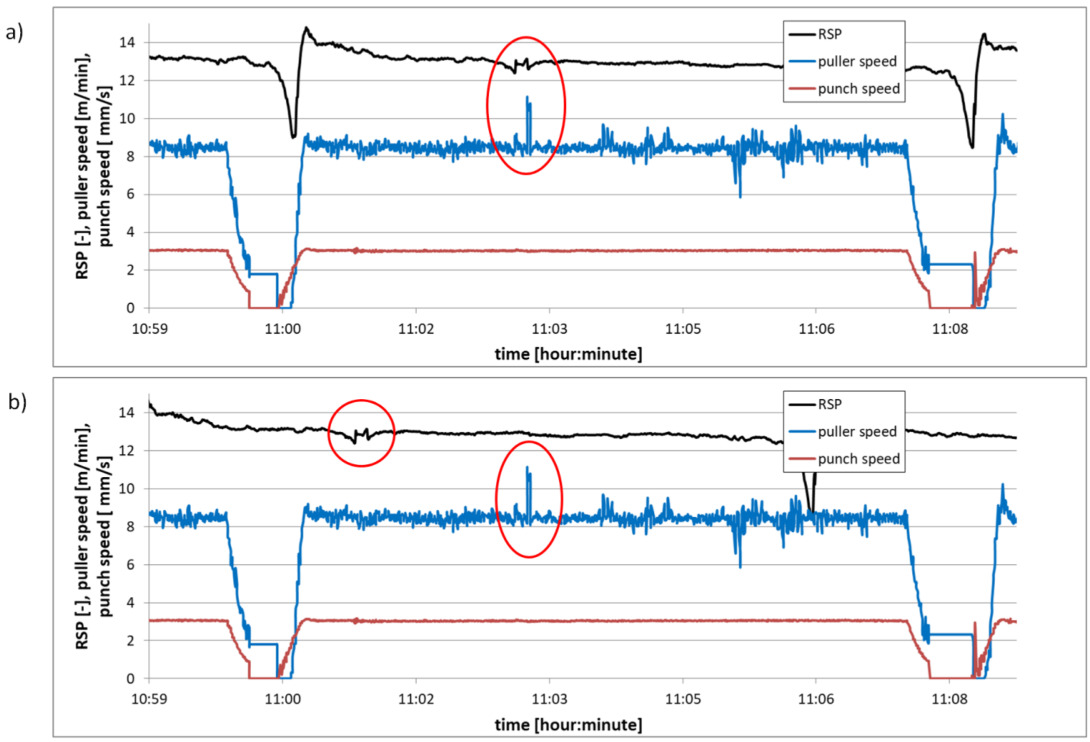

Fig. 9. The disturbance (marked in red), visible in the RSP comparison with puller and punch speeds with time shift (a) and without time shift (b)

ity of the profile surface, as indicated by RSP combined with the speed of the puller and punch without time shift (Fig. 9b). It turns out that the RSP disturbance occurs at a different time point than the velocity change.

The recorded changes in the RSP value and, therefore, changes in the quality of the profile surface cannot be fully explained by standardly recorded process parameters. However, apart from the standardly recorded parameters, there are a number of variables that influence the result of the profile extrusion process. One of such parameters is the condition of the die surface, which cannot be directly verified during extrusion. It is known that the die is subject to wear and dirt during operation, which directly affects the quality of the profile surface. This phenomenon is visible in the RSP course as a rapid decrease in its value in the initial period of extrusion, when the cleaned die surface undergoes rapid changes until it becomes relatively stable.

5. Conclusions

Based on the research conducted and the obtained results, it is possible to formulate the following conclusions:

- The vision system equipped with a line illumination enables the detection of changes in the surface quality of aluminium profiles, including roughness, during the extrusion process,
- The vision system based on a prototype illuminator and dedicated software enables adaptive adjustment of the measurement to various geometries and the number of simultaneously extruded profiles.
- The prototype vision system enables the detection of anomalies in the production process that may be difficult to find based on other parameters recorded on the line and allows to detect changes in surface quality also resulting from factors that cannot be directly monitored during production.
- Measurements based on the analysis of reflected light is sensitive not only to changes in the quality of profile surfaces, but also disturbances related to changes in profile geometry
- Due to the different locations of the production line measurement systems and the prototype vision system, special time synchronization of data is necessary.
- The location of the prototype station behind the cooling system ensured appropriate working conditions for its elements and an acceptable distance from the die exit.

Finally, it should be stated that the designed surface condition monitoring system allows the operator to make quick decisions in order to prevent the surface quality from decreasing below the assumed values.

REFERENCES

[1] Aluminium Market, Global Opportunity Analysis and Industry Forecast, 2021-2031, Allied Market Research 2022. https://www.alliedmarketresearch.com/aluminium-market, Nov. 2023

[2] T. Sheppard, Extrusion of Aluminium Alloys, Springer, (1999). DOI: https://doi.org/10.1007/978-1-4757-3001-2

[3] K. Laue, Verfahrenstechnik der Nichteisenmetall-Halbzeugindustrie: XVII. Möglichkeiten werkstoffgerechter Gestaltung von Leichtmetallprofilen. Int. J. Mater. Res. **54** (12), 667-671. (1963). DOI: https://doi.org/10.1515/ijmr-1963-541201

[4] S.Z. Qamar, J.Ch. Chekotu, M. Al-Maharbi, K. Alam, Shape Complexity in Metal Extrusion: Definitions, Classification, and Applications. Arab. J. Sci. Eng. **44**, 7371-7384 (2019). DOI: https://doi.org/10.1007/s13369-019-03886-8

[5] H. Sadłowska, A. Kochański, A. Cena, P. Grzegorzewski, Nowe podejście do klasyfikacji profili wyciskanych z aluminium, Materiały konferencyjne, XIV Konferencja Naukowa, Odkształcalność Metali i Stopów, 22-25 listopada 2022 r., Łańcut Zamek.

[6] F.M. Neuhauser, G. Bachmann, P. Hora, Surface defect classification and detection on extruded aluminum profiles using convolutional neural networks. Int. J. Mater. Form. **13**, 591-603 (2020). DOI: https://doi.org/10.1007/s12289-019-01496-1

[7] Yu Wang, Yun-Sheng Wei, Zhi-Ze Wu, Zhi-Huang He, Kai Wang, Ze-Sheng Ding, Le Zou, Adaptive convolutional neural network for aluminum surface defect detection. Comp. Mater. Sci. **227** (2023). DOI: https://doi.org/10.1016/j.commatsci.2023.112262

[8] A. Chondronasios, I. Popov, I. Jordanov, Feature selection for surface defect classification of extruded aluminum profiles. Int. J. Adv. Manuf. Technol. **83**, 33-41 (2016). DOI: https://doi.org/10.1007/s00170-015-7514-3

[9] P. Garbacz, T. Giesko, Inspection of aluminium extrusion using infrared thermography, 11th International Symposium on Measurement and Quality Control, September 11-13, 2013, Cracow-Kielce, Poland.

[10] P. Garbacz, T. Giesko, A. Mazurkiewicz, Inspection method of aluminium extrusion process. Archiv. Civ. Mech. Eng. **15**, 631-638 (2015). DOI: https://doi.org/10.1016/j.acme.2015.02.005

[11] H. Sadłowska, Ł. Morawiński, C. Jasiński, Strain measurements in free tube hydroforming process. Arch. Metall. Mater. **65**, 257-263 (2020). DOI: https://doi.org/10.24425/amm.2020.131725

[12] C.B. Rao, B. Raj, Study of engineering surfaces using laser-scattering techniques. Sadhana **28**, 739-761 (2003). DOI: https://doi.org/10.1007/BF02706457

[13] R.S. Lu, G.Y. Tian, On-line measurement of surface roughness by laser light scattering. Meas. Sci. Technol. **17**, 1496-1502 (2006). DOI: https://doi.org/10.1088/0957-0233/17/6/030

[14] C.J. Tay, S.H. Wang, C. Quan, C.K. Ng, Surface roughness measurement of semi-conductor wafers using a modified total integrated scattering model. Optik **113** (7), 317-321 (2002). DOI: https://doi.org/10.1078/0030-4026-00169

[15] H.E. Bennett, J.O. Porteus, Relation between surface roughness and specular reflectance at normal incidence. J. Opt. Soc. Am. **51**, 123-129 (1961).

[16] Z. Zhenrong, Z. Jing, G. Peifu, Roughness characterization of well-polished surfaces by measurements of light scattering distribution. Opt. Appl., XL (4), (2010)