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Data Availability
Data openly available in a public repository that does not issue DOIs. Source code and data are available on GitHub at the following URLs:

Project Home `https://github.com/pyroll-project`

Core Package `https://github.com/pyroll-project/pyroll-core`

Benchmark Input and Data `https://github.com/pyroll-project/pyroll-pub1-benchmark`

Conflicts of Interest
The authors declare no conflicts of interest.

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Rolling Process Variation Estimation Using a Monte-Carlo Method

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1 Introduction

All technical processes are subject to certain variations. Knowledge and control of these variations is crucial for process stability and product quality. Sources of variations in a process are the variations already present in the input workpiece and newly generated variations due to imperfections of the process itself. In the case of wire and bar hot rolling industry regarded here, not only the product geometry, but also the final material properties sre highly sensitiv to the process conditions. Especially the temperature evolution of the workpiece within the rolling line has high impact on the microstructural transformation processes happening before, during and after forming. The product's microstructural state determines the mechanical properties and therefore its behavior in further processing and application. Current alloy concepts in the steel industry increase this problem, as the process window gets more narrow to achieve the property requirements for high-tech applications. The controlled combination of forming and thermally activated material transformation is commonly subsumed under the term thermo-mechanical treatment.

The classic way of analysing variational behavior with mathematical tooling is the error propagation using first order Taylor series expansions (see f.e. [1]). This concept is widely used in science and industry, especially to determine the error of indirect measurement processes. This procedure has two main problems. First, one needs to determine the first derivatives of the regarded function in each dimension, either analytically or numerically, which is rather problematic if the function is complicated. Second, the error is commonly represented in terms of the variance, so there is only information about the spread, but not about the shape of the distribution inherent.

The usage of a Monte-Carlo Method circumvents these problems, and shall be proposed with this work. The term Monte Carlo Method (MCM) generally refers to a class of methods, which are characterized by the use of random numbers. These methods are rather diverse and serve different purposes. Here, the term shall be used for the concept of drawing random numbers as input for a function and analysing the results of several evaluations of this function, with different random inputs, with statistical methods. A detailed overview on this type of Monte Carlo methods is given by Lemieux [2]. The nature of the function can be complicated, even of a black-box type, where nothing about the internals of the function is known but the input and

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output interfaces. In this case, Monte Carlo methods can provide valuable information about the behavior of the function while altering inputs. Also, the complete distribution of the input variables is included in the estimation and is reflected in the results.

Here, the function equals the simulation procedure, so it is generally known, but complicated. For example, it is generally not possible, to compute derivatives of the outputs in dependence on the inputs in an analytical way. Even numerical derivation is hard, due to the multi-dimensional nature of most natural or technical systems and the pronounced non-linear behavior of the function.

The use of Monte Carlo methods for the analysis of variations in technical processes was reported before in the field of assembly of complicated structures, like in mechanical engineering and building construction (f.e. [3, 4, 5, 6, 7, 8]). However, in the field of rolling processes, there was no such attempt yet to the knowledge of the authors. The authors have previously used a similar approach to model powder morphology influences in sintering processes [9, 10]. The current work shall show the possibility of the application of Monte Carlo methods for the analysis of process variations in rolling processes. The focus lies hereby on the estimation of the workpiece temperature evolution and its impact on the microstructure state of the final product. The influence of variations in the initial workpiece and within the regarded process route is analysed and evaluated. Due to the need of a large number of function evaluations (simulation runs), the evaluation speed of the process model is crucial to the applicability of this approach.

Rolling simulation is currently dominated by the use of finite element (FE) based models. These are offering high accuracy and high resolution results at the expense of high computational resource usage. So these methods are inconvenient for the current need. Therefore, one-dimensional approaches shall be used here. These offer less accuracy and limited resolution, but are computable within fractions of seconds on typical personal computer systems. The current work is based on the open-source rolling simulation framework PyRolL [11], developed by the authors, which is a fast, open and flexible software package mainly aimed at groove rolling in reduction passes. The models used for the different parts of the problem can be exchanged and extended with low effort to the users needs.

2 Methods

2.1 Experimental Procedure

The object of the current investigation is the operation of the experimental semi-continuous rolling plant located at the Institute of Metal Forming, TU Bergakademie Freiberg. It consists of a two-high reversing roughing stand and four continuous finishing stands. The pass schedule of the current work consists of 10 oval-round reversing passes followed by 4 oval-round continuous finishing passes. A 50 mm round workpiece made of a mild structural steel is rolled down to 8 mm diameter. Details of the schedule are provided in Table 1 and Table 2, as well as in the supplemental material [12]. The supplemental material includes the whole code for data processing and simulation needed to reproduce the results of this work.

To achieve statistical certainty, about 50 rolling trials were performed. A major source of variation in these trials is the manual feeding of the workpiece into the reversing passes. The duration of those is scheduled with about 6 seconds. The actual time needed has to be investigated in this work, see subsection 2.3 for details.

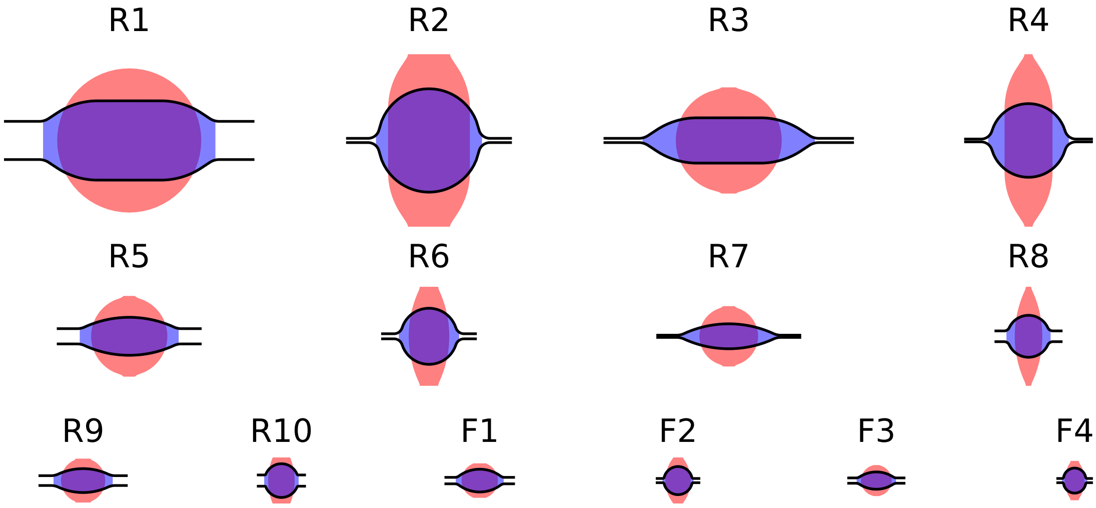

Figure 1: True Scaled Illustration of the Investigated Pass Sequence

Table 1: Principal Data of the Investigated Pass Sequence

#	Type	w mm	h mm	s mm	R_W mm	v $\mathrm{m\,s^{-1}}$
R1	swedish oval	60.0	28.0	13.5	160.5	1
R2	round	36.6	36.5	1.5	160.5	1
R3	swedish oval	60.0	16.0	1.5	160.5	2
R4	round	27.6	26.0	1.0	160.5	2
R5	circular oval	34.0	13.4	5.4	160.5	2
R6	round	20.4	19.8	1.8	160.5	2
R7	circular oval	34.0	8.8	0.8	160.5	2
R8	round	14.7	14.8	3.8	160.5	2
R9	circular oval	20.1	8.5	3.5	160.5	2
R10	round	11.3	12.0	4.0	160.5	2
F1	circular oval	16.1	8.1	2.3	107.5	4.9
F2	round	10.1	10.0	1.5	107.5	6.1
F3	circular oval	13.1	6.1	1.9	107.5	7.9
F4	round	8.0	8.9	1.5	85.0	10

Table 2: Principal Data of the Input Workpiece

d_0 mm	T_0 K	ϱ $\mathrm{kg\,m^{-3}}$	c_p $\mathrm{J\,kg^{-1}\,K^{-1}}$
50.0	1373.2	7500.0	690

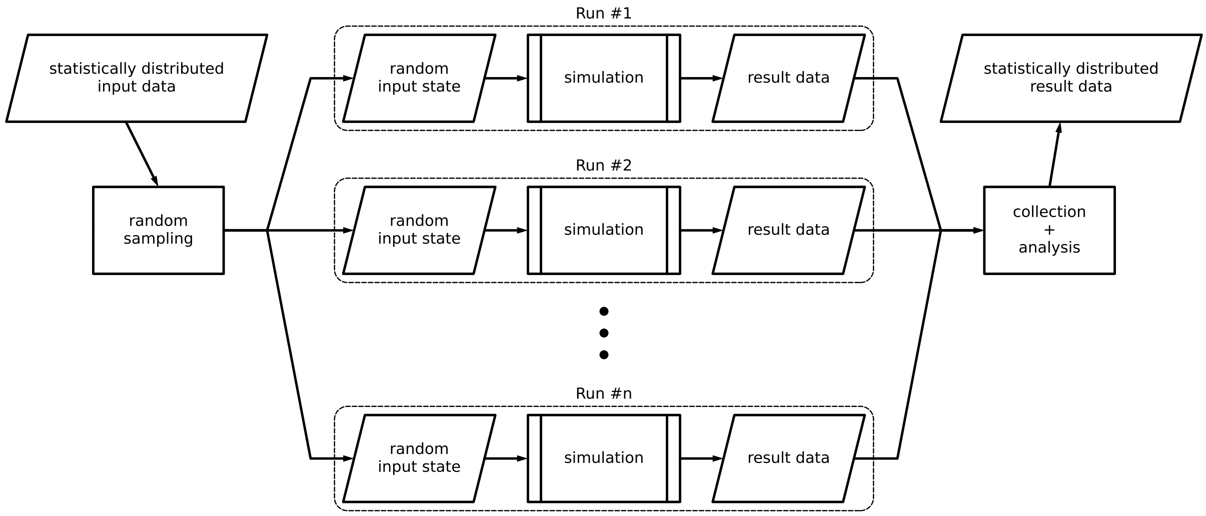

Figure 2: Chart of the Concept of Variation Estimation Using Monte Carlo Techniques

2.2 Monte-Carlo Approach

The basic idea of the approach shown here is to simulate the rolling process several times with different input values, which are drawn by a random number generator according to predefined statistical distributions. Afterwards, the distribution of the results can be analysed by classic methods of descriptive statistics to obtain information about the process' variational behavior. The principle is shown in Figure 2.

This approach provides information about the overall variational behavior of the process. If a single source of variation is introduced in the input, the reaction of the process on this variable can be analysed. The count of variation sources introduced is generally unbounded. In contrast to classic Taylor series error propagation, the computational effort does not directly increase remarkably with increasing count of investigated parameters. However, an increase in sample size can be necessary to achieve sufficient certainty. The tracing back of result variations to the input can be done using classic correlation methods of descriptive statistics, however, with the same typical caveats. The main benefit of the approach is, that no information about the internals of the simulation procedure is needed for variational analysis, especially there is no need for derivatives of result values in dependence on the input. The simulation procedure can generally be treated as black box with defined input and output interfaces.

The key problem is to obtain data describing the variations of the input variables. In this work two showcases shall be regarded: first the variation of the initial workpiece in diameter and temperature, second the variation of the inter-pass durations between the reversing passes. This choice was taken, since two fundamentally different types of variation sources were suspected. First, sources in the initial workpiece, which are applied only once, but traverse the whole process line. Second, variations in the process itself, which affect the workpiece state in each process step anew.

2.3 Statistical Data Acquisition

The pilot plant at IMF is equipped with several measurement and data collection systems. Data from a number of rolling trials have been collected and analysed to obtain the interpass durations

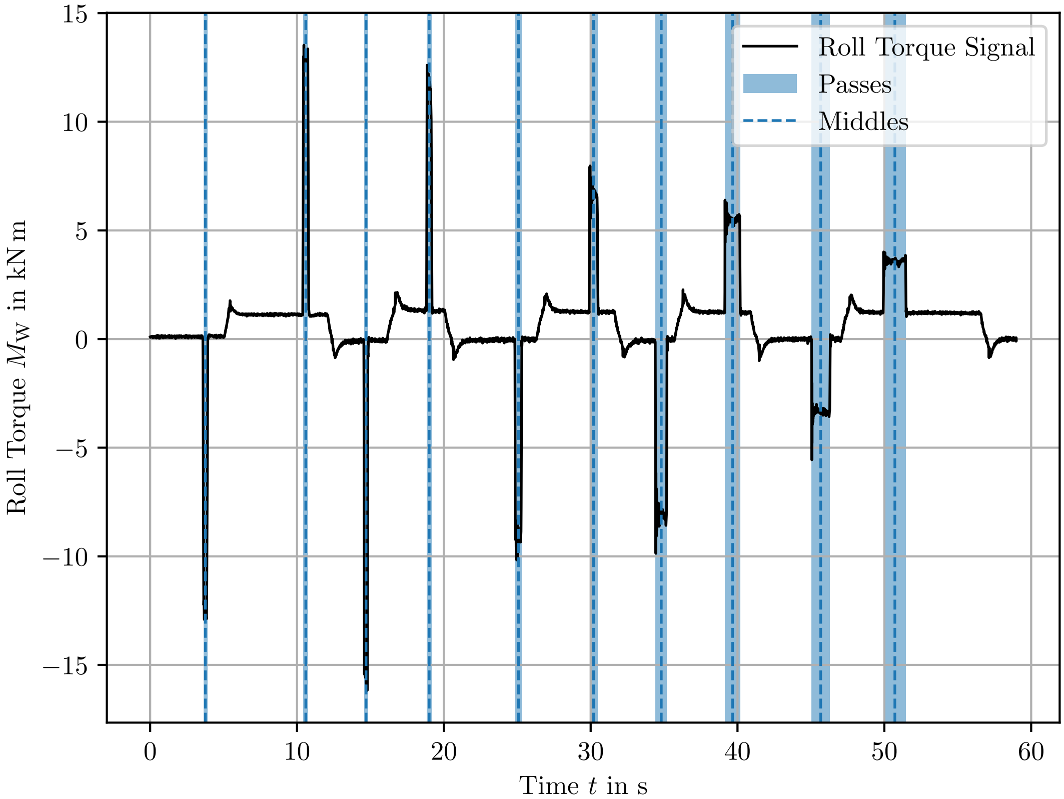

Figure 3: Example Roll Torque Signal With Automatically Determined Roll Pass Locations

t_P between the reversing passes. The complete dataset and analysis routines are available in the supplemental material [12].

The question of varying inter-pass durations is crucial for scientific experiments on microstructure evolution, but currently often neglected. Mostly, only flat durations between the reversing passes are included in the design calculations. Due to manual transport and feed of the workpiece to the following roll pass, the scheduled inter-pass durations are never realized in practice. Although, these deviations from the schedule influence the microstructure evolution of the sample, as well as the actual conditions in the roll passes. The current approach is aimed to help quantifying these deviations.

To obtain the pause durations from the timeline data, the passes have to be identified automatically. This is done by analysing the roll torque signal as plotted in Figure 3. The original signal is first downsampled and smoothed. Then, a difference filter is applied and the peaks of the resulting signal are determined. These peaks denote start and end times of the roll passes, the middle time of those is used as time coordinate of the roll pass. The distances of those are used as the inter-pass durations.

For the approximative description of the durations' distribution, a gamma distribution was used, which is a generalized exponential distribution. The probability density function (PDF) of the gamma distribution is defined as in Equation 1, where Γ is the gamma function and $\alpha > 0$ and $\beta > 0$ are parameters.

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} \exp(-\beta x) \tag{1}$$

Since the gamma distribution is only defined for $x > 0$, but no interpass durations below a certain value occur due to technical restrictions, the distribution was modified by introducing a minimal interpass duration t_{P0} with $x = t_{\mathrm{P}} - t_{\mathrm{P0}}$. So there are three free parameters α, β and t_{P0} for fitting of the distribution function. The fitting is done using least squares optimization of the resulting PDF function on the density histogram of the data.

Regarding the geometric variations of the input workpiece, the diameter of the samples was determined at multiple spots using a calibre. The initial temperature of the samples was determined using the pyrometer installed near the roll gap entry.

2.4 Core Simulation Procedure

In the current work, the open-source rolling simulation framework PyRolL [11] was used to simulate the rolling process. Generally, the shown approach can be used with every rolling simulation software available, since the procedure does not depend on any internals of the simulation. A fast simulation approach, however, is favourable, since the simulation has to be done several, up to hundreds of, times. The models used here are of one-dimensional type, thus, they lack of resolution in other directions as the rolling direction and provide only limited accuracy, but at the benefit of high solution speed. They typically combine empirical approaches with simplified analytical solutions. The simulation was done with the basic configuration of PyRolL, which includes the empirical roll force and torque model of Hensel and Spittel [13], an integral thermal model approach according to Hensel et al. [14], contact area estimation according to Zouhar [15] and roll flattening according to Hitchcock and Trinks [16]. Spreading was simulated using the equivalent flat pass according to Lendl [17, 18, 19] in conjunction with the spreading equation of Wusatowski [20]. Details of software construction and model equations are provided in the documentation of PyRolL [21].

The object of the current investigation is the operation of the experimental semi-continuous rolling plant located at the Institute of Metal Forming, TU Bergakademie Freiberg. The process consists of several reversing passes and up to four continuous finishing passes. The feeding in the reversing passes is done manually, so there is an obvious source of variation in process, since the human operator can not achieve precisely a defined duration between the passes. In this work the evolution of variation regarding temperature and microstructure state

3 Results

3.1 Experimental Results

3.1.1 Input Workpiece Variation

3.1.2 Pause Duration Variation

3.2 Simulation Results

In the following, three questions shall be investigated and answered:

1. What is the difference in behavior of variations sourced in the input workpiece and arising within the process?

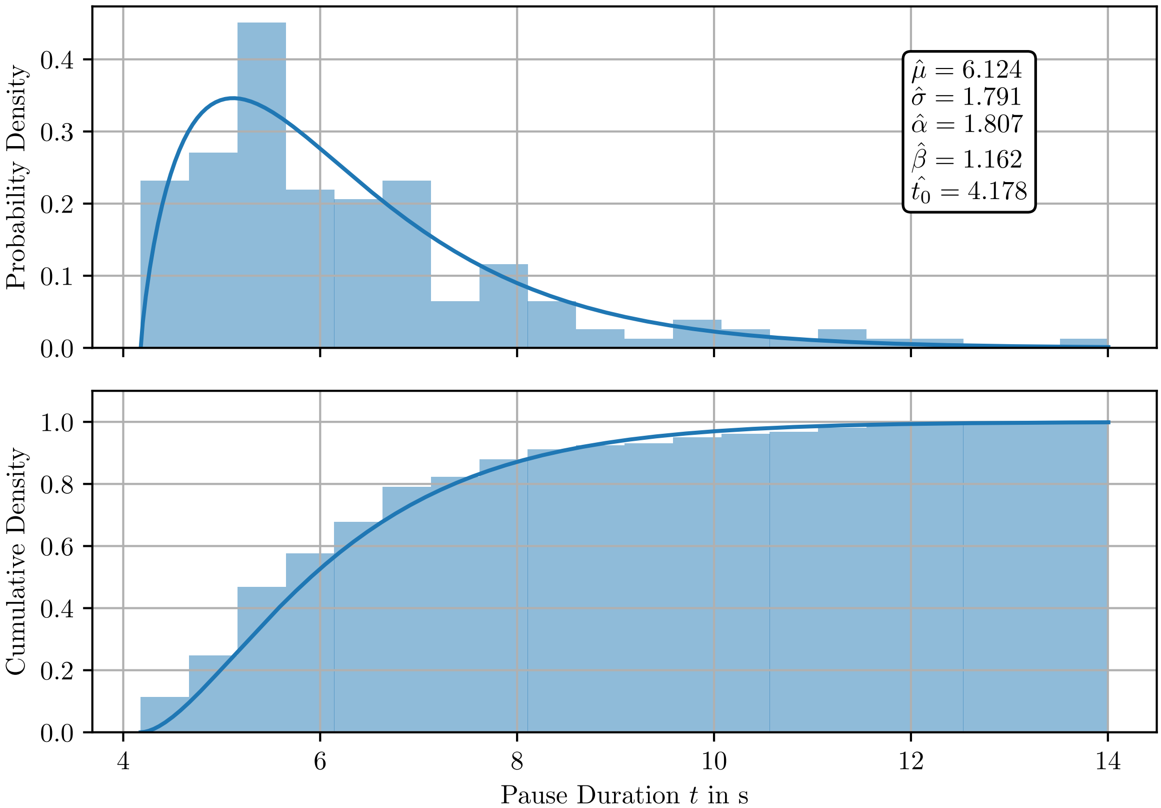

Figure 4: Density and Cumulative Histograms of Inter-Pass Durations With Fitted Gamma Distribution

2. What is the influence of elastic mill response on the variational behavior of the process?
3. Is there a minimum number of passes needed to eliminate variations of the input workpiece?

For this distinct simulations were carried out and compared with each other and the experimental data.

3.2.1 Different Sources of Variation

3.2.2 Influence of Elastic Mill Response

3.2.3 Elimination of Input Variation

4 Summary and Outlook

References

[1] H. H. Ku. "Notes on the Use of Propagation of Error Formulas". In: *Journal of Research of the National Bureau of Standards, Section C: Engineering and Instrumentation* 70C.4 (Oct. 1966), p. 263. ISSN: 0022-4316. DOI: `10.6028/jres.070C.025`. (Visited on 04/12/2023).

[2] C. Lemieux. *Monte Carlo and Quasi-Monte Carlo Sampling*. Springer New York, 2009. ISBN: 978-0-387-78165-5. DOI: `10.1007/978-0-387-78165-5`.

[3] C.-Y. Lin, W.-H. Huang, M.-C. Jeng, and J.-L. Doong. "Study of an Assembly Tolerance Allocation Model Based on Monte Carlo Simulation". In: *Journal of Materials Processing Technology* 70.1 (Oct. 1, 1997), pp. 9–16. ISSN: 0924-0136. DOI: `10.1016/S0924-0136(97)00034-4`. (Visited on 12/02/2022).

[4] Zhengshu Shen, Gaurav Ameta, J. J. Shah, and J. K. Davidson. "A Comparative Study Of Tolerance Analysis Methods". In: *Journal of Computing and Information Science in Engineering* 5.3 (May 16, 2005), pp. 247–256. ISSN: 1530-9827. DOI: `10.1115/1.1979509`. (Visited on 12/02/2022).

[5] J.-Y. Dantan and A.-J. Qureshi. "Worst-Case and Statistical Tolerance Analysis Based on Quantified Constraint Satisfaction Problems and Monte Carlo Simulation". In: *Computer-Aided Design* 41.1 (Jan. 2009), pp. 1–12. ISSN: 00104485. DOI: `10.1016/j.cad.2008.11.003`. (Visited on 09/30/2022).

[6] A.-J. Qureshi, J.-Y. Dantan, V. Sabri, P. Beaucaire, and N. Gayton. "A Statistical Tolerance Analysis Approach for Over-Constrained Mechanism Based on Optimization and Monte Carlo Simulation". In: *Computer-Aided Design* 44.2 (Feb. 1, 2012), pp. 132–142. ISSN: 0010-4485. DOI: `10.1016/j.cad.2011.10.004`. (Visited on 12/02/2022).

[7] H. Yan, X. Wu, and J. Yang. "Application of Monte Carlo Method in Tolerance Analysis". In: *Procedia CIRP*. 13th CIRP Conference on Computer Aided Tolerancing 27 (Jan. 1, 2015), pp. 281–285. ISSN: 2212-8271. DOI: `10.1016/j.procir.2015.04.079`. (Visited on 12/02/2022).

[8] C. Rausch, M. Nahangi, C. Haas, and W. Liang. "Monte Carlo Simulation for Tolerance Analysis in Prefabrication and Offsite Construction". In: *Automation in Construction* 103 (July 2019), pp. 300–314. ISSN: 09265805. DOI: `10.1016/j.autcon.2019.03.026`. (Visited on 09/30/2022).

[9] M. Weiner, M. Schmidtchen, and U. Prahl. “A New Approach for Sintering Simulation of Irregularly Shaped Powder Particles – Part I: Model Development and Case Studies”. In: *Advanced Engineering Materials* (Feb. 2022), p. 2101513. DOI: 10.1002/adem.202101513.

[10] M. Weiner, T. Zienert, M. Schmidtchen, J. Hubálková, C. G. Aneziris, and U. Prahl. “A New Approach for Sintering Simulation of Irregularly Shaped Powder Particles – Part II: Statistical Powder Modelling”. In: *Advanced Engineering Materials* (May 25, 2022), adem.202200443. ISSN: 1438-1656, 1527-2648. DOI: 10.1002/adem.202200443. (Visited on 05/27/2022).

[11] M. Weiner, Renzing, C., M. Stirl, and M. Schmidtchen. *PyRolL*. Version 2.0.2. Institute of Metal Forming, TU Bergakademie Freiberg. DOI: 10.5281/zenodo.7817100.

[12] M. Weiner, C. Renzing, R. Pfeifer, M. Schmidtchen, and U. Prahl. *Supplemental Material to 'Estimation of Rolling Process Variation by Usage of a Monte-Carlo Method' in ****. 2023. URL: https://placeholder.

[13] A. Hensel and T. Spittel. *Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren*. VEB Deutscher Verlag für Grundstoffindustrie, 1978.

[14] A. Hensel, P. Poluchin, and W. Poluchin. *Technologie der Metallformung*. Deutscher Verlag für Grundstoffindustrie, 1990.

[15] G. Zouhar. *Umformungskräfte beim Walzen in Streckkaliberreihen*. Vol. 1. Berlin: Akademie Verlag Berlin, 1960.

[16] J. H. Hitchcock and W. Trinks. *Roll Neck Bearings*. Report of Special Research Committee on Roll Neck Bearings. New York: ASME, 1935, p. 51.

[17] A. E. Lendl. “Rolled Bars - Part I - Calculation of Spread between Non Parallel Roll Surfaces”. In: *Iron and Steel* 21.14 (1948), pp. 397–402.

[18] A. E. Lendl. “Rolled Bars - Part II - Application of Spread Calculation to Pass Design”. In: *Iron and Steel* 21.14 (1948), pp. 601–604. ISSN: 0021-1532.

[19] A. E. Lendl. “Rolled Bars - Part III - Application of Spread Calculation to Diamond Passes”. In: *Iron and Steel* 22.12 (1949), pp. 499–501. ISSN: 0021-1532.

[20] Z. Wusatowski. *Fundamentals of Rolling*. Vol. 1. London: Pergamon Press, 1969. ISBN: 978-0-08-012276-2.

[21] M. Weiner, Renzing, C., M. Stirl, and M. Schmidtchen. *PyRolL*. Version 1.0.5. Institute of Metal Forming, TU Bergakademie Freiberg. URL: https://pyroll-project.github.io.