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Rolling process variation estimation using a Monte-Carlo method

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Abstract. No technical process is totally certain, but subjected to uncertainties. They may originate in the process itself or in the input materials and determine the precision of the product. Two questions are here especially of interest: 1) How do variations in the input workpiece evolve within the process? 2) Which process steps are crucial to influence this behavior? Answers to these questions can be obtained by analyzing production data or by numerical methods. The usage of Monte-Carlo-methods for estimation of variations and tolerances is a well proven approach in some fields, but was first applied by the authors to rolling processes. The inputs are all varied at once by drawing random samples from given distributions, so cross-dependencies are included in the analysis. The method has the favor of general applicability, i.e. the simulation procedure can be regarded as black box. So the method is generally agnostic to the used simulation core, but needs a large number of simulation evaluations, so fast simulation models are favorable.

Introduction

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 [1]. The nature of the function can be complex, even of a black-box type, where nothing about the internals of the function is known but the input and output interfaces. In this case, Monte Carlo methods can provide valuable information about the behavior of the function while altering inputs.

Here, the function equals the simulation procedure, so it is generally known, but complex. 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.

The use of Monte Carlo methods for the analysis of variations in technical processes was reported before in the field of assembly of complex structures, like in mechanical engineering and building construction (f.e. [2]–[7]). The authors have previously used a similar approach to model powder morphology influences in sintering processes [8], [9]. In [10] the authors showed the difference between variations originating in the input workpiece and within the process. Were the first tend to vanish along the process, the latter tend to accumulate. Here, the efficiency of input variation elimination shall be regarded more detailed to help identifying crucial points to act on in the process regarding variational behavior.

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, as a Monte Carlo based analysis of a rolling process needs hundreds to thousands of simulation runs, depending on the count and variance of inputs, as well as the sensitivity of the process. 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 uses the the open-source rolling simulation framework PyRolL [11] as simulation core, which is developed by the authors. PyRolL 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.

Methods

The Institute of Metal Forming operates a semi-continuous pilot rolling plant, which is the object of the current investigation. 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. The detailed properties of the schedule are of minor importance for the statements of this work and are therefore left out here.

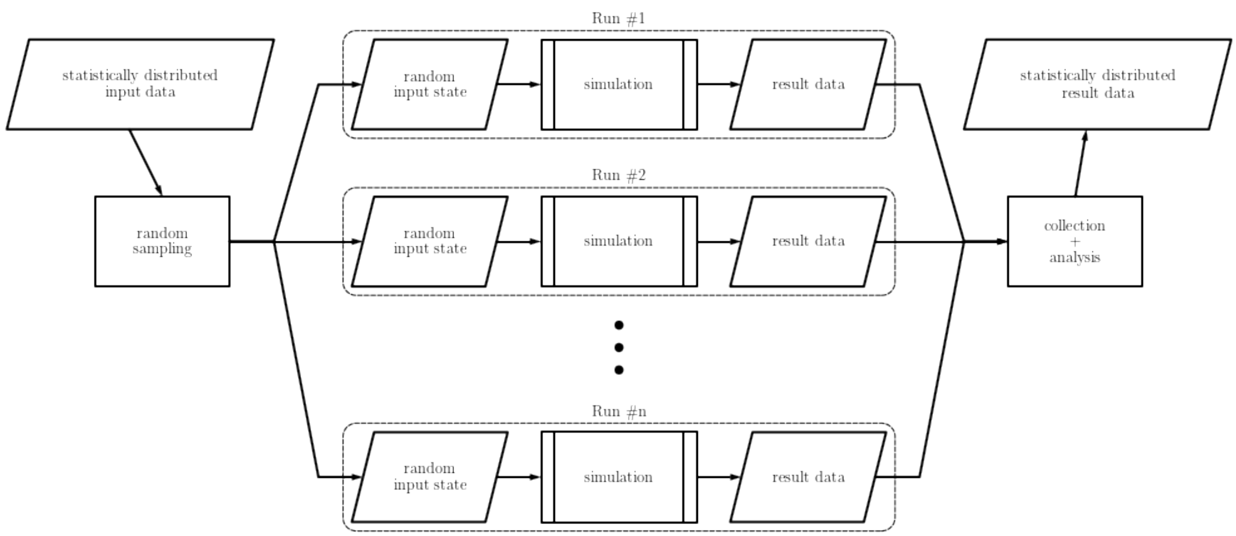

Figure 1: Chart of the Concept of Variation Estimation Using Monte Carlo Techniques

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 analyzed by classic methods of descriptive statistics to obtain information about the process' variational behavior. The principle is shown in Fig. 1. 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 analyzed. If needed, several input variables can be varied at once to regard their combined influence. 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.

Core Simulation Procedure. In the current work, the open-source rolling simulation framework PyRolL [11] was used to simulate the rolling process. PyRolL provides a large library of model aproaches to the partial problems of a rolling process. Here, models combining empirical approaches with simplified analytical solutions were used, because of their low computational effort. The simulation was done with the basic configuration of PyRolL, which includes the empirical roll force and torque model of Hensel and Spittel [12], an integral thermal model approach according to Hensel and Poluchin [13], contact area estimation according to Zouhar [14] and roll flattening according to Hitchcock [15]. Spreading was simulated using the equivalent flat pass method according to Lendl [16]–[18] in conjunction with the spreading equation of Wusatowski [19]. These models are well known and proven approximate approaches to the simulation of elongation passes. Details of software construction and model equations are provided in the documentation of PyRolL [20].

Results and Discussion

A commonly found statement from practical experience is, that the variation in the input workpiece is equalized after 3 to 4 passes. To prove this statement, several amounts of input workpiece variation in diameter and temperature were used to simulate the variational behavior with the Monte Carlo approach. The distributions of input diameter and temperature were assumed as normal with standard deviations chosen to be 1 %, 2 %, 5 %, and 10 % of the mean input value.

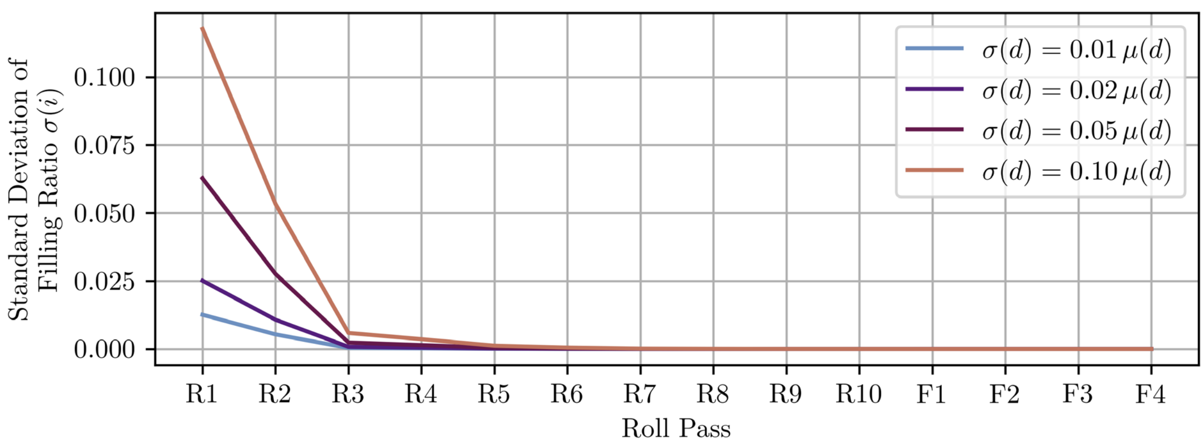

Figure 2: Evolution of Filling Ratio Deviation with Different Initial Standard Deviations of Diameter

The variation of input diameter was investigated by regard on the filling ratio (the ratio of current profile width to usable width of the groove) in each pass as shown in Fig. 2. One will notice, that the standard deviation of the filling ratio decreases rapidly in the first passes and is almost equalized after the third pass, no matter which initial deviation was used. So for the matters of shape the initial hypothesis can be confirmed. Regarding the workpiece temperature the case is different. Fig. 3 shows the standard deviations of workpiece temperatures after each pass. The deviation of workpiece temperature also decreases with each pass, but remains higher at higher initial deviations. Note, that deviations in workpiece temperature highly influence the evolution of the microstructure and therefore the product material properties. It can be stated, that shape deviations in input are of minor importance, because they are efficiently equalized in the rolling process. However, deviations in temperature tend to be still remarkable in the output workpiece.

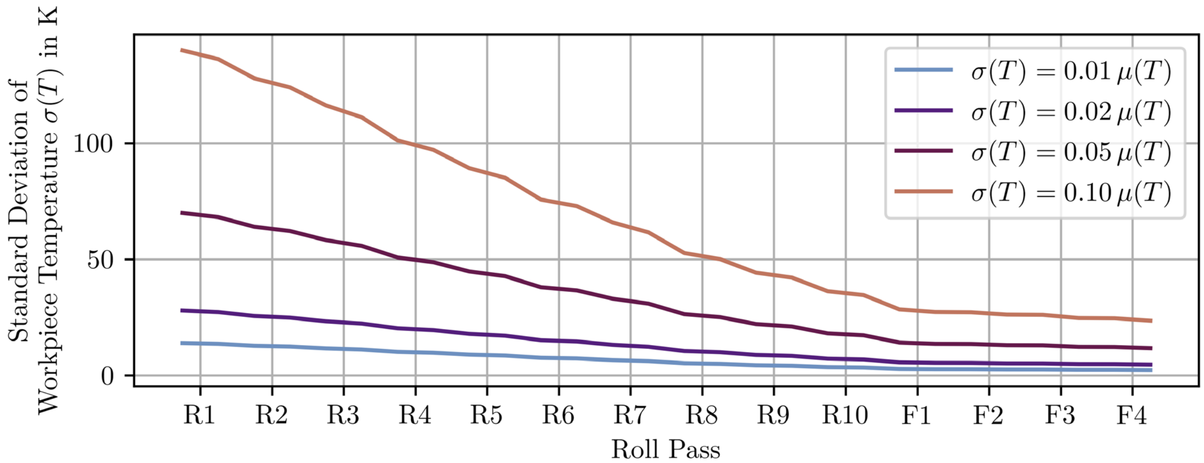

Figure 3: Evolution of Workpiece Temperature Deviation with Different Initial Standard Deviations of Temperature

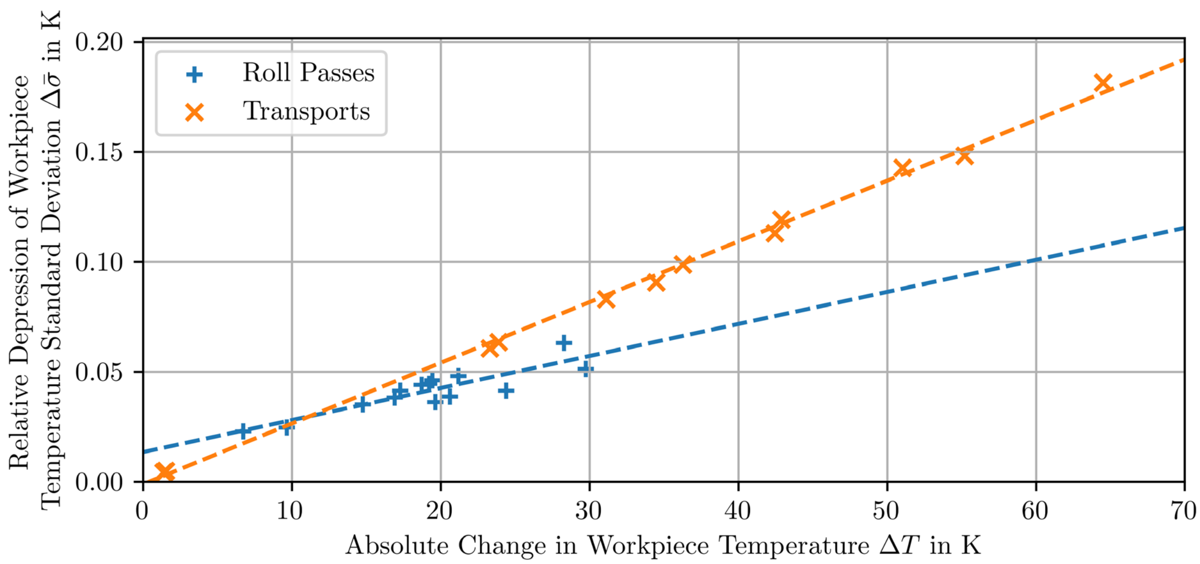

Figure 4: Correlation Between Temperature Change and Variation Elimination

Also, it can be observed in Fig. 3, that the distinct roll passes and inter-pass ranges differ in their influence on the elimination of temperature deviation. Fig. 4 shows the dependence of the relative change in temperature standard deviation, which is the absolute change in standard variation normed on the current standard deviation, in dependence on the absolute change in temperature within a pass or transport (inter-pass range). Approximately, linear correlations can be observed if roll passes and transport are regarded separately. The linear regression of the transports goes approximately through the origin, which seems natural, since no change in temperature will effect no change in temperature deviation as well. The case is different for the roll passes, were are zero temperature change does nevertheless effect a decrease of deviation. This is explained by counteracting temperature influences in roll passes. Zero temperature change in transports means that no heat flows occur. However, in roll passes, zero temperature change means that heat generation by deformation is in equilibrium with heat loss by roll contact.

Summary and Conclusion

A Monte Carlo method was applied to investigate the variational behavior of a rolling process regarding shape and temperature evolution. Variations were found to tend to vanish along the process line. Shape deviations were found to vanish rapidly within a few roll passes. Temperature deviations were found to decrease, but remain remarkable until the last pass. A linear correlation between the decrease in standard deviation and the temperature change within a roll pass or inter-pass range was identified. From previous investigations [10] it is known, that variations arising in the process tend to accumulate in contrast to the input variations investigated here.
These observations lead to the following conclusions regarding the variational behavior of rolling processes:

- Shape deviations of the input workpiece are of minor importance.
- Uniform heating preliminary to the rolling process is of high importance for uniformity of output workpiece properties.
- Large changes applied in processing steps on a certain property help to achieve low deviations in this property.
- Introduction of additional variations in the process has to be avoided.

These conclusions are in accordance to practical knowledge.

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