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# Defect detection in thread rolling processes – Experimental study and numerical investigation of driving parameters

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ABSTRACT

Thread rolling processes are typically used to manufacture threads in mass production. While these processes are well established, the process design is mostly based on individual experience. Also, the influence of the process configuration, such as maximum output rate and lubrication conditions, towards process limits, has not been studied yet. Thus, due to the lack of process understanding, a systematic design of thread rolling processes is not established. Within this paper, a systematic study of the influence of the process configuration and specimen preparation towards the occurrence of defects is performed. In order to enable the investigation of the rolling process, a sensor setup is introduced that allows to measure forming forces in feed and radial direction in direct force flow. Rolling experiments show that the tribological system influences the rolling process. An increase of the stroke speed leads to a significant increase of forming force accompanied by the emergence of seams within the root radius for specimens with a zinc-phosphate and polymer coating. Removing this coating prior to the experiments allows to execute trials without force increase nor seams. Accompanying numerical studies are validated with the help of geometrical as well as force measurements and show that these defects are caused by a shift of the relative sliding velocities within the contact zone.

## 1. Introduction

Manufacturing of small to medium sized threads is industrially mainly executed with forming operations (thread rolling) rather than with machining operations (thread cutting) since forming processes allow significantly higher output rates. Also, in addition to this economic advantage, formed threads exhibit technological advantages in relation to cut threads. These advantages include an increase in hardness due to strain hardening [1], introduction of compressive residual stresses [2] as well as increased fatigue strength [3] [4] while at the same time saving material [5].

The design of thread rolling processes is today mainly carried out by expert knowledge rather than a systematic approach. This approach may however lead to flawed processes which result in different types of defects within the work piece. These defects are mainly seams within the root radius and folds at the top of the thread [1]. While some of these seams and laps are permissible depending on the position of their occurrence (see Fig. 1), seams that lie below the pitch radius or exceed 25% of the pitch height are not permissible due to a significant weakening of the bolt [6]. The occurrence of these critical defects demands a redesign of the dies, resulting in additional time and financial cost.

In order to avoid this iterative and time consuming design process, current research is increasingly focusing on modeling the thread forming process with the help of Finite Element Analysis (FEA). *Martin* was the first to model the forming process of grooves by means of finite element analysis (FEA) [7] [8]. By using an adequate mesh discretization, *Martin* predicted the displacement of the material as well as, partially, the residual stresses. His work was succeeded by *Domblesky and Feng,* who numerically studied the influence of material, geometrical, and frictional variations within the thread rolling process in two dimensions. While friction was shown to influence the effective strains within the thread crest, *Domblesky and Feng* succeeded in matching the numerically calculated hardness values to the experimental studies [9]. Subsequently, their work focused on the three dimensional modeling of the thread forming process. However, the results illustrated the at the time limited processing capabilities, since no successful execution of the numerical model was possible [10]. With the emergence of more powerful processing capabilities, a successful modeling in three dimensions of a sleeper screw forming process was firstly presented by *Pater* et al. in 2004 [11]. Ensuing, further studies regarding the numerical modeling of external thread and gear forming were presented by *Chen* et al. [12], *Lee* et al. [13], and *Hsia and Pan* [14]. While *Chen* et al. varied the lengths of the

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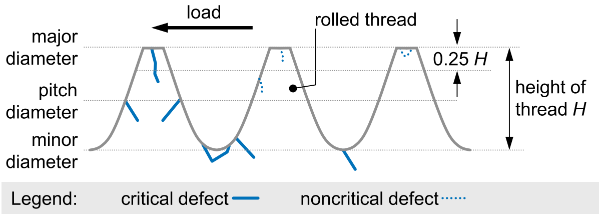

**Fig. 1.** Critical (continuous lines) and non-critical (dashed lines) work piece defects according to [6].

forming dies and observed a decrease of effective stress within the work piece with an increase of the die length and obtained a sound agreement of their model with experimental measurements in terms of hardness values, *Lee* et al. and *Hsia and Pan* exclusively focused on the numerical modelling of the process. *Kamouneh* et al. used indirect force and hardness measurements to verify their developed FEA model of a gear forming process [15]. *Tudor* et al. [16] and *Nitu* et al. [17] also managed to partially show the validity of their models by comparison of the numerically calculated force trends with indirect force measurements.

While the discussed studies are supported by experimental data, no previous studies are known that investigate the influence of the process configuration towards the development of defects under industrial conditions. Industrial conditions refer to the stroke rates as well as the employed lubrication system, while the process configuration relates to adjustments of the forming process within the product specifications. These pertain to, amongst others, the adjustment of the rate of formed parts per minute, the use of additional lubrication, and the surface topographies of the billets.

## 2. Motivation and aim of the study

Extensive studies have led to an improved general understanding of the thread forming process. Yet, despite the described progress, the influence of physical alterations of the process configuration has not been addressed. Due to the very limited as well as time and cost intensive abilities to respond to the occurrence of defects, a preliminary prediction of these flaws in dependence of the process configuration is necessary to ensure a reliable design of rolling processes. However, since no data is available as to the influence of the process configuration, a prediction of flaws within the final product is not possible as of today.

A premise to determining defect free process limits beforehand is the understanding of the interactions within the contact zone as well as the influence of the tribological system. With the work piece only being set into rotation through frictional connection with the dies, as is schematically depicted in Fig. 2, the tribological properties of the encompassing system play a crucial part in designing the final thread rolling process [5].

In order to enable a process design within defect free limits, two prerequisites need to be fulfilled. On the one hand, an approach to directly measure forming forces in profile rolling processes with high sensitivity to changing process setups is necessary. On the other hand, the underlying causes for the occurrence of critical defects (laps within the root radius) have to be revealed.

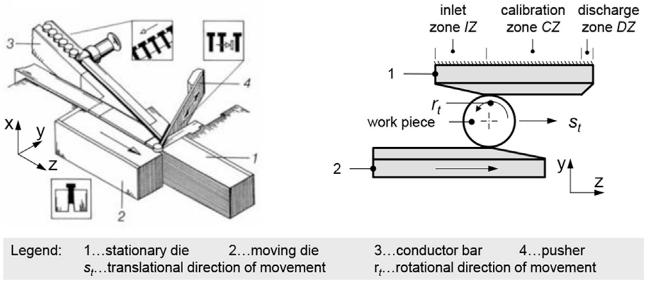

**Fig. 2.** Schematic depiction of the rolling process with flat dies (left) and depiction of forming zones (right).

Thus, in order to investigate the driving parameters that lead to the formation of work piece defects, a numerical model of the forming process needs to be validated with the help of experimental measurements. Thus, a novel die and sensor setup for the direct measurement of decompositioned forming forces will be presented. This setup will provide the data for the verification of the numerical model as well as provide the necessary sensitivity to detect deviations during the rolling process due to varied process parameters. We will then present an experimental investigation of different tribological systems and process properties and reveal a correlation between work piece defects, surface conditions of the rolled blanks, and the process setup, thus showing process limits. The ensuing discussion will focus on the underlying causes for the occurrence of these work piece defects.

## 3. Experimental and numerical setup

Within the following section, we describe the geometry of the forming dies as well as the numerical model. Then, the integration of the force measurement sensors within the dies and the rolling machine is described. To ensure that the measured signals are valid, the entire die and sensor setup will be calibrated with the help of an external loading force applied by a force testing machine. This section is concluded with an in-detail description of the experimental design of the rolling processes.

### 3.1. *Description of profile geometry and numerical model*

The main goal of this investigation is to explore the dependence of process feasibility in regards to process variations such as feed speeds and surface properties. In order to create a most sensitive setup towards these characteristics, a die geometry with grooves without pitch was chosen, see Fig. 3, right. This selection is based on the assumption that a geometry with a pitch larger than zero entails that the rotation and translation of the work piece is in part assumed by form fit. A plane symmetric geometry with two grooves was chosen to ensure that during the injection of the work piece with the help of the pusher (see Fig. 2) the work piece has two points of contact which allow for a repeatedly accurate insertion of all work pieces.

This geometry is also the basis for the numerical model. The rolling process was modeled with *simufact forming v13*. The model consists of two rigid dies and a cylindrical elastic-plastic work piece (diameter $d_0 = 9.08$ mm, height $h_0 = 10$ mm), see Fig. 4, top. Due to the plane symmetry of the profile, only half of the geometry is modeled, see Fig. 4, bottom. A symmetry plane is implemented to ensure boundary conditions. An initial mesh edge length of $e_0 = 0.3$ mm is chosen for the entire

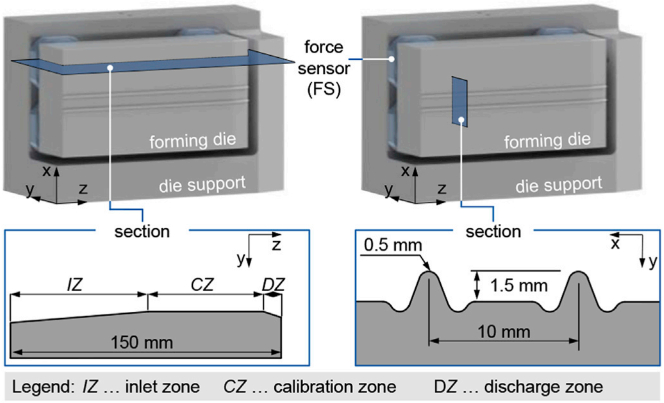

**Fig. 3.** Setup and geometry of fixed forming die.