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Investigation of the Influence of an Oscillation Superposition on the Wear Behaviour in an Industrial-like Process

Bernd-Arno Behrens[a], Hendrik Wester[a], Tim Matthias[a], Sven Hübner[a], Jonas Wälder[b], Philipp Müller[a]*

[a]*Institute of Forming Technology and Machines, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany*
[b]*Fischerwerke GmbH & Co. KG, Klaus Fischer-Straße 1, 72178 Waldachtal*

* Corresponding author. Tel.: +49 511 762 4021; fax: ++49 511 762 3007. *E-mail address:* mueller@ifum.uni-hannover.de

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Abstract

In cold forging processes as well as in sheet-bulk metal forming, vast contact stresses result in severe tool wear and thus in tool failures. In order to achieve a sustainable production, a new manufacturing process is developed within the subproject T06 in the transregional collaborative research centre 73 at the Institute of Forming Technology and Machines (IFUM). In this subproject the influence of an oscillation superposition on a forming process is investigated. The new type of sheet-bulk metal forming (SBMF) process manufactures a component with internal and external gearing. Contact normal stresses and thus tool wear could be reduced by applying an oscillation superposition in the main force flow of the machine. To verify the positive results in other processes, the oscillation method is applied to an industrial-like process based on anchor bolt manufacturing of Fischerwerke GmbH & Co. KG. For this purpose, a representative tool system is developed using numerical simulation. The numerical simulation is also used to investigate resulting local contact stresses and relative sliding velocities. Furthermore, cylinder compression tests with and without oscillation superposition are conducted for the workpiece stainless steel 1.4362 (AISI S32304), in order to qualify the reduction of contact stress.

Keywords: Wear; Oscillation Superposition; Sheet-Bulk Metal Forming; Simulation

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1. Introduction

In order to achieve a resource-saving and sustainable production, new production methods are to be developed. The technology of sheet-bulk metal forming (SBMF) combines the conventional sheet metal forming and bulk metal forming. Sheet-bulk metal forming has high benefits in terms of increased strain hardening due to forming, higher surface quality and a near-net-shape production [1]. To extend the production limits of this technology, a SBMF process for the production of a demonstrator component with an internal and an external gearing was developed at the Institute of Forming Technology and Forming Machines within the scope of the subproject A7 [2]. A hydraulically working oscillating device is installed in the tool system of the process to generate an oscillation superposition in the main force flow of the machine [3]. It could be demonstrated, that an oscillation superposition leads to an increase of the mold filling of the gear geometry, a reduction of the plastic work necessary for forming [4] and an increase of the surface quality by reducing the average surface roughness [5].

An explanation for the reduction of the average forming force due to an oscillation superposition is the elastic relaxation of the material during stress release [6]. The elastic relaxation causes that the amplitude minimum remains below the static forming force. Another explanation deals with oscillation induced effects between the tool and the workpiece surface. Therefore, Ulmer described an increased smoothing of surface roughness due to an oscillation superposition as a reason for friction reduction and therefore for forming force reduction [7]. The positive influence of an oscillation overlay on the wear behaviour could be demonstrated by Matsumoto et. al. [8].

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Verified and validated wear models which describe the ratio of the expected wear under the acting loads served as a basis for a realistic wear prediction. The loads are determined by means of Finite Element (FE) analysis. For this purpose, a multitude of mathematical wear calculation approaches have been developed. The approaches can be divided into two groups. One group of the wear models predicts a critical plastic deformation of the surface layer as material weakening and beginning of tool damage [10-12]. The other group of wear models is based on the approach of Archard or Holm [13-16]. The Archard approach is one of the best known and proven phenomenological models for describing wear in the contact zone of two bodies moving against each other either in its original or more advanced versions [17-18].

The main goal of this research project is the transfer of the knowledge gained in subproject A7 regarding the influence of oscillation superposition and the further development of numerical wear modelling to the forming process of extrusion. For this purpose, an industry-like reference process for the production of a bolt anchor is considered. Fig. 1 shows an example of the process chain for the production of a bolt anchor. In the first stage, the manufactured semi-finished product is rejunvenated at one end of the cylinder by means of cold extrusion. Similar to the first stage, the workpiece is further rejunvenated in the second stage. In the third stage, the material is piled up by upsetting between the tapered and non-tapered workpiece area, creating the first stop for the expanding clip. In stage four, the tapered area at the end of the workpiece is being set up further, resulting in the formation of the second stop. In the last process stage, a marking is applied to the bolt end face by stamping. In the first and second stage, impact extrusion causes increased wear due to the high contact stresses and the relative movement.

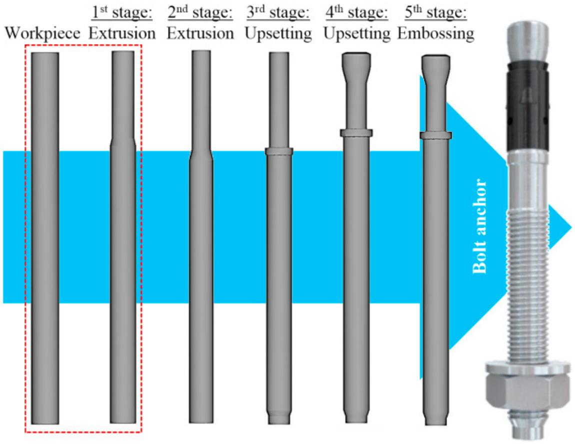

Fig. 1. Process-chain of the bolt anchor

Within the scope of this contribution, a model process for first stage investigations on laboratory level is designed based on of the Fischer industrial process [24]. In order to investigate the influence of oscillation superposition on the industrial process, it should be possible to carry out both oscillation-free and oscillation-superposed experiments at laboratory scale on the developed model process. By introducing an oscillation superposition in the main force flow of the machine, the contact stresses and tool wear can be reduced. In order to predict a numerical representation of the process precisely, it is necessary to determine the material behaviour. For this purpose, the flow curves under uniaxial compression are determined by means of the cylinder compression test. The cylinder compression test is a material testing procedure to determine flow curves, compressing a cylindrical sample between two compression stamps [19]. In addition, the force displacement curves for oscillation superposed and non-oscillation superposed forming are recorded.

2. Cylinder compression tests

The characterisation of the material is divided into two parts. In the following, the determination of the process-relevant flow curves, which are used for the later process and tool design is shown. Furthermore, the forming behaviour by oscillation-free and oscillation-superposed experiments is investigated. Therefore cylinder compression tests are conducted.

2.1. Material characterisation

The result of FE-simulations depend decisively on the exact modelling of the influencing factors on the forming process. Among other aspects, this includes the determination of the hardening behaviour of the workpiece material. For the simulation of the extrusion process, the flow curves of the wire rod were determined at process-relevant temperatures and strain rates.

The compression tests to characterise the workpiece material 1.4362 were conducted on the Gleeble 3800 GTC test system from Dynamic Systems Inc. to determine the flow curves under isothermal conditions. Cylinder compression tests were carried out with the specimen geometry of Ø10 mm x 15 mm and tungsten carbide punches.

The flow curves being used to model the thermomechanical material behavior of the steel alloy under investigation were determined at relevant temperatures T (°C) between room temperature (RT) and 250 °C in steps of 50 °C with constant strain rates $\dot{\varphi}$ of 0.1, 1 and 10 s^{-1}. At least three tests were conducted for each parameter combination. The resulting data from the testing machine were used to compute the coefficients for the analytical flow curve approach called Hensel-Spittel-10 which is depicted in the following equation (1) [20]:

$$\sigma_f = A \cdot e^{m_1 \cdot T} \cdot T^{m_8} \cdot \varphi^{m_2} \cdot e^{\left(\frac{m_4}{\varphi} + m_6 \cdot \varphi\right)} \cdot (1+\varphi)^{(m_5 \cdot T)} \cdot \dot{\varphi}^{(m_3 + m_7 \cdot T)} \tag{1}$$

To determine the material-specific coefficients A, m_1, m_2, m_3, m_4, m_5, m_6, m_7, and m_8, the Generalized Reduced Gradient (GRG)-nonlinear optimisation algorithm was used [20]. Subsequently, the flow modelling was validated with the aid of numerical mapping of the cylinder compression tests. The force-displacement curves and the geometry of the workpieces after the cylinder compression test were used as validation criteria. Fig. 2 (a) compares the experimentally determined flow curves and the calculated flow curves, showing a high agreement.

Fig. 2 (a) depicts the temperature-dependent flow curves between RT and 250 °C at a strain rate of $1\ s^{-1}$ and Fig. 2 (b) shows the strain rate-dependent flow curves for RT. The flow curves demonstrate a strong dependence of the flow stress on the forming temperature. As the forming temperature rises, the flow stress of the material decreases. In contrast, the strain rate dependence for this material is very small (see Fig. 2 b). Subsequently, the determined flow curves were implemented in the commercial FE-system Simufact Forming 16.0. The numerical model was used to develop and design the forming process of the anchor bolt.

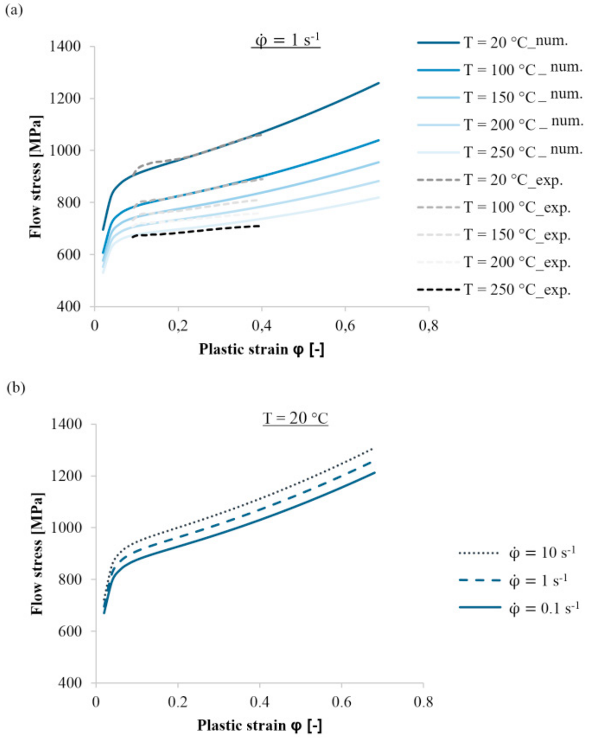

Fig. 2. (a) temperature dependent flow curves between 20 °C and 250 °C for $\dot{\varphi} = 1\ s^{-1}$; (b) strain rate-dependent flow curves between $\dot{\varphi} = 0.1\ s^{-1}$ and $\dot{\varphi} = 10\ s^{-1}$ for the forming temperature 20 °C

2.2. Experimental oscillation superposition

The experiments are conducted on the Hydraulic Press Hydrap HPDZb 63 at the IFUM. The cylinder compression test tool is installed above a hydraulically working oscillating device (see Fig. 3). The oscillating device is able to realise a frequency range between f = 0 Hz and f = 600 Hz and an amplitude range between $A_{path} = 0$ µm and $A_{path} = 50$ µm [3]. The compression stamps are made out of the tool steel 1.3344 (M3Class2). They were quenched and tempered to a value of 60 ± 2 HRC. Their surfaces were ground to a roughness of Ra = 0.8 in order to create a smooth surface, so that the material-related effects dominate and the impact of surface properties on the test is reduced. One pair of punches was used for all tests within this scope of work. The sample geometry is identical to that described in 2.1.

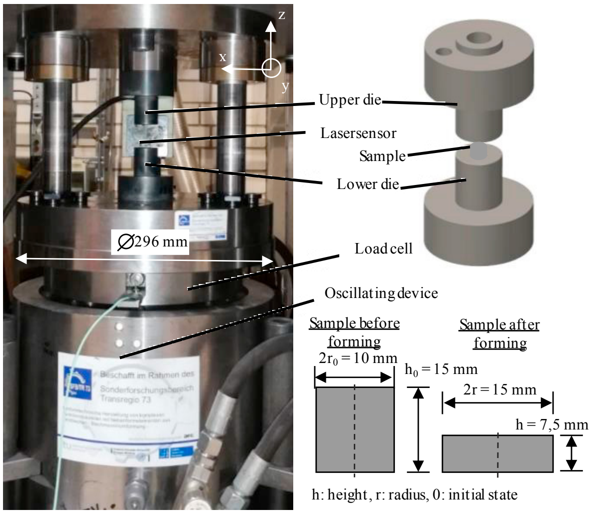

Fig. 3. Cylinder compression test tool for oscillation-superposed experiments

The force-displacement curves during the experiments are recorded with a laser as a displacement sensor and a load cell as a force sensor (see Fig. 3). The press is set at a constant speed of $v_{press} = 6$ mm/s. The oscillation superposed experiments are conducted with an oscillation overlay with a frequency of f = 100 Hz, f = 200 Hz and f = 300 Hz, because these frequency ranges has proven to be the most promising in previous work [5]. Five experiments per test parameter are conducted. The samples are compressed to half of its initial height. The force-pathways are determined from the load cell and laser-sensor measurements.

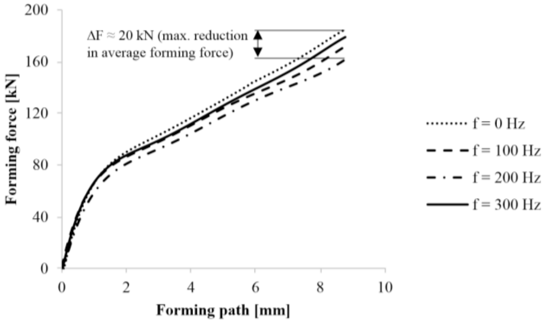

Fig. 4. Force-displacement curve for non-oscillation superposed and oscillation superposed cylinder compression tests

The force-displacement curves are plotted in Fig. 4. The average forming force is plotted without showing the amplitude. It can be seen that a frequency of f = 200 Hz leads to the greatest reduction in the average forming force ΔF. The maximum value of the average forming force decreases from max. F = 185 kN for oscillation free compression to max. F = 162 kN for an oscillation superposed compression with a frequency of f = 200 Hz. It is noticeable that a frequency of f = 100 Hz and a frequency of f = 300 Hz lead to a similarly strong reduction in the maximum value of the average forming force. Here a reduction to $F_{max.} = 172$ kN occurs for a frequency of f = 100 Hz and a reduction to $F_{max.} = 179$ kN occurs for a frequency of f = 300 Hz. A possible explanation is that for the same system pressure of p = 65 bar the force amplitudes are different for the three frequency ranges. Due to the applied frequency, a stronger or weaker oscillating of the hydraulic pressure occurs in the oscillating device. This causes the highest amplitude to occur in a frequency range of about f = 200 Hz. For a frequency of f = 200 Hz, the highest force amplitude is A = 23 kN. For a frequency of f = 100 Hz, however, only a force amplitude of A = 13 kN results, and for a frequency of f = 300 Hz, only a force amplitude of A = 6 kN results. The amplitude results indirectly from the frequency due to the operating behaviour of the oscillation device. Due to a change in oil volume flow because of the applied frequency, the hydraulic oil pad below the piston degrades to varying degrees, resulting in a change in amplitude.

This leads to the conclusion that the average forming force is primarily influenced by the amplitude of the applied oscillation superposition. The increased influence of the amplitude was also observed by Blaha et al. [21], being explained by a strong effect of the amplitude on softening mechanisms occurring in the material due to an oscillation superposition [22]. For the oscillation range investigated and the given material pairing in this experiment, this particular observation is confirmed. A softening occurring due the oscillation superposition is therefore primarily dependent on the amplitude.

3. Numerical investigation

The investigated extrusion process is a rotationally symmetrical forming process and was modeled in 2D. For a better visualization, the numerical results of the 2D model are transferred subsequently to a 3D representation. The forming simulations were modeled with the commercial FE system simufact.forming 16.0 considering the material data described above. As boundary conditions, a tool temperature of 20 °C and a constant friction coefficient of 0.3 were set. The tools were designed as rigid bodies for the first consideration of the material flow. It should be ensured that the required forming force does not exceed the limit of the oscillation superposed tool system of 300 kN. Fig. 5 shows the numerical force-displacement curve of the extrusion process. At approximately 40 kN, the force required is significantly lower than the possible forming force of the oscillation-superposed tool system. Furthermore, the simplified numerical process design allowed to avoid workpiece errors in the process, such as wrinkles or buckling. Fig. 6 shows the final FE model of the active components and the resulting effective plastic strain of the anchor bolt after the first forming step. The tool analysis of the die were also carried out with an axisymmetric 2D model, because the deformation and the heat transfer are axisymmetric. In addition, the coupled analysis approach was used, in which the deformation and the stress of the elastic tools are calculated parallel in each step. Thereby the thermal and mechanical interactions are considered. In this case the 2D simulation can effectively save calculation time and resources.

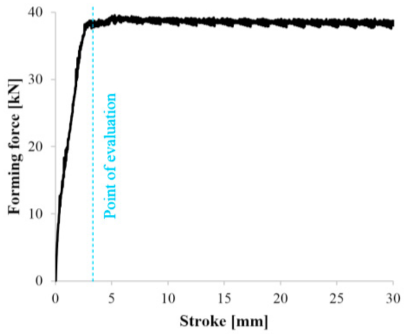

Fig. 5: Numerical force-displacement curve of the extrusion process

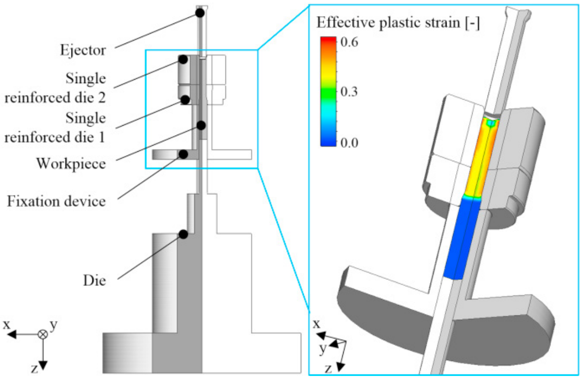

Fig. 6: FE-model and the resulting effective plastic strain of the anchor bolt

In Fig. 7 the die stress analysis results of the upper die are shown, which is formed at the force maximum described above after 3 mm forming stroke (see Fig. 5). To compare and assess the process loads of the upper die, the first principal stress, which is an indicator for crack initiation, as well as the v. Mises stress, which indicates regions of critical plastic deformations are taken into account.

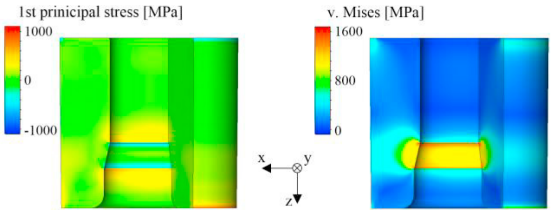

Fig. 7. Die stress analysis results of the forging process for the upper die

The maximum v. Mises stress and the first principal stress are below 1600 MPa. Due to the internal pressures of about 1600 MPa, a single-reinforced die was designed for the tool system (see Fig. 9). The limit values for the number of reinforcement rings can be taken from [23].

In the present forming stage, increased wear in the die is expected during extrusion due to the high contact normal stresses and the relative speed between the die and the workpiece. High die wear reduces the component quality and thus leads to a shorter lifetime of the components. Fig. 8 shows the resulting relative speeds that occur due to the rejuvenation of the die geometry as well as the wear-critical areas in the die using the Archard wear model. Industrial experience has shown that the current wear models do not show high agreement with the experimental measured wear, so further research is planned to develop an extension of the Archard model for the numerical calculation of tool wear for cold forging processes with high contact stresses.

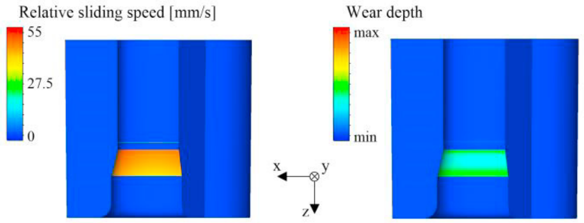

Fig. 8. Results of the resulting relative speeds (left) and the wear critical areas in the tool using the Archard wear model

4. Design of the tool system

An experimental test bench is designed to create the wear occurring on the tool die due to an extrusion process. In addition, the test bench should be able to implement an oscillation superposition in the process. For this purpose, a cylindrical bolt is rejuvenated by pressing into the die. The occurring maximum component and tool loads are drawn from the simulation for the non-oscillation superposed case. From this, the tool design is derived (see Fig. 9). The lower tool system consists of a compression stamp on which the semi-finished product is positioned and a guiding device which is fixed by four screws and positioned vertically with spiral springs being installed on the hydraulically working oscillating device. The upper part of the tool system contains the tool die and the ejector, which are installed under the ram.

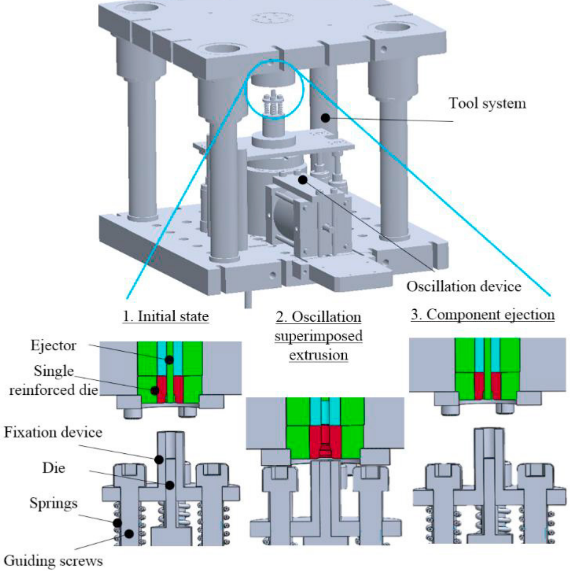

Fig. 9. Tool system for oscillation superposed wear experiments in an industry like extrusion process

Experiments can be conducted in three process stages with the tool system (see Fig. 9). First, the semi-finished product is positioned on the compression stamp in the guiding device. Next, the oscillation overlay is activated and the tool system moves together. Afterwards, the bolt is pushed into the upper tool die. To prevent the bolt from buckling, it is laterally fixed by the guiding device during the extrusion process. During the forming process, there is contact between the guiding device and the tool die. The oscillation device is activated and the different oscillation frequencies can be set. The oscillation is introduced vertically into the semi-finished product by the punch. Thus the semi-finished product oscillates during the insertion into the die. When the guiding device is at the bottom stop (see Fig. 9 – 2. Oscillation superposed extrusion), the forming process is complete. After forming, the tool moves upwards, the guiding device is displaced upwards by the compressed spiral springs and the component is ejected from the tool die.

5. Conclusion

Within the scope of this paper, a tool concept was designed which will allow the investigation of the influence of an oscillation superposition in an industry-like impact extrusion process for the production of a bolt anchor. For this purpose, a comprehensive material characterisation of the stainless steel 1.4362 was conducted on the Gleeble 3800 GTC test system. The analytical flow curve approach by the experimental results were used for the numerical process design of the industry-like reference process. It could be demonstrated that the required forming force did not exceed the limits of the available equipment. In addition, the numerical process design was able to avoid workpiece defects in the process, such as buckling and wrinklings. Subsequently, a tool analysis was carried out on the basis of a tool modelling in the form of elastic bodies in order to adapt the tool geometries and components with respect to a safe process control in case of critical tool loading.

Furthermore, the forming behaviour of the sample material was investigated in dependence of an oscillation superposition. An oscillation superposition with a frequency of $f = 200$ Hz and an amplitude of $A = 23$ kN proved to be the optimum of the investigated oscillation parameters with respect to a reduction of the average forming force. This can be explained by an increased oscillation induced material softening during the forming process. This effect is enhanced by higher amplitudes.

Within the scope of the subproject T06, in which the influence of an oscillation superposition on wear in a forming process is investigated, an extended wear model according to Archard was developed on the basis of the combined friction model for solid sheet metal forming. This wear model is to be further developed for cold forming within the scope of this project. Future work will focus on the further development of a numerical tool wear model for the production of the bolt anchors. In cold forming processes, a tool life optimised process design based on FEM, taking the wear into account, is of great importance and contributes decisively to an economic process design. As the current wear models do not correspond with practical experience, further work in the field of wear calculation is required here.

An experimental validation of the influence of an oscillation superposition on the tool wear will take place on the newly developed test setup in future work. Also the optimal frequency range of f = 200 Hz will be investigated more intensive.

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