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Dry rotary swaging with structured tools

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Abstract

Rotary swaging is a cold bulk forming process. The diameter of the workpiece is reduced incrementally by oscillating movement of the tools. The established processes use lubricants which fulfill necessary functions such as lubricating, cooling and cleaning of the tools. Disadvantages caused by the use of lubricant are costs of recycling, replacement of lost coolant and for the cleaning of the workpiece. To eliminate the lubricant it is necessary to substitute the functions of the lubricant in other ways. For example by means of coating and structuring of the tools. In this study infeed rotary swaging with structured tools is investigated using finite element simulations. Different structures are implemented in the reduction zone of the tools. The influence is investigated by the radial and axial process forces. Additionally first structured tools are manufactured and experimentally tested. The results of modeling and testing are discussed.

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Keywords: cold forging; dry metal forming; structured tools

1. Introduction

Rotary swaging is an incremental cold forming process and has an important field of application in the automotive industry for the production of axes, steering spindles and gear shafts. It allows the reduction of the diameter of rods and hollow shafts and features advantages like improved material properties as increased tensile strength, undisturbed fiber flow and for hollow shafts the adjustable wall thickness in case of an optimal use of material resources. Thus rotary swaging belongs to the near net shape and suitable production techniques, with great potential for lightweight construction. The forming of the workpiece is achieved incrementally by the oscillating tool stroke h_T. The principle setup of the infeed rotary swaging process is shown in Fig. 1. The workpiece is axially fed into the swaging head with the feeding force F_f. Due to the radial forming force F_{RI} in the reduction zone (I) and the tool angle α an axial reaction force F_A counteracts to F_f. To reduce the axial reaction force the effective friction in the reduction zone of conventional tools is increased by a tungsten carbide layer [1]. At the same time the friction in the calibration zone is low to prevent wear due to manually polishing.

Commonly, the rotary swaging process is studied using finite element method (FEM) [2,3,4]. The investigations are conducted to examine strain and stress distributions with regard to the influence of axial feed velocity [3] or friction and tool angle [4]. Also, different designs of the reduction zone of the tools are investigated like convex, concave and hybrid contours [5]. Simulation of the process is of great potential to determine the influence of tool geometry, friction etc. for the rotary swaging process.

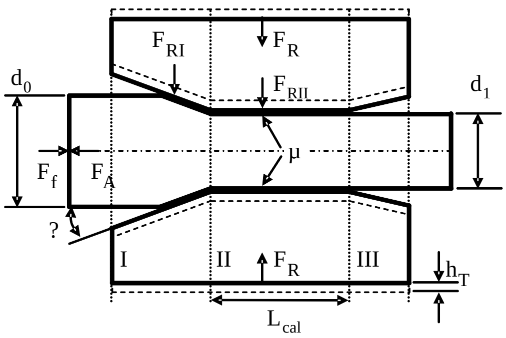

Fig. 1. Principle setup of infeed rotary swaging.

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Nomenclature

α	°	tool angle
β	°	exit tool angle
μ	-	friction coefficient value
λ	mm	wavelength
A	mm	amplitude
d_0	mm	initial diameter
d_1	mm	final diameter
f_{st}	Hz	stroke frequency
F_A	N	axial reaction force
F_f	N	feed force
F_R	N	radial force
F_{RI}	N	radial force in zone I
F_{RII}	N	radial force in zone II
H	mm	overall height
h_T	mm	tool stroke
L	mm	overall length
l_{cal}	mm	length of zone II
l_{tool}	mm	tool length
r_0	mm	initial radius
r_1	mm	final radius
Ra	µm	roughness
s	mm	wall thickness
x	mm	feed length
I	-	reduction zone
II	-	calibration zone
III	-	exit zone

From both the economical as well as the ecological point of view the interest of dry metal forming becomes larger. In case of rotary swaging a large amount of lubricant based on mineral oil is still used. The elimination of the use of lubricants results in three significant advantages [6], reduction of financial costs, of environmental impacts and of possible health burden.

The reduction of the costs is based on the elimination of process steps like the recycling of lubricant and cleaning of the workpiece. Also no replacement is necessary of lost lubricant due to the release during the process. Especially for the forming of tubes a lot of lubricant is removed with the workpiece from the process. Furthermore the design of the machine is simplified. But the lubricant fulfills essential functions like the reduction of friction and thus the reduction of tool load and wear. Furthermore it serves as separation layer to minimize cold welding processes. In addition it cools the process and flushes the working zone to remove particle abrasion.

The basic feasibility of dry rotary swaging in the micro range is presented by Moumi [7]. It is shown the process window, i.e. the applicable feed rate could be extended in swaging of aluminium but is reduced in swaging of steel. Furthermore the dry rotary swaging in the macro range is tested. The analysis of the recorded process parameters and the formed geometry of the workpiece reveal the potential of dry rotary swaging, but also the difficulties that arise. Dry rotary swaging needs a modification of the process and system parameters as well as an adjustment of the tools [8]. Also the function of the lubricant must be realized in another way.

The proceeding to cope with this challenge is to control the material flow and thus the required forces by a combination of coating and structuring of the reduction zone of the tools. The first approach is a coating on the whole tool with a low friction coefficient to reduce wear and tear as well as cold shuts [9]. However this creates a conflict, due to the reduction of the friction coefficient the axial reaction force increases. The common tungsten carbide layer is not applicable any longer because in dry swaging the flushing effect of the lubricant with cleaning the tools from swarf is missing. Therefore a deterministic geometric structure in the reduction zone of the tools in contrast to a smooth zone is intended to increase the effective friction. In this work simple contours are investigated by numerical simulations to obtain a basic understanding of the impact on the process. A qualitative comparison of the simulation results reveals promising structures for the reduction zone and first structured tools which are identified by the simulations are manufactured and experimentally tested.

2. Simulation

2.1. Modeling

First investigations with the simulation model which is used for this study are conducted by Moumi [2]. This 2D-axisymmetric model is necessary to study a great variety of different structures. The model is implemented with the software ABAQUS 6.13-1 and consists of two parts the tool and the workpiece (see Fig. 2). The tool is implemented as rigid body. As friction model the penalty formulation and the coulomb friction coefficient is used. This model is used due to the simplicity and the good results in cold metal forming simulations [10]. The numerical method is based on Abaqus/Explicit due to the fast dynamic rotary swaging process. With an Intel® Core™ i5-4670 processor the FEM-simulation of one process for one structured tool needs with 4 cores about 4 hours.

It is not necessary to provide the complete length of the workpiece with a fine mesh but only the first 35 mm. After the feeding of the first 35 mm into the swaging unit the tool is completely filled and a quasi-steady state is reached in the process. The elements are reduced integrated A 4-node bilinear axisymmetric quadrilateral with hourglass control. The mesh size in the deformed area of the workpiece is chosen as small as possible and as large as possible to limit the computation time. Preliminary investigations showed that these restricting constraints do not falsify the results. The workpiece is modeled as an elastic-plastic isotropic material with parameters from literature [11]. Additional settings for the simulation are summarized in table 1.

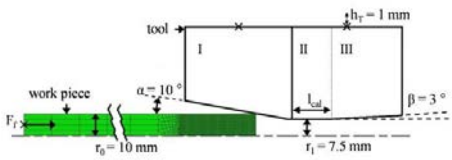

Fig. 2. 2D-axisymmetric-FE-model with process parameters.

Table 1. Process settings for the simulation.

parameter	value	parameter	value
feed velocity v_f	30 mm/s	feed length	35 mm
zone II length l_{cal}	20 mm	tool length l_{tool}	100 mm
stroke frequency f_{st}	37,5 Hz	element type	CAX3R
material	AISI304	elements size (fine)	0.5x0.29 mm
friction coefficient	0.1	elements size (tall)	2.5x12.75 mm

A cosine structure was chosen in order to allow both, the provision of a surface structures with distinct impact on the frictional properties and within highlighted geometrical range the application of ball-end milling tools of larger diameter (d ⩾ 0.5 mm) to distinctly reduce the machining time when transferring structures to the surfaces of rotary swaging tools. The varied parameters are the wavelength λ and the amplitude A, see Fig. 3. The parameters values are λ = 0.9, 1.1, 1.3 mm and A = 10, 30, 40, 50, 100, 150, 200 μm. The overall height H = 8.28 mm and overall length L = 47 mm are fixed which leads to α = 10 °. The friction coefficient in the reduction and calibration zone is fixed to μ = 0.1 for all simulations derived from the intended coating (without lubrication) and lubrication (without coating) of the tool [12].

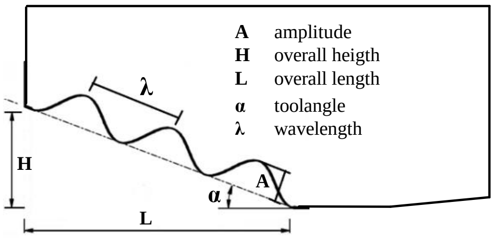

Fig. 3. Cosine geometry in the reduction zone of a structured tool.

2.2. Results

The simulation results are analyzed to observe the effects of the geometrical parameters on the radial and axial force. The considered axial and radial forces are the average of the maximum axial and radial forces per stroke over the complete quasi-steady state of the process, the radial force is considered for one tool. The results of the comparative simulation without steps are set to 100 %.

The radial and axial forces are represented versus the amplitude A with the three different wavelengths. For the radial process force no clear effect of the amplitude is noticeable, see Fig. 4. But a taller wavelength leads to a lower radial force. Only a reduction to F_R = 96.8 % in comparison to the simulation without structured reduction zone is possible for a cosine shape with λ = 1.3 and A = 0.05 mm. A stronger effect on the axial process force is shown in Fig. 5. While the amplitude rises the axial force decreases. Also a taller wavelength leads to a reduction of the axial force. A reduction to F_R = 34 % in comparison to the simulation without structured reduction zone is achievable however for λ = 1.1 mm and A = 0.2 mm. The axial force is reduced by the benefited material flow. This is due to the geometry since the flow is less impeded due to the space generated by the cosine geometry as well as the altered distribution of strain.

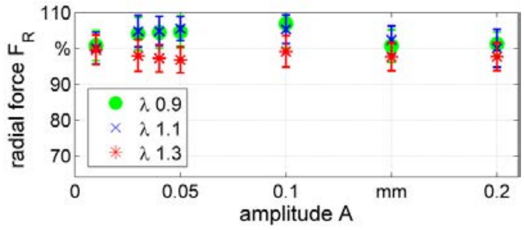

Fig. 4. Radial force.

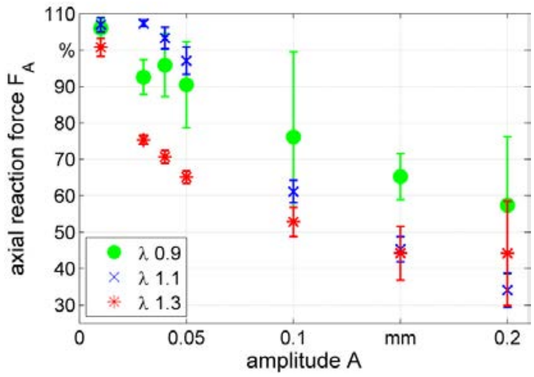

Fig. 5. Axial force.

3. Experimental procedure

3.1. Setup

To compare the results of the forming process with structured tools as well as the workpiece results also investigations with other tools were carried out. At first conventional tools with a tungsten carbide layer (T1) in the reduction zone are used (see Fig. 6 a)). Furthermore tools with a smooth reduction zone (T2) were used to form tubes with and without lubricant (see Fig. 6 b)).

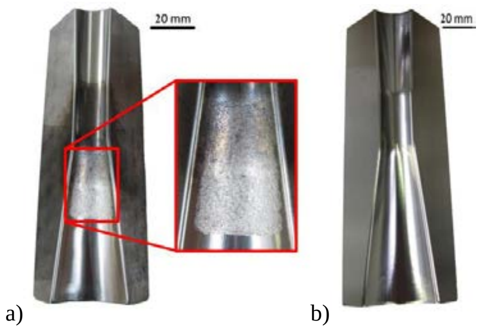

Fig. 6. Rotary swaging tools; a) conventional tools with a tungsten carbide layer (T1), b) smooth tools (T2).

A first experimental implementation of a structure in the reduction zone for rotary swaging tools are realized. Therefore a cosine shape with wavelength of λ = 1.3 mm and a amplitude of A = 150 μm is chosen. The tool T3 consisting of the material 1.2379 is visualized in Fig. 7.

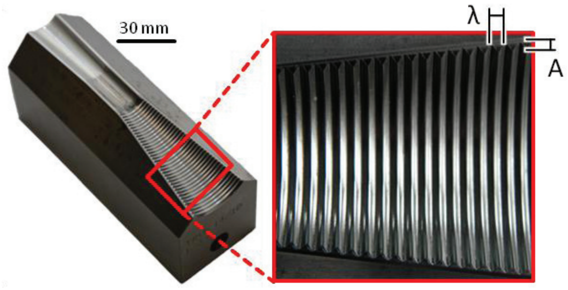

Fig. 7. Rotary swaging tool with cosine geometry (T3).

The experiments were conducted with a swaging unit HE32 with four tools. The workpiece was fed into the swaging unit by a linear direct drive over a feed length of x = 130 mm. Four different feed velocities were used with as well as without lubricant. For the forming without lubricant the tools were cleaned each time. The steel tubes were formed from an initial diameter of d_0 = 20 mm with a wall thickness of s = 2 mm to a final diameter of d_1 = 15 mm. The experimental settings are summarized in Table 2.

Table 2. Process settings for the experiments.

parameter	value	parameter	value
feed velocities v_f	500, 1000, 1500, 2000 mm/min	workpiece material	1.0038
tool material	1.2379, ASP 2023	feed length x	130 mm
tool angle α	10 °	initial diameter d_0	20 mm
tool stroke h_T	1 mm	final diameter d_1	15 mm
stroke frequency f_{st}	37,5 Hz	zone II length l_{cal}	20 mm

3.2. Results - process

The process parameters were measured and the mean of the maximal value per stroke is calculated. The data were analyzed for the different phases separately but only the results for the stable process phase are discussed because they allow the best statement. The actual and the set value of the feeding drive position were measured continuously. Thus, the tracking error Δx were calculated by the difference between actual and set value of the feeding drive position. This difference is due to the axial reaction force F_A of the forming process and thus allows a statement about this force. The increase of the tracking error with increasing velocity is also determined by the gain factor value in the position closed loop controller. The plot of the theoretical tracking error $\Delta x_{theoretical}$ is sketched in Fig. 8.

The tracking error is lower for all feed velocities for rotary swaging without lubricant in comparison to rotary swaging with lubricant (see Fig. 8). For the tools T2 rotary swaging with lubricant generates the highest tracking errors for all feed velocities due to the lowest friction coefficient value. The tracking error for the forming with lubricant and tools T1 is lower but also high due to the still low friction coefficient value. For the forming without lubricant and the tools T1 and T2 the tracking error is lower due to the higher friction coefficient value. The tools T3 generate the lowest tracking error. The lubrication condition has a very small influence but for dry rotary swaging the tracking error is slightly lower. For the forming with tools with high friction coefficient value the increasing of the tracking error with increased feed velocity is higher than for the forming without lubricant respectively with structured tools. In summary it can be said, that structured tools reduce the tracking error and thus also the axial reaction force.

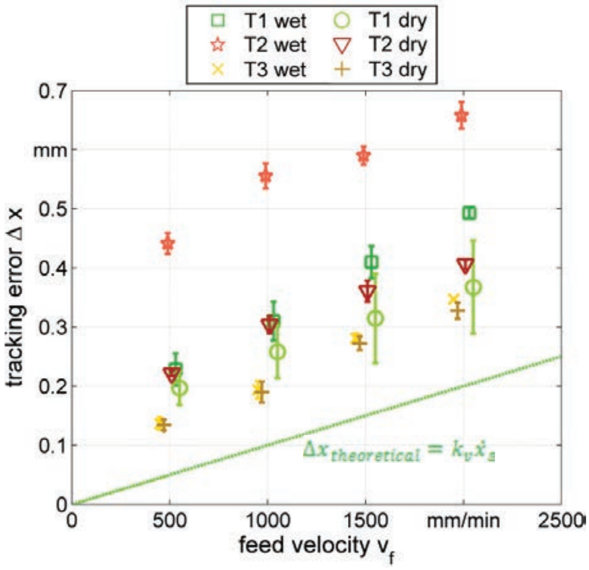

Fig. 8. Tracking error for different feed velocities, wet and dry.

3.3 Results - workpiece

The work quality was investigated by measuring the roundness deviation and surface roughness. Therefore the roughness was measured for all three tools for the forming with and without lubricant with a feed velocity of v_f = 500 mm/min. The roundness deviation was only measured for the workpieces formed with the tools T1. It is a value for the deviation of the profile form from the perfect circular form and indicates the distance between the maximal positive and the maximal negative deviation of the perfect circular form. The roundness deviation increases with higher feed velocities irrespective of the lubricant condition. The roundness value for dry formed workpieces is worse and the variance is higher than for the wet forming (see Fig. 9).

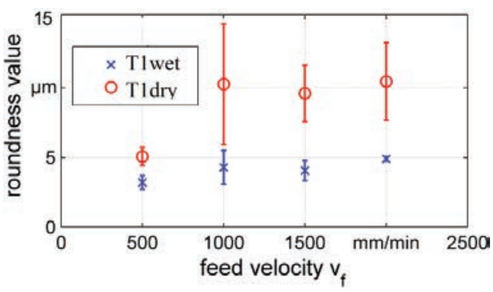

Fig. 9. roundness value for different feed velocities, T1 wet and dry.

Furthermore the roughness is worse for the dry formed workpieces formed with the tools T1 and T2 compared to the lubricated forming (see Fig. 10). For the forming with the tools T3 the roughness is the highest for wet as well as dry forming due to the structure in the reduction zone of the tools. But the roughness after wet forming is worse than after dry forming.

After the forming of one tube without lubricant a large amount of particle abrasion adhered at the surface of the tools T1 and the particle abrasion covered the tungsten carbide layer. The higher amount of particles can be explained with the higher friction coefficient during dry forming. Due to the missing of the flushing function of the lubricant the particles adhered to the tools. The same was seen at the workpiece where a lot of particles are on the surface after forming without lubricant. The particles abrasion was struck into the workpiece surface what could be observed when cleaning these. This is one of the reasons for the high roughness. For the same experiment with the tools T1 with lubricant much less amount of particle abrasion was observed.

The particle abrasion after dry forming with the tool T2 were much less compared to dry forming with the tools T1. The difference of the amount of particles was slightly higher for dry forming. Summarized the quality for tubes after the forming with the tools T1 and T2 is better with lubricant. For the forming without lubricant the quality for tubes is better with the tools T2.

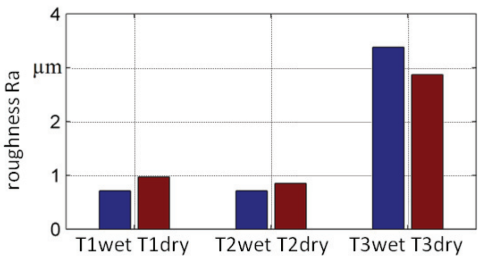

Fig. 10. roughness of the workpieces with a feed velocity of v_f = 500 mm/min for T1, T2 and T3, wet and dry.

After the forming with structured tools (T3) the surfaces had the worst quality compared to the forming with tools T1 and T2. In the valley of the structure of the tools T3 gather the particle abrasion of both processes, dry and wet (see Fig. 11). Pictures of the surfaces of the workpieces are shown in Fig. 12-17 for all tools with wet and dry conditions. Fig. 16 and 17 show the surface of a workpiece formed wet or dry with the tools T3. There are valleys to recognize in peripheral direction produced by the structure in the reduction zone of the tools. They occur for wet and dry forming. This valleys return at regular intervals, which can be seen in the profile line in Fig. 18. The valleys are generated by the structure of the reduction zone of the tools. The surface finishing in the calibration zone of the tools is not possible anymore due to the strong disruption. The figures of the surface of the workpieces formed with the tools T1 (see Fig. 12 and 13) and T2 (see Fig. 14 and 15) show a better surface quality without valleys irrespective of the lubricant condition.

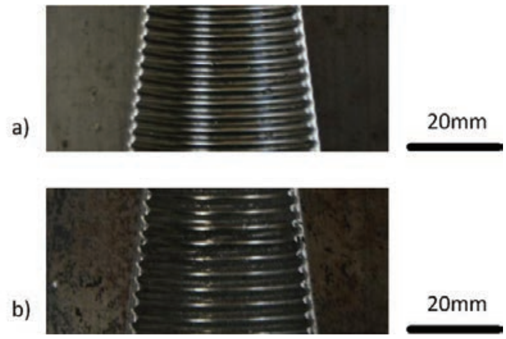

Fig. 11. Structured tools after forming with v_f = 500 /mm/min; a) wet, b) dry.

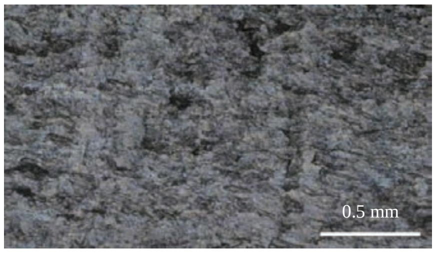

Fig. 12. Workpiece surface after forming with T1wet (v_f = 500 mm/min).

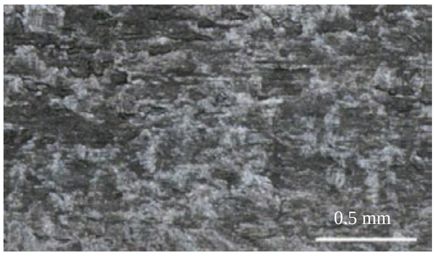

Fig. 13. Workpiece surface after forming with T1dry (v_f = 500 mm/min).

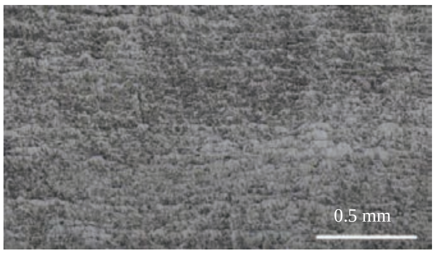

Fig. 14. Workpiece surface after forming with T2wet (v_f = 500 mm/min).

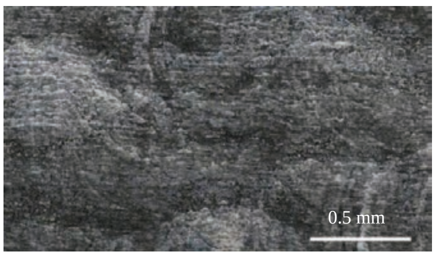

Fig. 15. Workpiece surface after forming with T2dry (v_f = 500 mm/min).

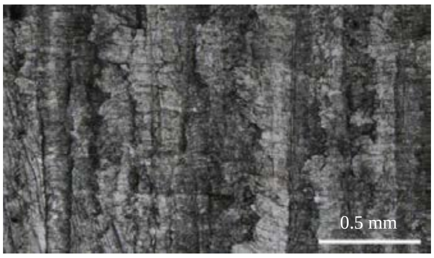

Fig. 16. Workpiece surface after forming with T3wet (v_f = 500 mm/min).

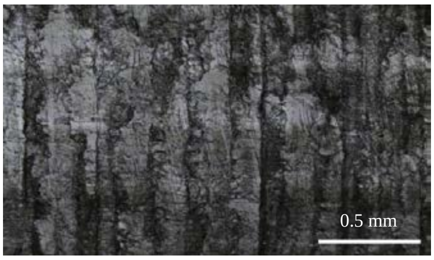

Fig. 17. Workpiece surface after forming with T3dry (v_f = 500 mm/min).

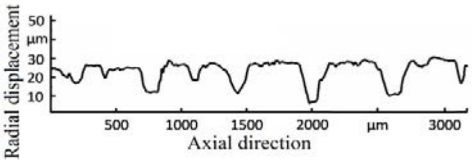

Fig. 18. Axial profile line of the workpiece surface after forming with T3dry.

4. Summary

Forming with structured tools under different lubrication conditions in comparison to forming with conventional and smooth tools is studied during infeed rotary swaging. Therefore steel tubes are reduced in diameter and the process parameters as well as the formed geometry are examined. The feasibility is shown in particle and also the difficulties that arise. Following conclusions are drawn:

- Dry rotary swaging features modified recorded process parameters in comparison to forming with lubricant. The tracking error decreases due to the increased friction coefficient.
- Forming with structured tools also leads to a decrease of the tracking error. Whereas the use of tools with smooth reduction zone shows the highest tracking error for the forming with lubricant.
- During dry forming with conventional tools which have a tungsten carbide layer a high amount of particle abrasion adhere to the tools and the workpiece. Also during dry rotary swaging with smooth and structured tools particle abrasion adhere to the tools and the workpieces.
- The workpiece quality of the tubes formed by dry rotary swaging is disadvantageous due to the worse roundness and roughness. But especially tubes formed with structured tools exhibit strong disruption at the surface independent from the lubricant condition.

A first application of structured tools for rotary swaging is examined. It influences positively the process parameter tracking error. Due to the particles abrasion and the disadvantageous surface generated by the missing lubricant and the structure in the reduction zone the tools need an additional modification. The structure in the reduction zone is too high. Therefore a smaller value for the amplitude A has to be found which leads still to a decrease of the tracking error while the negative influence on the surface quality is minimized. One idea for further investigations is a changing amplitude A which decreases to the calibration zone. In addition a skew cosine should be of interest due to the potential to have the same positive influence on the tracking error while smaller amplitude A and less impact on the surface quality. In a next step coated tools have to be investigated to identify the decrease of the particle abrasion. Furthermore other structures for example with a smaller amplitude or a skew cosine have to be examined to get a better surface quality. Finally both tool modifications, structuring and coating, have to be combined to show the complete potential of dry rotary swaging. The change of the temperature conditions due to the missing cooling of the lubricant needs also further investigations

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