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Graded Structured Tools for Dry Rotary Swaging

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Abstract

Nowadays cold forming processes, especially the incremental process rotary swaging, use high amounts of lubricants with disadvantages like costs of recycling, replacement and for cleaning of the workpieces. But the lubricant fulfill necessary functions such as lubricating, flushing and cleaning of the tools. To enable dry forming without lubricant, it is necessary to substitute the functions by means of coating and structuring of the tools. In this study infeed rotary swaging with graded structured tools is investigated by FEM simulations and by experiments. The simulated process forces are in good accordance to the measured ones. Finally, the practicability of dry rotary swaging with graded structured tools is demonstrated.

Keywords: radial forming, incremental forging, dry forming, finite element method

NOMENCLATURE

A = amplitude
α = tool angle
d_0 = initial work piece diameter
d_1 = final work piece diameter
F_A = axial force
F_{Norm} = normalized force
F_R = radial forming force
F_f = feed force
F_x = substitude force
f_{st} = stroke frequency
h_t = tool amplitude
l_{cal} = length of the calibration zone
λ = wavelength
r_0 = initial radius
r_1 = final radius
RONt = roundness
s_0 = initial wall thickness
Sa = surface roughness
S = structure value
v_f = feed velocity
Δx = tracking error
T_{flat} = tools without structuring
T_{graded} = tools with graded structuring
T_{cosine} = tools with cosine structuring
μ = friction coefficient

1 Introduction

Rotary swaging is an incremental cold near-net forming process and has an important field of application in the automotive industry for the production of axes, steering spindles and gear shafts. The final workpiece features advantages like improved material properties as increased tensile strength and undisturbed fibre flow. Especially for hollow shafts the wall thickness can be adjusted by the process to yield an optimal use of material resources and to exploit the full potential of light weight products. While the swaging unit is rotating, the base jaws are passing the cylinder roller and by the cam all tool are pushed radially to the center [1], see Figure 1 a).

In the process the diameter of the workpiece is incrementally reduced by this oscillating motion of the tools with amplitude h_T. A stable phase in the process is reached if the tools are completely filled by the workpiece. During infeed rotary swaging the workpiece is

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axially fed in the swaging unit with the feed force F_f. Against this force counteracts the axial reaction force F_A which is caused by the radial forming force F_R, see Figure 1 b). Due to the limited stiffness of the feeding system, the axial reaction force results in the back pushing of the support. It can be measured by the tracking error Δx of the feeding axis. This tracking error is a measure for the axial reaction force. To reduce this reaction force conventional tool sets feature a tungsten carbide layer in the reduction zone to increase the effective friction [1].

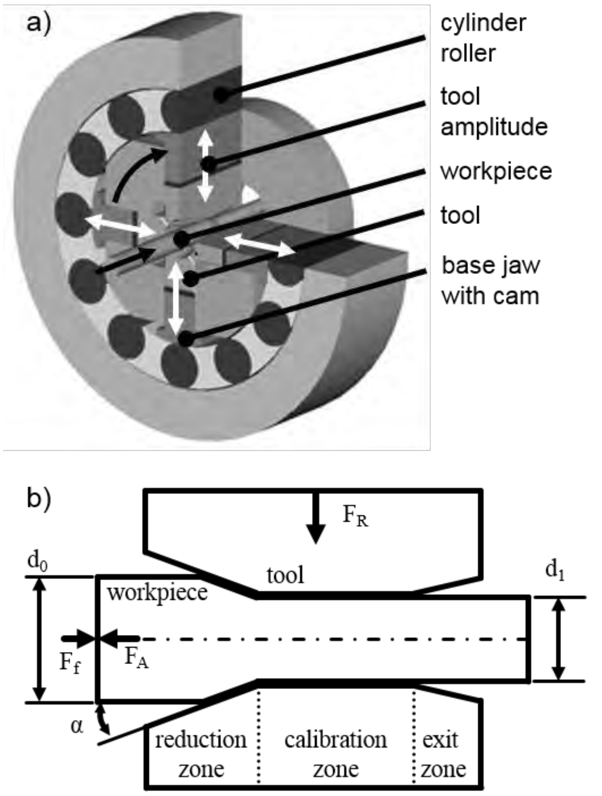

Fig. 1: Principle of infeed rotary swaging process; a) swaging head, b) longitudinal section of the process.

In cold forming processes lubricants based on mineral oil are still used. Especially in the case of rotary swaging a large amount of lubricant is needed to enable a stable process and to ensure a good workpiece quality. In the process important functions are fulfilled by the lubricant like the reduction of friction and thus the reduction of tool load and wear. Furthermore, the lubricant serves as separation layer to minimize cold welding processes. In addition, it cools the process and flushes the forging zone to remove abraded particles. However, some disadvantages arise, like the recycling of lubricant and cleaning of the workpiece. Furthermore, the replacement of lost lubricant which is removed during the process, especially for the forming of tubes, causes high costs. Hence, the elimination of lubricant offers three significant advantages: reduction of financial costs, less environmental impacts and reduction of possible health burden. For this reasons, the interest in dry metal forming is highly increasing [2].

To cope with the challenges of dry forming a combination of two approaches is intended. Firstly, a coating on the tools is intended to reduce the friction und thus to minimize wear of tools and workpieces [3]. But with a low friction coefficient the axial reaction force increases [4]. To improve the grip of the workpiece and thus to reduce the axial reaction force, a tungsten carbide layer is applied on the surface of commonly used tools. However, in dry rotary swaging the flushing effect of lubricant for the cleaning of the tools from wear particles is missing, thus this carbide layer will be inoperative and so it is no longer applicable. Hence, an additionally structuring of the tool surface is needed to enable an adjustment of the tribological conditions [5,6]. An overview on this approach is given in Figure 2.

The priciple feasibility of dry rotary swaging in the micro and macro range was already presented [7,8]. But robust dry rotary swaging needs a modification of the process and an adjustment of the tools [9]. However, by analysing the recorded process parameters and the measured formed geometry and quality of the finished workpieces some challenges are carved out. On the one hand the structured tool surface generates a low workpiece quality [10], on the other hand the interaction of coating and structuring needs to be enhanced [11] and the discharging of abrasives out of the swaging unit has to be improved [12]. In this work the structuring of the tools is investigated. Graded structured tools are examined with the finite element method as well as with experiments under wet and dry lubrication conditions. It is shown that the axial reaction force can be reduced effectively by the shaping of the structure.

Fig. 2: Interdisciplinary approach for a dry rotary swaging process.

2 Modeling and simulation

Two-dimensional axisymmetric models based on finite element method (FEM) are commonly used to simulate rotary swaging, due to the shorter computational time compared to three-dimensional simulations [13,14,15,16]. For example, the strain and stress distributions with regard to the influence of axial feed velocity is examined [13], also the material flow depending on friction [14] and the process forces and residual stress for different process settings [15]. Also, different designs of the reduction zone of the tools are investigated like convex, concave and hybrid contours [16].

The investigation in this work were done with a 2D-axisymmetric model, see Figure 3. The tool was realized as rigid body and the workpiece (tube) as an elastic-plastic iso-tropic material with parameters from literature (material 1.0037) [17]. The model was realized with the software ABAQUS/Explicit 6.16. For the friction model the penalty formulation and the coulomb friction was used due to the simplicity and the good results in cold metal forming simulations [18]. After the workpiece is fed the first 35 mm in the swaging unit the tools are completely filled and a quasi-steady state is reaches. Only this length of the workpiece was provided with a fine mesh. The element type A 4-node bilinear axisymmetric quadrilateral elements were used with reduced integration and hourglass control. Figure 3 shows some rotary swaging process parameters, further are: feeding velocity $v_f = 2000$ mm/min, stroke frequency $f_{st} = 37.5$ Hz, length of the calibration zone $l_{cal} = 20$ mm, material steel 1.0037.

Different cosine structures in the reduction zone of the tool were investigated. However, all structures featured: the tool angle $\alpha = 10°$, the wavelength $\lambda = 1.3$ mm and the maximum amplitude $A = 50$ µm [19]. The variation was a grading of the amplitude falling to the calibration zone, see Figure 4. To assess the structure a structure value S was calculated. Therefore, the sum of all amplitude heights of the waves which are in contact were summed. For the forming from a final diameter of $d_0 = 20$ mm to an initial diameter of $d_1 = 15$ mm with a tool angle of $\alpha = 10°$, eight cosine waves are in contact, see Figure 4 b). Thus, for a no graded structure eight times the amplitude $A = 50$ µm are in contact, which yield a value for the structure of $S = 400$. However, for a graded structure starting with the eighth amplitude the value for the structure is $S = 225$ and for no structuring $S = 0$. The higher the structure value S, the more pronounced is a structure.

The friction coefficient values were: $\mu = 0.1$; 0.15 and 0.2. The axial reaction force F_A of the last strokes, when the process is in the stable phase is averaged. Then the force F_A were normalized F_{Norm} to the highest axial reaction force of the simulation with no structure and the lowest friction coefficient of $\mu = 0.1$.

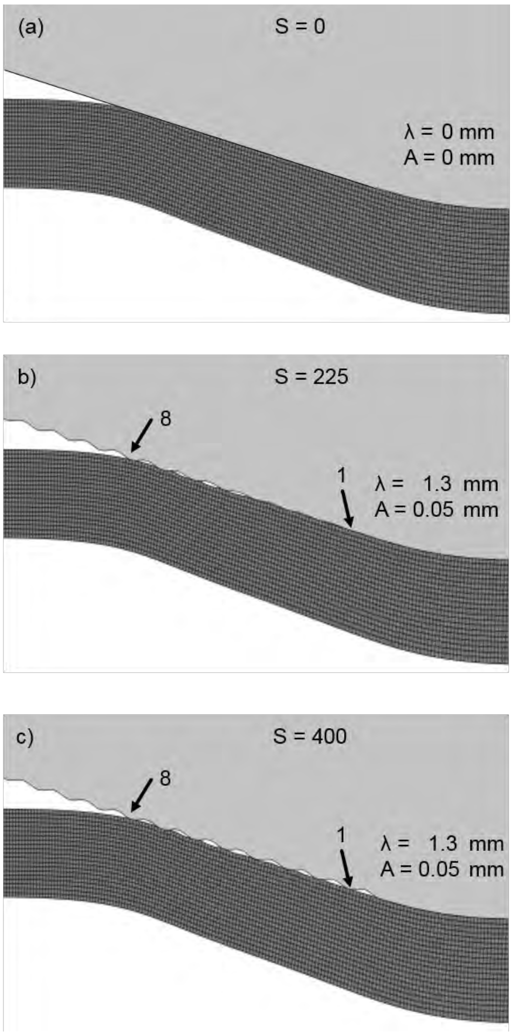

Fig. 4. Structure value for different tools; a) no structure, b) graded structure from wave eight, c) cosine structure.

3 Experimental procedure

To validate the findings of the simulations rotary swaging experiments were conducted with different tools. All tools were made of the material 1.2379, with the same tool angle $\alpha = 10°$, calibration length $l_{cal} = 20$ mm and final diameter d1 = 15 mm. The first

Fig. 3: 2D-axisymmetric model.

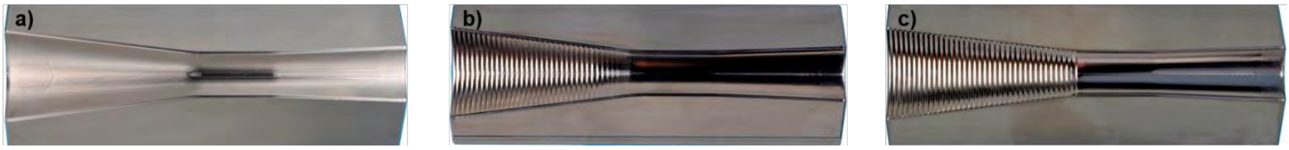

Fig. 5: Tools; a) tool without structuring (T_{flat}), b) tool with graded cosine structuring (T_{graded}), c) tool with cosine structuring, (T_{cosine}).

tool featured no structuring (structure value $S = 0$) (T_{flat}), see Figure 5 a), the second features a graded cosine structure (structure value $S = 225$, $\lambda = 1.3$ mm, $A = 0.05$ mm) to the calibration zone starting of the wave eight (T_{graded}), see Figure 5 b), and the last tool features a cosine structure (structure value $S = 400$, $\lambda = 1.3$ mm, $A = 0.05$ mm) (T_{cosine}), see Figure 5 c).

With all tool sets the same steel 1.0037 tubes with a wall thickness of $s_0 = 2$ mm were reduced in diameter from initially $d_0 = 20$ mm to finally $d_1 = 15$ mm. The tubes were fed with a linear direct drive into a swaging unit. Experiments with four different feeding velocities ($v_f = 500, 1000, 1500, 2000$ mm/min) were carried out, each with and without lubrication of the process. The experiments were repeated with five samples each. Before each dry rotary swaging the tools were cleaned thoroughly using ethanol. The stroke height of the tools was set to $h_T = 1$ mm and the stroke frequency to $f_{st} = 37{,}5$ Hz. During the entire process the process parameters were recorded and the results for the stable phase were analyzed. Continuously the actual and the set value of the feeding drive position were measured and by the difference the tracking error Δx was calculated. The mean of the maximum of this value per stroke is calculated which occurs due to the axial reaction force F_A respectively the tribological conditions during forming. This yield a substitute force value F_x which holds for an estimation of the axial process force.

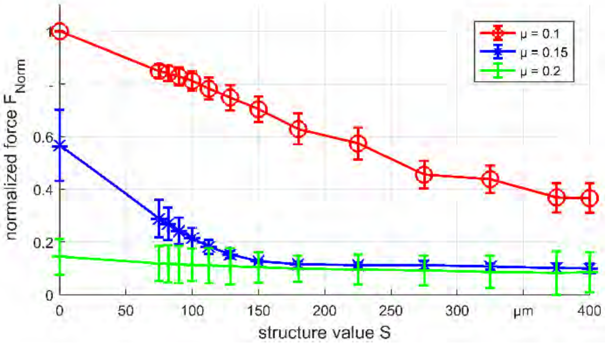

Fig. 6: Normalizes axial reaction force for different graded structures and different friction coefficients.

4 Results and discussion

The results of the simulation reveal, that for the lowest friction coefficient value the axial reaction force is the highest, see Figure 6. Furthermore, the structure is more effective. With every increase of the structure value S the axial reaction force is decreasing. Compared with the other two higher friction coefficients the axial reaction force is lower for all structures. For $\mu = 0.15$ a strong effect exists just till a structure value of $S = 150$, but for higher structure values the effect is indiscernible. In the case of $\mu = 0.2$ the effect is barely till the structure value $S = 150$ and for higher values of S not present. This shows, that for slightly higher friction coefficients also graded structures brings a decreasing of the axial reaction force. Only for low friction coefficients a higher value of the structure brings further lowering of the axial reaction force.

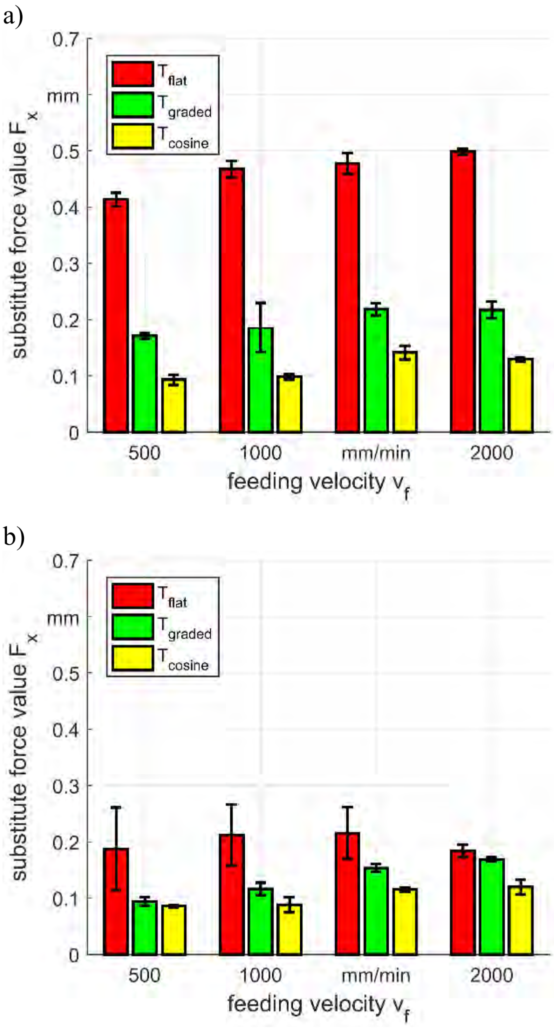

Fig. 7: Substitute force value Fx for different tools and different feeding velocities during the forming of steel tubes; a) with lubricant; b) without lubricant.

All substitute force value F_x measured during the forming without lubricant are much closer together, see Figure 7 b). Thus, F_x of forming with tools T_{cosine} is just two times lower compared to F_x of forming with tools T_{flat}. Furthermore, the difference of the substitute force value F_x of forming with both tools T_{graded} and T_{cosine} is much lower compared to F_x when forming with lubricant.

To compare the results of the simulation and of the experiments, the axial reaction force F_A from the simulation and the measured substitute force value F_x are normalized F_{Norm}. Figure 8 shows the comparison for both tribological conditions, on the one hand forming with lubricant (experiment) and the low friction coefficient value $\mu = 0.1$ (simulation), and on the other hand forming without lubricant (experiment) and the high friction coefficient value $\mu = 0.2$ (simulation). For the forming with lubricant in the FEM and in the experiments a significant effect of the structure can be observed, for both the axial reaction force can be reduced for higher value of the structure, see Figure 8 a). However, for the dry forming the effect of the structure is much lower, so the axial reaction force is reduced less both in FEM and experiments, see Figure 8 b).

For both tribological conditions it is shown that a not graded cosine structure on the tools (T_{cosine}) reduces the axial reaction force during the rotary swaging process most effectively. However, a graded cosine structure of the tools T_{graded} also effects a significant reduction, but depending on the actual friction condition less pronounced.

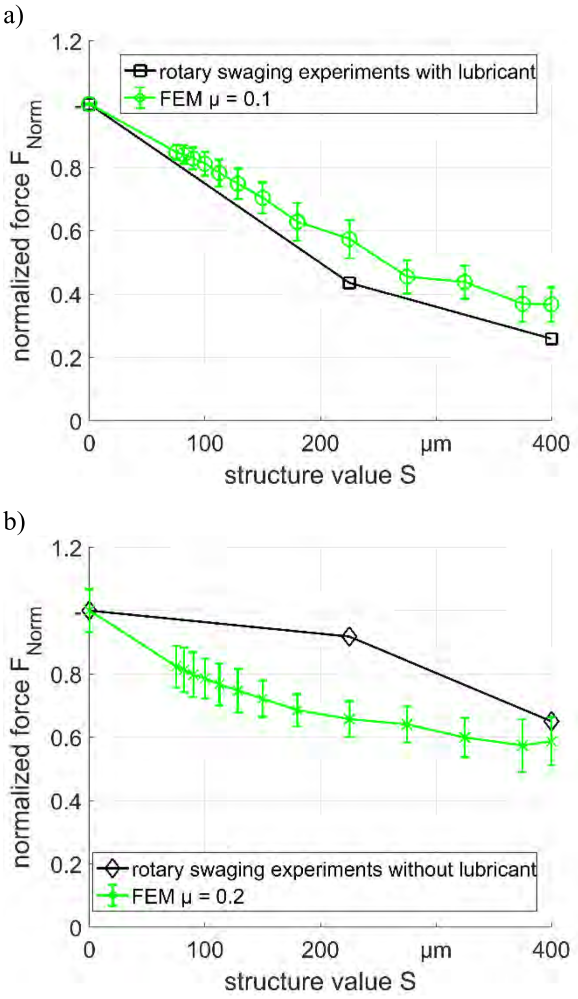

Fig. 8: Comparison of the normalized axial reaction force respectively the tracking error of simulation and experiment for different tribological conditions; a) forming with lubricant, b) forming without lubricant.

The generation of a good workpiece quality is also an important function of the tools. Two measured values are used to describe the workpiece quality, the roundness deviation Ront and the surface roughness Sa. The roundness deviation is the highest for tubes after forming with tools T_{cosine}, it is up to four times higher compared to workpieces formed with tools T_{flat}. Thus the workpiece quality is worse. This negative effect can be observed for both lubrication conditions, see Figure 9. The roundness deviation for workpieces formed with tools T_{graded} is also higher but only about two times compared to tubes after forming with tools T_{flat}. The increasing of the feeding velocity leads also to a raise of the roundness deviation independent of the lubrication condition. The forming without lubricant leads for the workpieces formed by tools T_{flat} and tools T_{graded} to a rising of the roundness deviation. However, the roundness deviation of the tubes formed by tools T_{cosine} are very high independent of the lubrication condition.

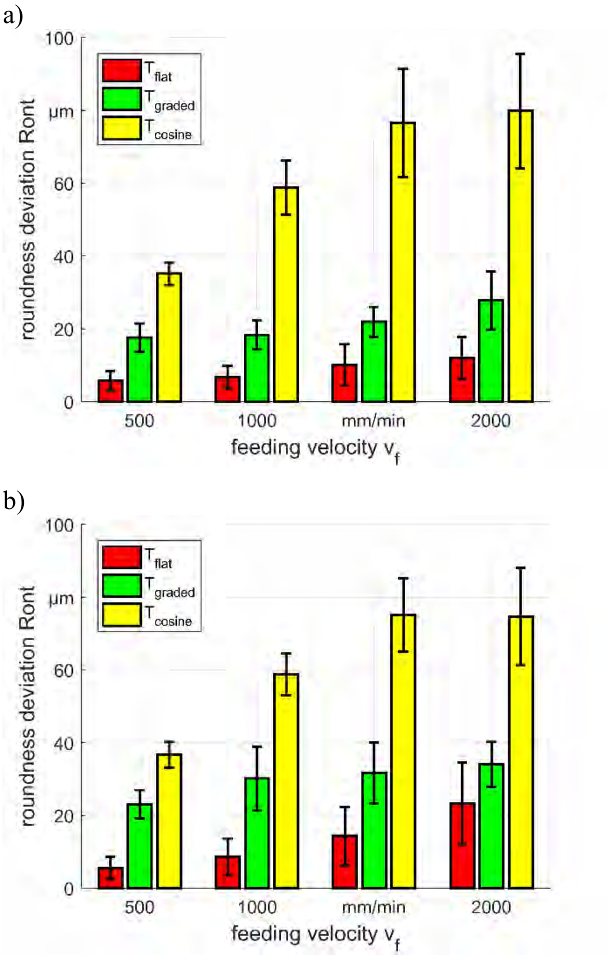

Fig. 9: Roundness deviation Ront of steel tubes after forming with different tools and different feeding velocities; a) with lubricant; b) without lubricant..

The different tools have also a significant effect on the surface roughness of the formed tubes. Again, the tubes formed with the tools T_{cosine} shows the highest value for the surface roughness Sa, see Figure 10. So the value is up to four times higher compared with the surface roughness of tubes formed with tools T_{flat}. Furthermore, the standard deviation of the surface roughness is much higher compared to the other surface roughness values. Thus the workpiece quality is worse. The workpieces deformed by tools T_{graded} shows just a bit higher values for the surface roughness then the tubes deformed by tools T_{flat}. By increasing the feeding velocity no explicit trend is observed. The forming without lubricant results for the workpieces manufactured by tools T_{flat} and tools T_{graded} to a rising of the surface roughness. In contrast, the surface roughness of the tubes formed by T_{cosine} are independent of the lubrication condition.

So it can be said, that forming with cosine structured tools leads to the lowest axial reaction forces. But the manufactured tubes feature the worse workpiece quality due to the high value of the roundness deviation as well as of the surface roughness. However, the rotary swaging with graded structured tools leads also to a decreasing axial reaction force and the workpiece quality shows only slightly deterioration by a little increasing of both quality features.

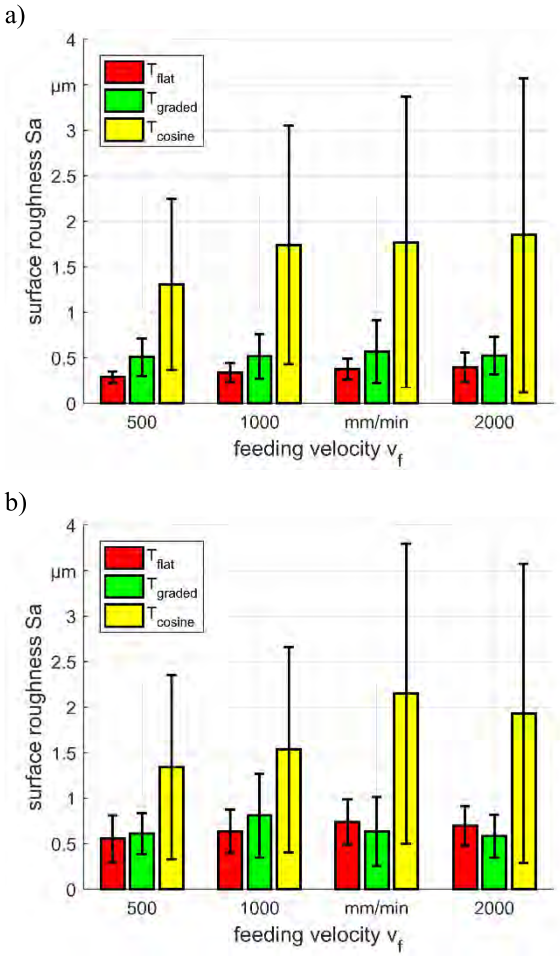

Fig. 10: Surface roughness of steel tubes after forming with different tools and different feeding velocities; a) with lubricant; b) without lubricant.

5 Conclusions

Rotary swaging with graded structured tools was investigated by finite element method as well as physical experiments. The influence of differently graded structured tools were examined for different friction coefficients in the simulation. Three forming tools were manufactured and tested with and without lubrication of the process for different feeding velocities. The recorded process parameters and the measured formed geometry of the produced workpieces were analysed.

Following conclusions are drawn:

- The simulation results showed, that the effect of the structuring of the tools decrease the axial reaction forces. This effect is stronger with lower friction coefficient value.
- The results from the simulation and the results from the physical experiments are in good accordance.
- The reduction of the axial reaction force is enable by the structured tools at the expense of the workpiece quality like surface roughness and roundness deviation.
- The grading of the structuring is an appropriate measure to realize a good compromise between force reduction and resulting workpiece quality.

In future word the graded structured tools will be coated to study the effect with low friction without lubricant. Furthermore, the effect of the structure collectively with the coating on the amount of particle abrasion and on the workpiece quality needs to be analysed. Last but not least, it is necessary to study the interaction of the graded structure and the coating and thus the adhesion strength and the long-term performance.

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