

High productivity micro rotary swaging

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Abstract. Rotary swaging is an incremental forming process with two main process variations plunge and infeed rotary swaging. With plunge rotary swaging, the diameter is reduced within a limited section whereas the infeed rotary swaging enables a diameter reduction over the entire workpiece length. The process is now subject to intensive investigation for manufacturing of micro parts. By increasing the process speed, failures occur particularly due to inappropriate material flow. In plunge rotary swaging, the workpiece material can flow radially into the gap between the dies and thus the workpiece quality suffers. In infeed rotary swaging the workpiece material flows against the feeding direction and can provoke bending or braking of the workpiece. Therefore, additional measures to control both the radial and the axial material flow to enable high productivity micro rotary swaging are investigated. The radial material flow during plunge rotary swaging can be controlled by elastic intermediate elements that enable an increase of productivity by factor three. A spring-loaded clamping device that enables an increase of the productivity by factor four can temporarily buffer the axial material flow in infeed rotary swaging against the feeding direction.

Keywords: Cold forming, Micro forming, Feed rate

1 Introduction

Rotary swaging is an incremental open die forging process for rods and tubes [1]. The process is subject to intensive investigation in the micro range with focus on machine and workpiece behavior, achievable dimensions and workpiece properties [2, 3]. According to CIRP micro parts are those with at least two dimensions smaller than 1 mm [4], which means for cylindrical workpieces that their diameter is smaller than 1 mm. However, many challenges related to the stiffness of the workpiece and the tolerances of the forming machine have to be overcome. In rotary swaging, two or more synchronously oscillating

dies act on the workpiece. Material flow takes place mainly in radial (reduction of the diameter) and in axial direction (elongation of the part). Figure 1 shows the two most important process variants, the infeed and the plunge rotary swaging. An outer ring encloses the dies and other mechanical components that are necessary for the die motion and the forming. The two process variants differ particularly in the direction of the feed. In plunge rotary swaging, the workpiece is positioned between the dies prior to the forming, then a radial displacement with a feed rate v_r in the direction of the workpiece and an oscillating movement with an amplitude h_T (stroke) of the dies take place simultaneously.

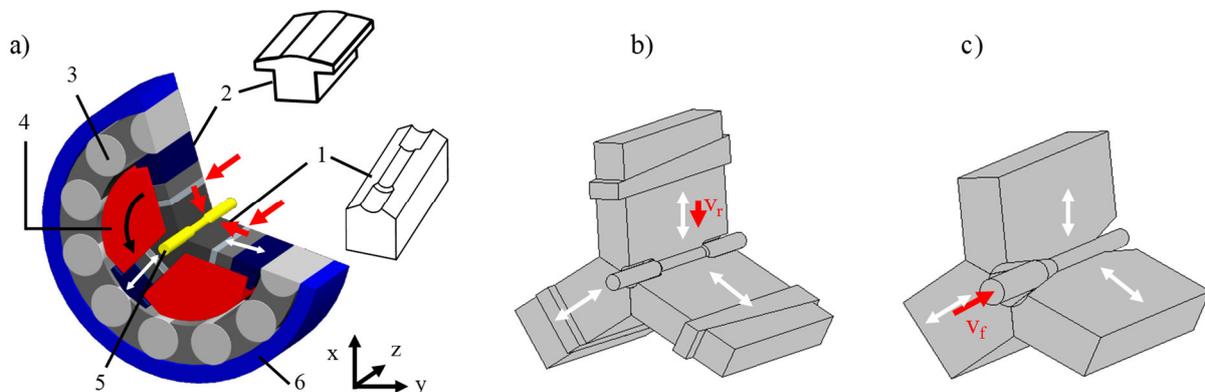


Fig. 1. Principle rotary swaging: a) swaging head 1 die, 2 base jaw, 3 cylinder roller, 4 drive shaft, 5 workpiece, 6 outer ring; b) plunge rotary swaging; c) infeed rotary swaging.

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In infeed rotary swaging however, the workpiece is fed with an axial feed rate v_f in the swaging head and the dies perform only the oscillating motion. In both variants, a relative rotation between the workpiece and the dies is necessary to produce cylindrical workpieces.

It was found in previous investigations that the utmost limitations in micro rotary swaging are due to bending, break or the emergence of flashes on the surface of the workpiece [5]. These failures occur particularly due to inappropriate material flow in the forming zone. When the forming volume per stroke is increased by increasing the radial feed rate v_r in plunge rotary swaging the workpiece material can flow radially into the gaps between two adjacent dies and thus generates flashes on the workpiece surface [6]. A high surface quality is not guaranteed any more. In axial direction, the dies do not enclose the workpiece and by this the material flow is completely unguided in this direction. When the forming volume per stroke is increased by increasing the axial feed rate v_f in infeed rotary swaging the workpiece material flows in and against the feeding direction. The material flowing backwards leads to high loads in the workpiece and the feeding system, which provokes bending of the workpiece.

To increase the feed rate and thus the productivity while avoiding process failures and enabling even higher workpiece quality, additional measures to control both the radial and the axial material flow in micro rotary swaging are presented.

2 Plunge rotary swaging

2.1 Initial situation

In classical plunge rotary swaging the cross section of a region of a bar or tube with an initial diameter of d_0 is reduced to a final diameter of d_1 . The length changes from l_0 to l_1 . The forming die with the geometry to be reached is generally made out of hard metal or of tool steel. The die with its characteristic regions as well as the workpiece before (Figure 2a)) and after forming (Figure 2b)) are given below.

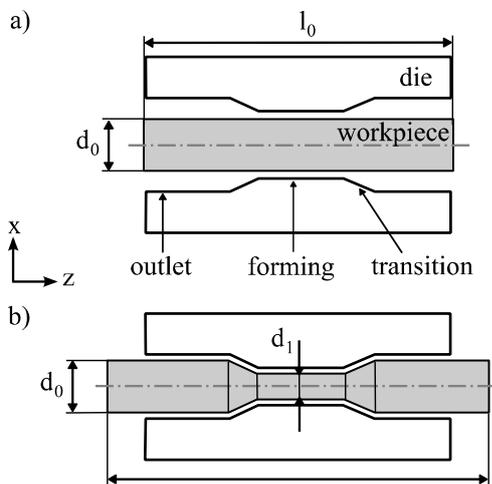


Fig. 2. Geometry of the die and the workpiece in plunge rotary swaging; a) before forming, b) after forming.

This process variant is ideal for generating local geometrical denting and allows a broad diversity of possible part designs. However, a limitation of the process is the discrepancy between the geometry of the closed set of dies and the formed workpiece. In micro range the forming accuracy could be improved by controlling the axial material flow [7]. Furthermore, it was found during manufacturing of micro parts that the process was highly constrained by the radial feed rate and the formation of flashes. Generally, the flashes are parallel to the longitudinal axis of the workpiece and their number is equal to the number of dies that are used [6]. For example, three flashes will occur in the case of a set three dies as presented in Figure 3. A cross section in the forming zone of the workpiece in which the contours of the dies are schematically drawn is presented. The geometry can be approximated to a polygon (triangle).

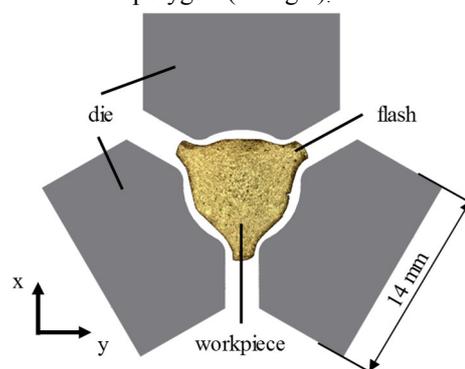


Fig. 3. Flash formation in plunge rotary swaging with three dies

To achieve the goal of a high radial feed rate, one measure is to control the flow of material in the radial direction. From this consideration, a new concept has emerged, based on the use of elastic intermediate elements (EIE) in rotary swaging. Comparable approaches for other forming processes are mentioned in [8, 9]. The use of elastomers in metal forming was summarized in [8] and in [9] micro patterning of thin metallic plates using rubber in a forming container was investigated. For micro plunge rotary swaging, the basic idea is to position an elastic intermediate element in the set of dies to prevent any workpiece material to flow into the gaps between the single dies. Conceivable intermediate elements could be made of super-elastic metallic or polymeric substances with a high tear resistance.

2.2 Experimental procedures and results

As workpiece material austenitic steel 304 alloy and pure copper CW004A were used. The initial diameter was $d_0 = 1.5$ mm for both materials, and was reduced using dies with a nominal diameter of $d_{nom} = 985$ μ m. The nominal diameter is defined as the inside diameter of the forming zone of a closed die set. The forming zone was 20 mm long. A stroke heights of $h_T = 0.3$ mm for each die was applied. The workpieces were lubricated during the process. During the forming, the elastic deformation of the outer ring of the swaging machine was monitored by strain gauges. The response of the strain gauges is

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proportional to the deformation of the ring and thus can be also taken as a measure of the radial forming force. Prior to the forming the workpiece is clamped into a chuck and the elastic intermediate elements (EIEs), which are available as hose, are cut into the desired length and fitted on the workpiece area, that has to be reduced. Thermoplastic polyurethane (Elastollan C78A1000, C98A10000 and 1174D11000) intermediate elements were tested. They were available with three different hardness values (low hardness = ILH; middle hardness = IMH and high hardness = IHH). The outer diameter of the thermoplastic hoses was 2.5 mm and the wall thickness was 0.5 mm. Some characteristics of the EIEs are summarized in Table 1.

Table 1. Characteristics of the elastic intermediate elements (according to manufacturer).

	units	ILH	IMH	IHH
hardness	Shore A	80		
	Shore D	(~30)	52	75
tensile elongation	%	650	550	380
E-modulus	MPa	-	160	560

Forming experiments were conducted with different radial feed rates v_r . Through a gradual increase of v_r , possible processing windows in which workpieces could be produced without failure were framed. The stroke frequency of the swaging machine was kept constant at 102 Hz and the same bottom dead center of the dies was applied for all experiments. After forming, the final diameter (d_1) of the deformed area of the workpiece was measured by means of an optical micrometer.

Forming results for 304 alloy

With the stroke height $h_T = 0.3$ mm and without intermediate element the maximum feed rate of $v_r = 0.26$ mm/s was reached. However, this boundary was caused by strong vibrations of the machine. For the mentioned reason higher feed rates as well as IMH and IHH were not tested for this alloy. An assessment of the radial extension of the outer ring of the rotary swaging machine during forming with and without EIE is given in Figure 4. The measured signals were graphically synchronized with respect to the bottom dead center of the dies, which also corresponded to the end of the closing motion of the dies (point C in Figure 4). The starting points of the forming are different for both cases, earlier with EIE (point A) and later without EIE (point B). The die closing takes place between the points A and C respectively B and C. From the point C the dies reopen. During the forming with EIE a small extension of the ring occurs first, which then dropped again. This can be attributed to a compacting of the EIE (extension) followed by a flow into the gap (release of the extension). The forming of the workpiece started almost equally with or without EIE. Apart from the points A and B the course and the amplitude of the ring extensions are comparable.

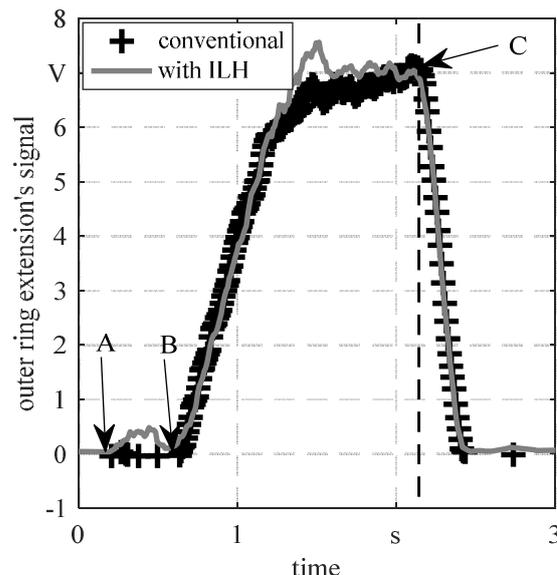


Fig. 4. Elastic extension of the outer ring of the swaging head during forming of 304 alloy with $v_r = 0.18$ mm/s without and with elastic intermediate element.

The mean final diameters of five samples each, measured in the middle of the deformed area of the workpiece (see Figure 2) were 1123 ± 6 μ m for conventional plunge rotary swaging and 1108 ± 9 μ m for plunge rotary swaging with ILH. The difference between the two values is in the range of the standard deviations whereas nominal diameter of $d_{nom} = 985$ μ m was not reached. The time for forming without EIE is about 1.48 s compared to an expected time of 1.42 s. The expected time for the forming with ILH cannot be properly estimated. However, the actual time from the measurement was 1.92 s. The greater diameters after forming with and without EIEs can be explained by the resilience of the swaging head, which leads to an extension of the outer ring, thus the die closure is limited. A measure to reduce these two effects could be by using a calibration time at the end of radial feed of the dies towards the workpiece. The ILHs were not reusable as presented in Figure 5.



Fig. 5. ILH and workpiece after forming with $v_r = 0.07$ mm/s.

Forming results for copper CW004A

With $h_T = 0.3$ mm a feed rate of $v_r = 0.34$ mm/s was reached before flash or break occurred. The feed rate was increased when EIE was applied, see in Figure 6.

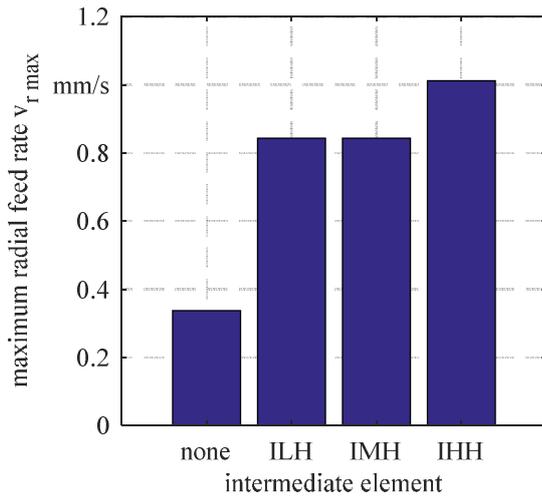


Fig. 6. Maximum radial feed rate in plunge rotary swaging of copper CW004A with different elastic intermediate elements.

The EIEs allowed to increase the feed rate up to about 200 % for $h_T = 0.3$ mm (IHH). It was noticed during forming with higher stroke that the EIEs were easily rotating around the workpiece. It can be assumed that the EIEs will flow first in the gap of the dies, but if they are hindered in their motion early in the process flashes and breaks can still occur, for example at high feed rates. As for the 304 alloy, the EIEs were not reusable. After forming, they presented a structure like on Figure 5 in some cases they were torn apart. The type of EIE influenced not only the feed rate but also the elastic radial extension of the outer ring of the swaging head. For a feed rate of 0.44 mm/s, the extensions of the outer ring given in Figure 7 were measured. Again, the starting point of the forming is earlier for the process with EIE.

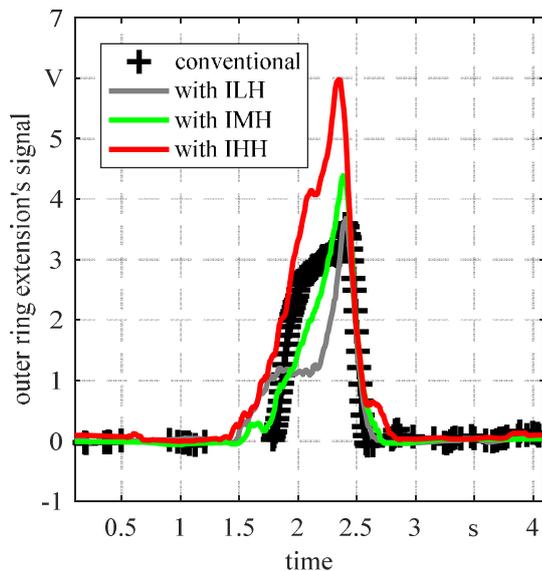


Fig. 7. Elastic extension of the outer ring g of the swaging head during forming of copper with $v_r = 0.44$ mm/s with different elastic intermediate elements.

A relationship between the hardness of the EIE and the reaction of the outer ring can be seen. Harder EIE induced higher extensions of the ring. Nevertheless, the ring

extension during forming with the weakest EIE is comparable to the one of the conventional forming. For this same feed rate the smallest diameter of $d_1 = 991 \pm 16$ μm was achieved with ILH and the highest $d_1 = 1041$ μm with IHH. The increase of the diameter with the hardness of the EIEs correlates with extension of the outer ring. The harder EIE flowing into the gaps between the dies contributed to increase the ring extension that led to a reduced die closure and as result, the workpiece diameter increased.

3 Infeed rotary swaging

3.1 Initial situation

In infeed rotary swaging the cross section of a bar with an initial diameter of d_0 was reduced over the complete feeding length to a final diameter of d_1 . In this procedure, the length changed from l_0 to l_1 . The die with its characteristic regions as well as the workpiece before (Figure 8a)) and after forming (Figure 8b)) are given below.

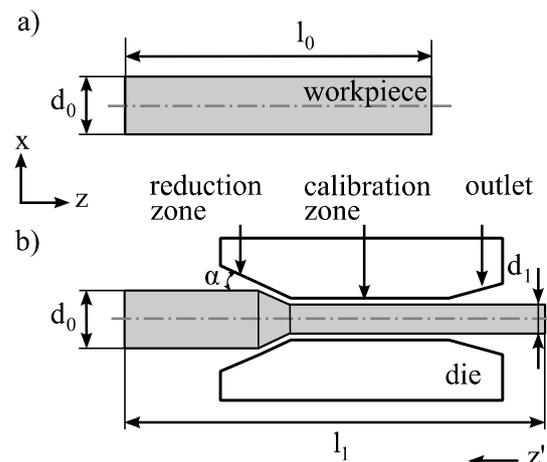


Fig.8. Geometry of the die and the workpiece in infeed rotary swaging; a) before forming, b) after forming.

Previous investigations had shown that the process is suitable for micro manufacturing. Workpieces with final diameter down to 300 μm were achieved [3]. However, the process is constrained by bending or torsion of the workpiece between the collet and the reduction area of the dies. An example of workpiece with bending is given in Figure 9.

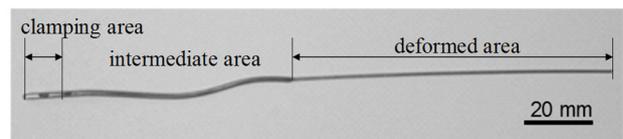


Fig. 9. Workpiece with bending

Concerning the different phases of rotary swaging, bending can be related to the closing phase of the dies. The clamping device in which the workpiece is fixed is fed with a constant feed rate in all process phases and the workpiece material flows axial in (forwards) and against

(backwards) the direction of the feed motion. This material flow increases not only with diameter reduction but also with the feed rate. Bending will occur when the critical bending load is reached. This load depends on the Young's modulus (E -modulus), the initial diameter and the length of the workpiece. Especially for the micro range, the critical load is particularly low due to the small initial diameters. The theoretically critical bending load for different initial diameters with respect to the Young's modulus is given in Figure 10. In this case, one end is fixed (clamping), and the other end is guided. A buckling/bending length of 60 mm was considered.

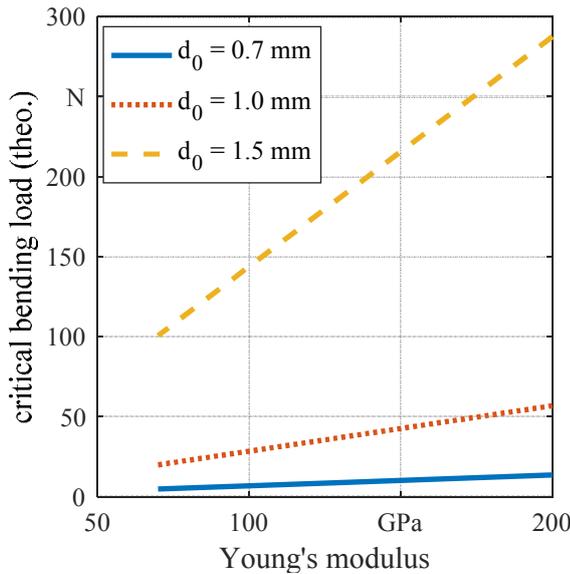


Fig. 10. Critical bending load with respect to the Young's modulus and the workpiece diameter.

A measure for reducing the bending and hence increasing the productivity is by controlling the backward material flow. This can be done in a small range by increasing the friction in the reduction zone [10]. This contribution focuses on another approach: the spring-loaded clamping, which allows an axial shift of the workpiece during forming and reduces the compressive force. The concept of the spring-loaded clamping device is presented in Figure 11.

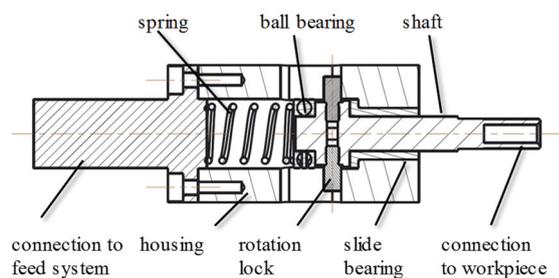


Fig. 11. Spring-loaded clamping device.

By using the spring directly between the feed system and the workpiece, the rebound that is caused by the forming in the reduction zone is absorbed and stored in the spring. When the dies reopen, the spring is decompressed and the

buffered back pushing is added to the feed into the swaging head.

3.2 Experimental procedures and results

The workpiece material was the austenitic steel 304 alloy with an initial diameter of $d_0 = 1.0$ mm. The set of dies had a nominal diameter of $d_{nom} = 750 \mu\text{m}$. Forming experiments were proceeded with a stroke frequency of 102 Hz and a stroke height of $h_T = 0.2$ mm. The workpieces were lubricated during the process. The feed rate was gradually increased from test to test until a process failure like bending occurred. Beside of the elastic radial extension of the outer ring, the final diameter was characterized contactless by an optical micrometer. The diameter of the workpiece was measured starting from the tip every 2 mm along the workpiece axis at three different rotation angles.

Feed rate and final diameter

It was found that the spring-loaded clamping device could substantially increase the feed rate. Workpieces were formed with a feed rate up to 100 mm/s compared to a maximum feed rate of $v_f = 25$ mm/s that was possible with a fixed clamping. At even higher feed rates, bending and flashes occurred again.

Figure 13 shows the diameter evolution along the deformed workpiece for different axial feed rates. The tip of the workpiece was located at $Z' = 0$ mm. It can be noticed that the final diameters increased not only according to the feed rate but also according to the position in the workpiece, especially at high feed rates. The diameter values rose monotonically with the distance to the tip.

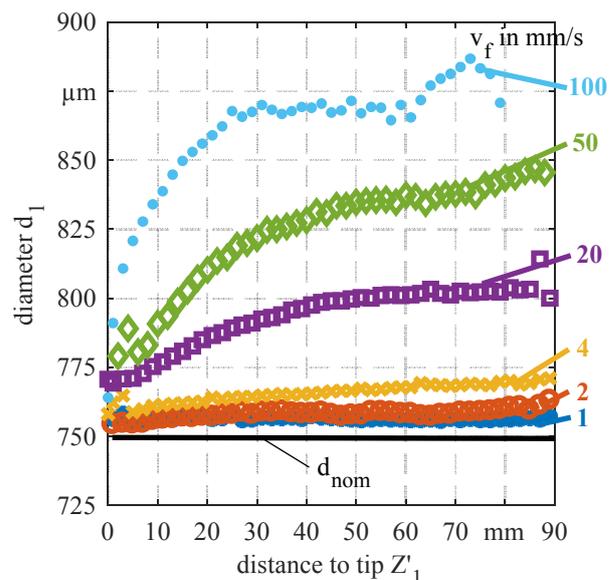


Fig. 13. Diameter evolution with regard to the axial feed rate.

Workpieces with final diameters close to d_{nom} and constant within the processed length were those manufactured with feed rates up to 2 mm/s. For these

settings, the stiffness of the outer ring of the swaging head was high enough to prevent the diameter evolution. In Figure 14 the envelope function of the strain gauges measurements clearly indicates the correlation between the diameter evolution and the equivalent radial forming force.

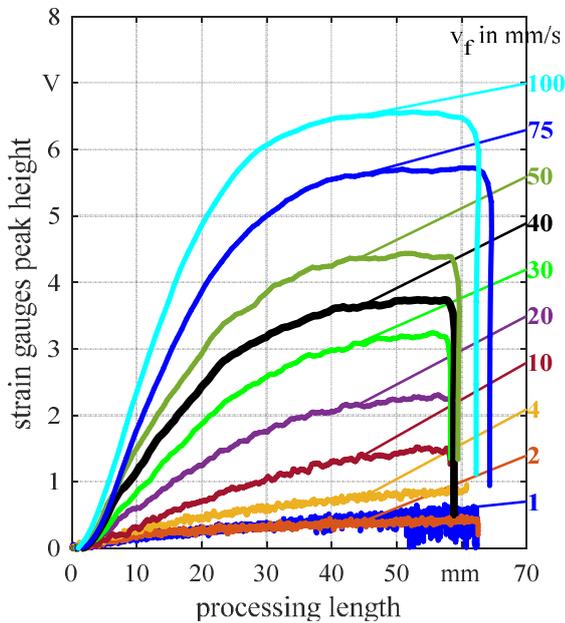


Fig. 14. Peak height of the strain gauge signals over the processed length of the workpiece.

Due to the increase of the deformation of the outer ring, the closing of the dies was not ensured any more with higher axial feed rates. This could be confirmed by high-speed video recording.

From this result, it can be stated that the size respectively the stiffness of the used swaging head without further measures was not suitable for forming with high feed rates with high quality. Therefore, solutions for compensating the diameter increase are necessary to reach high geometry accuracy during high feed rates. Among others, a closed-loop control of the feed motion of the workpiece considering the actual load of the outer ring could be a solution. The possibility of influencing the final diameter by an in-process adjustment of the wedges was proved by experiments. A combined feeding in radial and axial direction with constant feed rates of $v_r = 8 \mu\text{m/s}$ and $v_f = 20 \text{ mm/s}$ resulted in a more homogeneous diameter chart (Figure 15). Better results are to be expected if the motion of the wedges is closed-loop controlled.

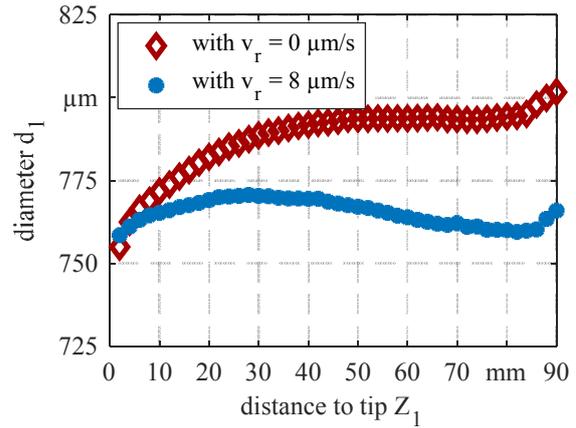


Fig. 15. Forming with $v_f = 20 \text{ mm/s}$ without and with simultaneous radial feeding.

4 Conclusions

In this study, measures to control the material flow in plunge and infeed rotary swaging to increase the productivity are presented. Elastic intermediate elements were used in plunge rotary swaging to control the radial material flow and a spring-loaded clamping device was deployed to control the axial material flow in infeed rotary swaging. Following main results could be drawn:

For plunge rotary swaging:

- Elastic intermediate elements enabled dependent on their hardness higher radial feed rates v_r up to three times compared to forming without these elements.
- The final diameter depends on the stiffness of the elastic intermediate element with bigger diameter for harder elements.

For infeed rotary swaging:

- A spring-loaded clamping device enabled four times higher axial feed rates v_f , however the final diameter of the workpiece increased and was not constant along the length.
- The rising value of the final diameter over the length of the workpiece could be positively manipulated by a continuous radial feed during the process.

The presented results facilitate high productive micro rotary swaging for plunge as well as for infeed rotary swaging. Further studies need to focus on the adjustment of the final diameter after plunge rotary swaging by including a calibration time in the process. In addition, an implementation of a reusable elastic intermediate element is of interest. In the case of infeed rotary swaging, the regulation of the diameter evolution by the process control will be examined.

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