



Abrasive Particle Generation in Dry Rotary Swaging

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Abstract

Rotary swaging is an incremental bulk metal forming process for the manufacture of cylindrical lightweight components. Whilst conventional rotary swaging is still carried under the intense use of lubricants to provide desired work piece quality and to avoid forming die wear, recent scientific work focuses on the design of a dry process layout. Novel functionalized rotary swaging dies were introduced, exhibiting both diamond like carbon (DLC) hard coated and structured surfaces to encounter complex and opposing tribological requirements when dry machining. Such dies were successfully applied to infeed rotary swaging experiments machining steel 1.0038 and aluminum 3.3206 tubes. Although primary targets were achieved, the dry rotary swaging process is subject to an increased abrasive particle generation from the work piece material and accumulation of such particles in the forming zone. Abrasive particles provoke a loss of work piece quality and ultimately lead to a clogging of the swaging unit, associated with a significant earlier termination of the forming process. This work presents the investigation of the particle generation when dry rotary swaging with functionalized forming dies in dependence on the work piece material and the process parameter feed velocity. Subsequently, improvements of the die's design are discussed which are to reduce the generation of abrasive particles and conveying the particles from the swaging unit, indispensable for the robust layout of dry rotary swaging processes.

Keywords: bulk metal forming, radial forging, functionalized forming dies

1 Introduction

Rotary swaging is an incremental bulk metal forming process for the manufacture of rotational symmetric lightweight components such as axles and steering spindles. Compared to those machined by turning and milling, work pieces machined by rotary swaging exhibit advantageous material properties. These properties are a result of the strain hardening occurring while forming as well as an undisturbed material fiber flow. Besides, rotary swaging allows for the generation of variable wall thicknesses of hollow workpieces, and therefore the optimal use of material resources. For the case of infeed rotary swaging, the work piece is fed axially into the swaging unit and being incrementally reduced in its diameter by the repetitive die strokes. The radial forging force F_R results in an axial reaction force F_A counteracting the feed force F_f applied to the work piece. The magnitude of the axial reaction force directly depends on the rotary swaging die's design – particularly the die angle α – and the tribological conditions between the

dies and the work piece material; compare Figure 1. Common for bulk metal forming processes, rotary swaging is characterized by high pressures per unit area and high process forces [1]. To allow for a robust process layout, adequate lubrication of forming dies and work pieces is inevitable. Functions of the lubricant are mainly:

- the avoidance of abrasive forming die wear when machining steel work pieces,
- the avoidance of adhesive forming die wear when machining aluminum work pieces,
- the provision of work piece's excellent surface finish and dimensional accuracy,
- and the purging of abrasive particles generated from the work piece material.

The application of lubricants, however, leads to a distinct increase of the axial reaction force. To come up against reaction forces exceeding the maximum force of the work piece feed system, commercially available rotary swaging dies exhibit a rough layer of thermally

sprayed tungsten carbide, increasing the effective friction between dies and the work piece and therefore reducing the axial reaction force.

Recent scientific work focused on the development of a dry process layout of rotary swaging. Novel functionalized rotary swaging dies were introduced, exhibiting both hard coated and structured surfaces to encounter complex and opposing tribological requirements when dry machining [2]. Tungsten doped amorphous diamond like carbon coatings (a-C:H:W) of excellent hardness and fracture toughness were applied to reduce friction between dies and work pieces when dry machining as well as protection against abrasive and adhesive forming die wear [3, 4]. Structured reduction zones, i.e. the application of sine wave structures with amplitudes A of several tenths of micrometers and wave lengths λ of about one millimeter, are used to control the axial reaction force [5, 2]. This is necessary, as rough layers of thermally sprayed tungsten carbide cannot be applied in dry rotary swaging due to immediate clogging. The principles of this new approach are sketched in Figure 1.

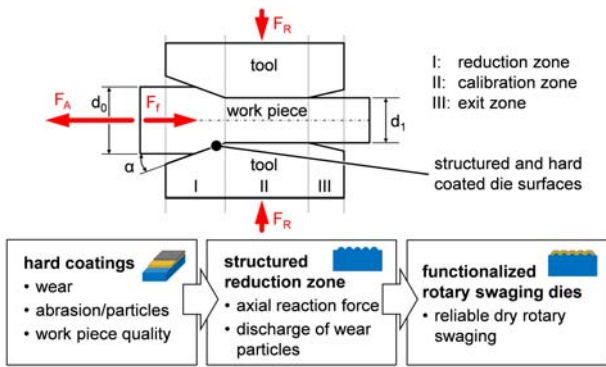


Fig. 1: Principles of infeed rotary swaging displayed in cross-sectional view and approaches for a dry process layout.

The successful application of functionalized rotary swaging dies was shown in various studies. Solely DLC coated rotary swaging dies were used for the machining of aluminum 3.3206 tubes. The coating successfully suppressed adhesion of aluminum on the die's surfaces while providing excellent surface finish of the work pieces, comparable to conventional, lubricated rotary swaging [6]. Forming dies exhibiting sine wave structures of $A = 0.05$ mm amplitude and $\lambda = 1.3$ mm wavelength in the reduction were applied to the machining of tubes from 1.0038 construction steel. In comparison to unstructured rotary swaging dies the die's design allowed to reduce the tracking error of the feed system associated with the axial reaction force F_A by 50 % for dry machining and up to 400 % when machining under lubricated conditions [7]. Furthermore, such structured forming dies with additional tungsten doped amorphous DLC coating (a-C:H:W) were tested against steel tubes. Successful dry rotary swaging was achieved without failure of the hard coating under given harsh conditions [6]. However, surface finish of work pieces machined with the presented functionalized rotary swaging dies is not sufficient, requiring for an adaption of the structure design in the reduction zone. Besides, an increased abrasive particle generation from the work piece materi-

al and accumulation of such particles in the forming zone was observed, associated with a loss in work piece quality and a clogging of the swaging unit.

Aim of this work is the characterization and quantification of abrasive particle generation when dry rotary swaging with functionalized forming dies. Dry rotary swaging experiments are conducted varying the material machined and the feed velocity. Abrasive particles are collected and investigated by means of optical microscopy. Results of the analysis build the foundation of the ongoing design process of functionalized forming dies, suitable for a robust dry rotary swaging.

2 Experiments

The dry rotary swaging experiments were carried out on a Felss HE-32 machine tool with a four die swaging unit setup. The swaging frequency is depending on the rotational speed of the swaging unit and was set to 37.5 Hz. The stroke height h_s of the dies was 1 mm. The machine tool is equipped with a linear direct driven feed unit for axial work piece feed, able to apply a maximum feed force F_f of 20 kN.

Functionalized rotary swaging dies from own manufacture were applied in the experiments, presented before in [6]. The bulk material is 1.2379 hardened tool steel (hardness 62 ± 0.6 HRC). The dies exhibit a die angle of $\alpha = 10^\circ$ and allow for the diameter reduction of rods and hollow shafts from $d_0 = 20$ mm down to $d_1 = 15$ mm. A Cr/CrN/Cr+WC/a-C:H:W multilayer hard coating system with additional a-C:H top layer was applied to the dies by physical vapor deposition (PVD). The reduction zone of the dies exhibits a sine wave structure with an amplitude of $A = 0.05$ mm and a wavelength of $\lambda = 1.3$ mm for friction control, compare Figure 2. The presented forming dies allow for the dry rotary swaging of work pieces from aluminum and construction steel.

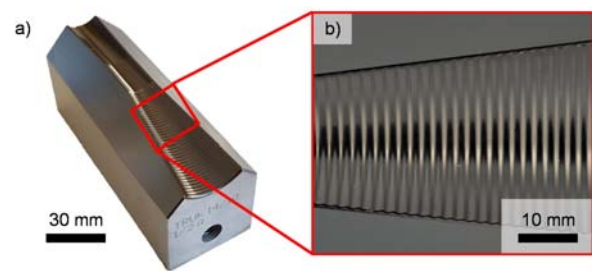


Fig. 2: a) Functionalized rotary swaging die applied in experiments, and b) detail view of the sine wave structured ($A = 0.05$ mm, $\lambda = 1.3$ mm) and DLC coated reduction zone of the die.

Three different types of work pieces were applied to the machining experiments. Aluminum 3.3206 (AlMgSi0.5) tubes, 1.0038 construction steel tubes exhibiting obligatory rust-protective layer of zinc phosphate, and 1.0038 construction steel tubes without any additional protective layer. All work pieces were of the same geometry: initial length $l_0 = 300$ mm, initial diameter $d_0 = 20$ mm, and initial wall thickness $s_0 = 2$ mm.

The experimental procedure comprised of the dry rotary swaging of two workpieces in a row and subsequently the disassembly of the four rotary swaging dies

Tab. 1: Results of particle analysis in dependence on the machined material and the feed velocity.

work piece material	feed velocity v_f mm/min	particles collected from reduction and calibration zone		particles collected from the tapered flanks of the dies	
		areal expanse A_{max} mm ²	amount	areal expanse A_{max} mm ²	amount
aluminum 3.3206	500	1.2	A	27.7	A
	1000	3.9	B	479.2	D
	1500	3.2	C	335.1	B
	2000	7.0	D	234.3	C
steel 1.0038 with zinc phosphate layer	500	2.3	D*	29.6	J*
	1000	1.6	J*	9.8	G*
	1500	0.1	J*	7.2	E*
	2000	0.2	G*	30.6	D*
steel 1.0038	500	3.5	C	3.0	C
	1000	3.6	B	7.2	B
	1500	1.9	B	6.3	B
	2000	1.3	B	4.4	B

* evaluation for steel abrasive particles only, no dust particles of zinc phosphate rust-protective layer encountered.

from the swaging unit, investigation of the dies, and collection of abrasive particles. For each work piece material experiments were conducted at feed velocities $v_f = 500$ mm/min, 1000 mm/min, 1500 mm/min, and 2000 mm/min, what sums up to an overall number of experiments of twelve and the machining of 24 work pieces. In preparation for every experiment the forming dies were thoroughly cleaned by rinsing and wiping using ethanol. After the experiments the dies were visually inspected. Particles were first collected from the reduction zone and the calibration zone from each of the four forming dies. Here, actual contact of die's and work piece's surfaces occur when rotary swaging. The particles were rinsed into petri dishes for later investigation using acetone. Particles adhering to the tapered rotary swaging die's flanks were collected by carefully removing those using a brush; compare Figure 3.

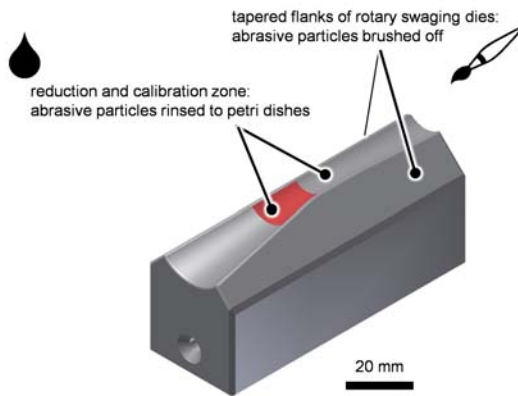


Fig. 3: Sketch of rotary swaging die and indication of abrasive particle collection procedure.

The particle analysis was carried out using a Sensofar Plu 2300 optical profilometer in microscope operation mode. The maximum particle areal expanses A_{max} in mm² were derived for each of the samples taken from the reduction and calibration zone, and from the tapered flanks, respectively. Furthermore, a comparative analysis of the amount of abrasive particles generated in the

various experiments was conducted. For this purpose, the categories A to J for the assessment of the amount of abrasive particles are introduced, where A is attributed to the minimum amount of particles over all 12 experiments and J attributed to the maximum amount of particles. This analysis is solely qualitative. Within limits, it allows for the derivation of trends regarding the abrasive particle generation when rotary swaging in dependence of the work piece material and the feed velocity, but is afflicted to a comparably high uncertainty.

3 Results

Distinct abrasive particle generation was found for all experiments. The expanse, the amount, and characteristics of the particles are primarily determined by the work piece material. The influence of the feed velocity v_f on the abrasive particle generation is of second order, only when machining aluminum a more distinct dependency of the particle size on the feed velocity can be found. The results of the optical abrasive particle analysis for all experiments are given in Table 1.

In Figure 4 a) two of the four rotary swaging dies after the machining of aluminum 3.3206 tubes are displayed. Representative for all four experiments machining aluminum and varying the feed velocity, the forming dies exhibit tinsels of greater areal expanse on the tapered flanks. A strong increase of the particles areal expanse and the amount of particles generated was found, when increasing the feed velocity v_f from 500 mm/min to 1000 mm/min. The tinsels of largest areal expanse of $A_{max} = 479.2$ mm² were found when machining with a feed velocity of 1000 mm/min. For greater feed velocities a decreasing trend for particle areal expanse and particle amount can be observed. In comparison, the reduction zone and the calibration zone were free of larger tinsels and barely exhibited any abrasive particles at all. This is reflected in the small amount of particles rinsed into the petri dishes after the experiments; compare Figure 4 b). It is expected that the majority of the abrasive particles generated while forming is pushed in the gaps between the forming dies and

compressed to tinsels of greater areal expanse at the tapered flanks when the dies repetitively come into contact with every die stroke. The originate particle areal expanse generated from the work piece may not exceed 10 mm^2 for the machining of 3.3206 tubes.

The disassembled rotary swaging dies after the machining of 1.0038 steel tubes with zinc phosphate rust-protective layer ($v_f = 1000 \text{ mm/min}$) are shown in Figure 5 a). Smaller tinsels and fine abrasive particles were found on the tapered flanks of the forming dies, obviously formed by the repetitive die strokes. This phenomenon was observed for all the four experiments machining 1.0038 work pieces with zinc phosphate rust-protective layer varying the feed velocity. The tinsels were identified to be an agglomeration of small steel tinsels and greater amounts of dust particles of the rust-protective layer with comparably loose cohesion. The maximum areal expanse A_{\max} of the tinsels varied from 7.2 mm^2 to 30.6 mm^2 . A dependency of the areal expanse and the amount of particles on the feed velocity cannot be observed. The reduction zone and the calibration zone were distinctively contaminated with dust particles of the rust-protective zinc phosphate layer and their amount increased with increasing feed velocity; compare Figure 5 b). These particles excessively agglomerated in the valleys of the sine wave structures of the reduction zone, impeding the cleaning operation

after each experiment. Besides, greater amounts of small steel abrasive particle were found in the reduction and calibration zone. Their maximum areal expanse was found to be 2.3 mm^2 when machining with a feed velocity of 500 mm/min . For the experiments machining steel 1.0038 tubes with zinc phosphate rust-protective layer the majority of the generated abrasive particles was found on the tapered flanks of the rotary swaging dies, similar to the machining of the aluminum work pieces.

The last four experiments comprised the machining of steel 1.0038 work pieces without the obligatory rust-protective layer of zinc phosphate. For all experiments the rotary swaging dies exhibited greater amounts of tinsels with smaller areal expanse on their tapered flanks after machining; compare Figure 6 a). Independent from the chosen feed velocity, the abrasive particles exhibited almost the same maximum areal expanse A_{\max} in a range from 3.0 mm^2 to 7.2 mm^2 . The tinsels at the tapered flanks, as in the other experiments, are expected to be formed by the die strokes, after being pushed in the gaps between the rotary swaging dies. However, far smaller tinsels were found compared to the experiments machining aluminum work pieces. Small tinsels of the work piece material were rinsed from the reduction and the calibration zone into the petri dishes for optical inspection after the experiments machining 1.0038 steel tubes without zinc phosphate layer; as displayed in

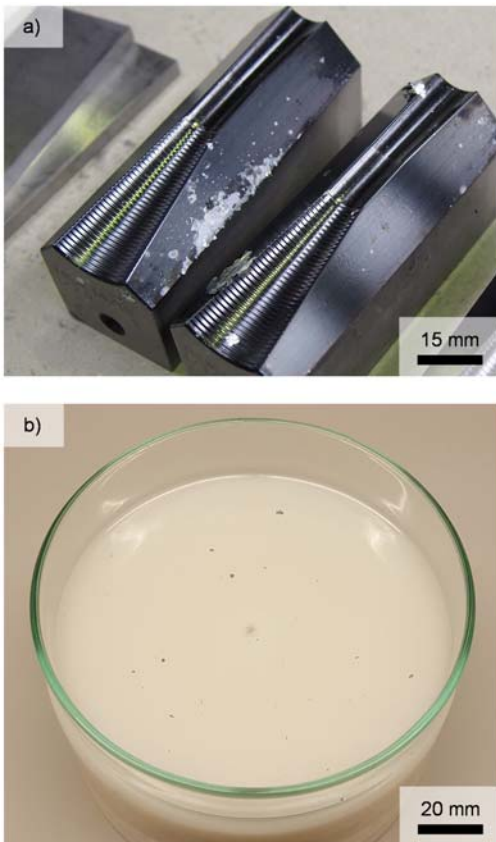


Fig. 4: a) Rotary swaging dies after the machining of 3.3206 work pieces ($v_f = 1000 \text{ mm/min}$) exhibiting tinsels of comparably great areal expanse at the tapered die flanks, and b) petri dish with small aluminum tinsels rinsed from reduction and calibration zone for the same experiment.

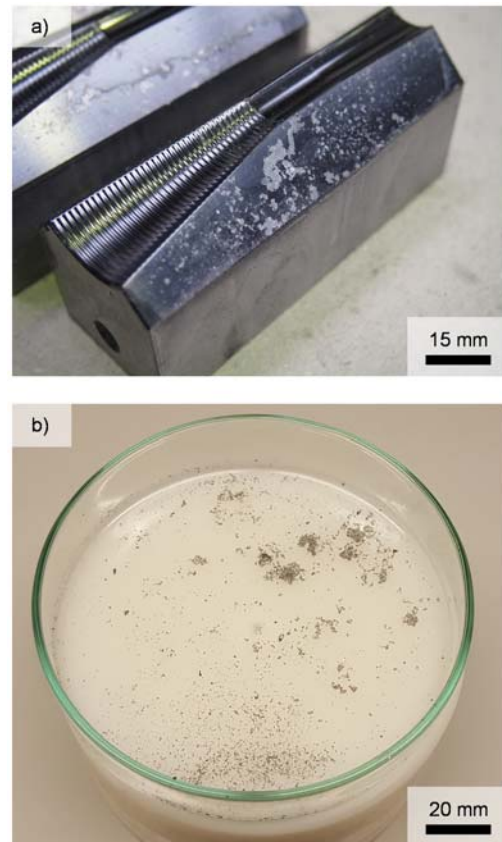


Fig. 5: a) Rotary swaging dies after the machining of 1.0038 work pieces with zinc phosphate rust-protective layer ($v_f = 1000 \text{ mm/min}$) exhibiting comparably small tinsels and fine abrasive particles on the tapered die flanks, and b) petri dish with dust particles of predominantly zinc phosphate and small steel abrasive particles rinsed from reduction and calibration zone for the same experiment.

Figure 6 b). The maximum areal expanse of these particles did not exceed 3.6 mm^2 for any of the applied feed velocities. This again is a similar result compared to that gained from the experiments with aluminum work pieces, with a slight increased overall amount of abrasive particles.

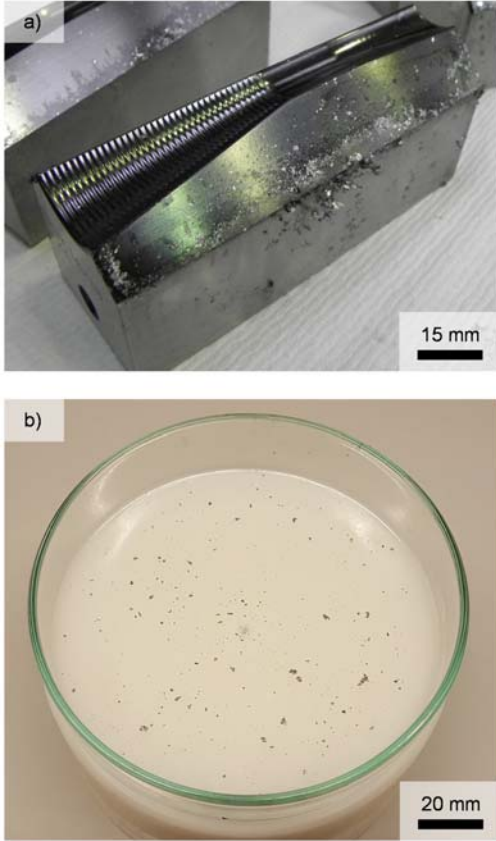


Fig. 6: a) Rotary swaging dies after the machining of 1.0038 work pieces without zinc phosphate layer ($v_f = 1000 \text{ mm/min}$) exhibiting a distinct amount of tinsels of smaller areal expanse on their tapered flanks, and b) petri dish with small steel abrasive particles rinsed from reduction and calibration zone for the same experiment.

4 Discussion

Dry rotary swaging with functionalized forming dies is subject to an increased generation of abrasive particles from the work piece. This phenomenon was observed for all experiments, independent of the machined material. The generation of these abrasive particles while rotary swaging is explained with the particular conditions when the sine wave structured reduction zone of the functionalized dies and the work piece come into contact. Alternating local strain and compression of the surface near material layer of the work piece occurs; local strain once the material is pressed into a valley of the sine wave structure, local compression when the material is pressed onto a peak of the sine wave structure. Local strain and compression lead to a distinct strain hardening of the surface near work piece material layer accompanied with ongoing local embrittlement. This ultimately leads to the failure of the surface near material layer and with that the detachment of tinsels from the work piece's surface. The areal expanse of the

primary tinsels found in the reduction and the calibration zone correlates with the ductility of the machined work piece material. The maximum areal expanse of aluminum 3.3206 tinsels A_{\max} was 7.0 mm^2 , the maximum areal expanse of steel 1.0038 tinsels was slightly smaller with $A_{\max} = 3.6 \text{ mm}^2$. A distinct dependence of the tinsel's areal expanse and the amount of tinsels on the feed velocity v_f cannot be determined from the experiments results. When machining steel 1.0038 tubes with zinc phosphate rust-protective layer, besides metallic abrasive particles from the work pieces, a distinct amount of small dust particles of zinc phosphate was found in the reduction and the calibration zone of the dies. These particles are expected to be small enough that surface related forces become dominant supporting their adhesion to the surfaces of the reduction and the calibration zone. This explains the strong contamination of especially the valleys of the sine wave structures with dust particles of zinc phosphate.

For all experiments the largest amount of abrasive particles was found on the tapered flanks of the rotary swaging dies. Particles generated predominantly in the reduction zone are subsequently pressed into the gaps between the forming dies and are formed to tinsels of greater areal expanse by the repeating die strokes. The revolving motion of the swaging unit is expected to facilitate this phenomenon. For ongoing machining the buildup of greater amounts of work piece material in the gaps between the forming dies is expected. This ultimately hinders the complete closing of the dies whilst the die stroke and leads to geometrical inaccuracy of the machined work pieces and a significant earlier termination of the forming process. A robust dry rotary swaging cannot be achieved for the given conditions and requires for a further development of the rotary swaging die's design.

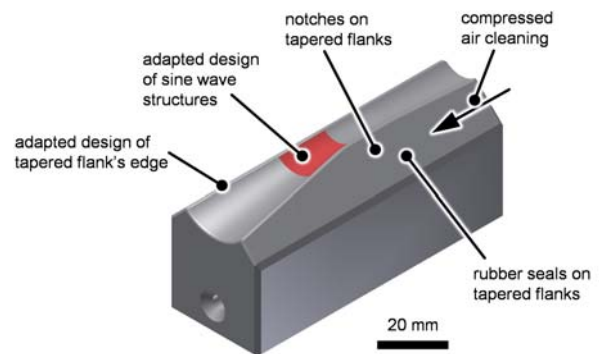


Fig. 7: Improvements of die's design reducing abrasive particle generation and abrasive particle agglomeration on the tapered flanks in dry rotary swaging.

The design of the rotary swaging dies must encounter both, the reduction of abrasive particle generation and measures preventing particles to be pressed into the gaps between the dies and their agglomeration on the tapered flanks; compare Figure 7. A reduced particle generation can be achieved by a re-design of the sine wave structures in the die's reduction zone. Sine wave structures with fading amplitude towards the calibration zone are a possible compromise between control of

process forces and minimizing the generation of abrasive particles. Besides, this structure design can provide improved surface finish of the machined workpieces. An adaptation of the edge between reduction and calibration zone and the tapered flanks allow reducing the amount of particles pressed in the gaps between the rotary swaging dies. Particles still able to enter the gaps between the dies can be entrapped in notches on the tapered flanks, effectively preventing the buildup of greater amounts of abrasive particle material. A compressed air cleaning system could be applied to purge those particles from the notches out of the swaging unit. Additional rubber seals alongside the tapered flanks shall avoid abrasive particles to penetrate deeper into the mechanics of the swaging unit. Subsequent work will comprise the transfer of highlighted measures to the next generation of functionalized rotary swaging dies, allowing for robust dry rotary swaging.

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