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Influence of increased die surface roughness on the product quality in rotary swaging

FENERCIOĞLU Tevfik Ozan[1,a *], SARIYARLIOĞLU Eren Can[1,b], ADIGÜZEL Erdem[1,c], ŞIMŞEK Ahmet Kürşat[1,d], KOLTAN Umut Kağan [1,e] and YALÇINKAYA Tuncay [2,f]

[1]Repkon Machine and Tool Industry and Trade Inc. Şile/Istanbul/Turkey

[2]Department of Aerospace Engineering, Middle East Technical University, 06800 Ankara/Turkey

[a]ozan.fenercioglu@repkon.com.tr, [b]eren.sariyarlioglu@repkon.com.tr, [c]erdem.adiguzel@repkon.com.tr, [d]kursat.simsek@repkon.com.tr, [e]umut.koltan@repkon.com.tr, [f]yalcinka@metu.edu.tr

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Abstract. Rotary swaging is an ascendant forming method for manufacturing axisymmetric parts. High production rate with excellent net shape forming is achieved in recent automation developments. However, precise machine design and tailored process developments are necessary to transfer the high impact type forming loads to workpiece efficiently. The failure of this transfer results in high vibrations of the machine structure and poor product quality, due to the impact loads with high frequencies. The centerpiece of the process development to prevent these disruptive effects is to resolve die specifications such as shape and surface properties. In general forming applications, surface roughness of the dies is perceived as a disruptive element for the product quality and only a small amount is provided to settle lubricants. However, for rotary swaging applications, an optimized surface roughness to increase the load transfer between the die and the workpiece without disrupting the final product surface quality is essential. In this study, for a fixed die shape, the relation between the die surface roughness and the product quality is investigated for macro rotary swaging applications. In particular, the effective transfer of the forming forces to the workpiece is analyzed by using finite element analysis within the scope of surface friction. Consequently, a die set with roughened surface conditions is manufactured by using a novel technique. Real process trials are conducted to validate the results of the analysis.

Introduction

Rotary swaging is an incremental forging operation for tubes and bars. Operation principal of a rotary swaging machine is shown on Figure 1(a). An internal ring with translational sliders is rotated inside a roller cage. Translational sliders hold die assemblies. During the rotation of the internal ring, dies are retracted to an open position due to centrifugal effects and other peripheral supports (support springs). When the die assembly reaches a roller, dies are translated to closed position. Continuous movement of the die assembly results in consecutive blows of dies and cold forging of the workpiece. Hence, the outer diameter of the part decreases with a possible reduction of the cross-section area and with the elongation of the total length. Rod, pipe and tube parts can be shaped by this method and axisymmetric parts can produced. By the addition of a pre-shaped mandrel inside tubular workpiece, it is also possible to form complex shapes inside the workpiece. The mandrel steers the material such that the internal shape of the workpiece reflects the outer shape of the mandrel.

Performance and final mechanical properties of the workpiece are dictated by process parameters and parts (die and mandrel). In particular, dies play the most important role. During the process, the workpiece is forced to deform with large loads transferred by dies to reduce the outer diameter. To moderate the disruptive effects of the die impact, dies are designed with a tapered entrance. In this way, shearing of the workpiece is prevented. However, this tapered entrance geometrically results in unwanted axial reaction forces. Each blow of the die pushes back the workpiece in the opposite direction of the elongation. These reaction forces show disruptive effects on overall swaging performance. In the open literature, these disruptive effects are studied in detail under the scope of micro metal forming. Small tubes for needles and concentric bimetallic tubes are manufactured using rotary swaging. Vollertsen called these forces, rejection forces and explained that increased rejection forces result in workpiece buckling [1]. To solve this problem, Böhmermann et al. suggested to increase the effective friction on the forging section between die and workpiece to decrease the reaction forces (Fig. 1 (b)) [2]. By increasing the friction, as the die descends, the end of the tapered section pulls the workpiece and the reaction (rejection) force of the sinking section is supported. Herrmann numerically characterized effects of die friction for macro rotary swaging applications using finite element analysis [3]. 50% reduction is achieved in axial reaction forces by increasing friction coefficient from 0.1 to 0.5 in reduction zone.

Similar investigations were also made for radial forging. Rotary swaging and radial forging are similar processes with different machine configurations. Hence, research results are valid for both applications. Apart from the differences in die motions, another difference is observed in workpiece feeding between both applications. Workpiece feeding is usually force controlled and applied by hydraulic cylinders in radial forging which is replaced by position control systems in modern rotary swaging machines. Hence, when reaction forces reach the limit force of the hydraulic cylinders, feeding fails in radial forging. Semiatin suggested not to use any lubricant between die and workpiece when entrance taper angle is more than 6° [4]. In this way, the effective friction is increased between the die and workpiece. In some applications, forging zone of the die is roughened by hardfacing to increase effective friction and to reduce axial reactions. Recent patents are published where hardfacing (conventional method for surface roughening) is replaced by surface structuring (see e.g. [5]). A wave form is machined on the forging zone to create holding forces to balance reaction forces especially for micro rotary swaging applications.

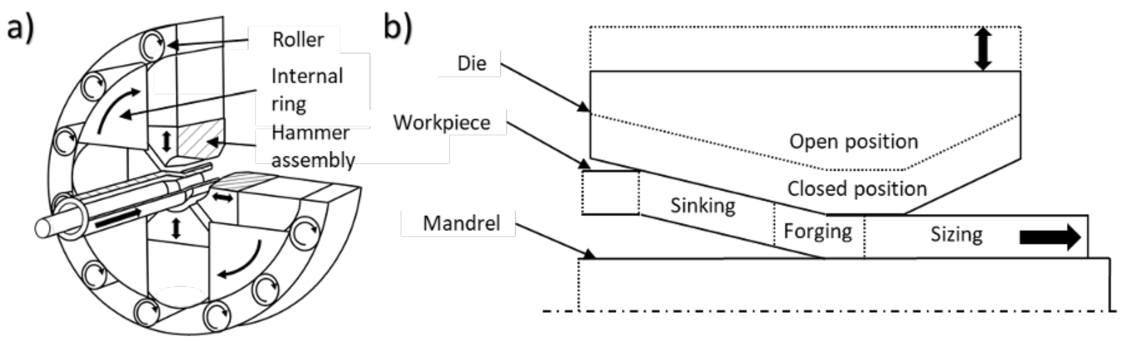

Fig. 1. Schematics of rotary swaging a) Clock-wise rotation of the internal ring rotates die assembly and leads to translational blows when upper surface reaches a roller b) Cross-section of swaging process.

Formerly, effects of the process parameters and parts (die and mandrel) are characterized by process trials. Nevertheless, by the development of reliable metal forming simulations, trial and error methods are evolved to be a final validation tool. Different approaches are found in the literature for the evaluation of rotary swaging and radial swaging. It should be noted that the die-workpiece interactions are similar in rotary swaging and radial forging. Initial studies to foresee the material flow and final mechanical properties are conducted by Grosman and Piela [6]. An axisymmetric model is developed where the volumetric change of the cross section during forging sequence is imposed by a radial rigid translation in the simulation. Lahoti and Altan derived an analytical expression to determine process forces and resulting stresses using the upper slab method [7]. This analytical study is further pursued by finite element analysis and experimental validations to develop a die design methodology [8]. As a result of these analysis, the relation between effective friction and forging forces are numerically shown. Also, Tseng et al. put a further step by including thermal effects in analytical expressions [9]. After initial studies of Domblesky et al. on the application of flow formulations for radial forging [10], Yamaguchi et al. developed a simulation and experiment method to predict the grain size of radial forged materials [11]. Recently, Poursina et al., Ameli and Movahhedy, Fan et al, Liu et al. applied displacement formulations for swaging operation using ABAQUS/Explicit and the results showed significant compatibility with the experimental results [12-15]. Load predictions converged to experimental results of Uhlig with an error <5% [16].

Validation of different simulations by experiments ensures the reliability of material process simulations. Displacement formulations with an explicit time scheme will be applied in this study to evaluate the process loads and its relation to surface properties. Although, a solution for high axial reactions by roughening die surface is widely suggested in the literature. A correlation between the surface roughness and mechanical vibrations and reactions is not experimentally shown for macro swaging applications. This study aims to clarify the mechanism behind the surface roughening and to evaluate the disruptive effects of reaction forces. A comparison for different friction conditions is numerically conducted through finite element analysis. Results are validated by product contours and also by position feedbacks of the workpiece pusher system. Moreover, a novel simple method is suggested for surface roughening. In this regard, the current study is unique for correlation of reaction forces on product and process quality and proposes an alternative method to hard facing for the swaging industry in die design.

The paper is organized as follows. Rotary swaging method and the effects of the reaction forces on product quality is briefly presented here, section 2 addresses the finite element analysis of the process cycle. Section 3 validates the numerical analysis through experiments. Then the study is concluded in Section 4.

Finite Element Analysis

ABAQUS/Explicit 2016 solver is used in this study after the quasi-static condition is validated using simulation energy outputs. Kinetic energy of the process is compared to internal energy as suggested in the ABAQUS documentation [17]. Less than 2% kinetic energy is calculated during the process. Hence, the method is found valid and doubts about the stimulation of artificial energy modes are removed. Also, this low amount of kinetic energy let the usage of a mass scaling factor (25). Geometrical simplifications are not applied to better converge to further experiments. Schematic shown on Fig. 1 (b), is represented in Fig. 2 (a) and (b) in association with rotary swaging machine elements and modelling aspects, respectively. Axial motion of the workpiece into dies is given by using workpiece pusher. Movement and forces of the workpiece pusher is recorded during the analysis to evaluate reaction forces. Fig. 2 (b) shows initial and final steps (total simulation duration: 4 seconds) of the simulation. Workpiece is modeled using reduced integration elements with combined stiffness hourglass control (C3D8R, size: 1.2 mm). Hourglass control method is determined by restricting artificial energy to internal energy ratio (<1% achieved). For boundary conditions, both translation and rotation are applied to the workpiece during feeding. Cylindrical kinematic element is used to control the feeding motion. A torsional spring is added to cylindrical connector to prevent the torsion on the workpiece with an extrapolated nonlinear elasticity definition (48kNmm/rad). Elastoplastic properties of the workpiece are constructed from the experiments of Ceschini et al. for 33CrMoV Steel material [17]. Process tools are modeled using rigid body surface elements (R3D4, size: 1.5 mm). Dies rotate around the median axis and translates in the radial direction to perform die blows. This kinematic motion is applied to reference points of die surfaces using translator connectors. Penalty contact method with finite sliding is used to model contact interactions between deformable and rigid bodies. Die surface is divided into 3 subsections to separate forging and sizing regions as in Fig. 1 (b). Two models are constructed with forging region having 0.1 and 0.8 friction coefficient values. These two extremum points are selected by considering wall lubricated metal-metal friction (0.1) and non-lubricated (or roughened) metal-metal friction (0.8). Because of the design of the rotary swaging machine, unlike radial forging, a lubricant always operates between workpiece and dies. Hence, suggestions of Semiatin for radial forging in [4] are not possible for rotary swaging process and a roughened surface is the solution.

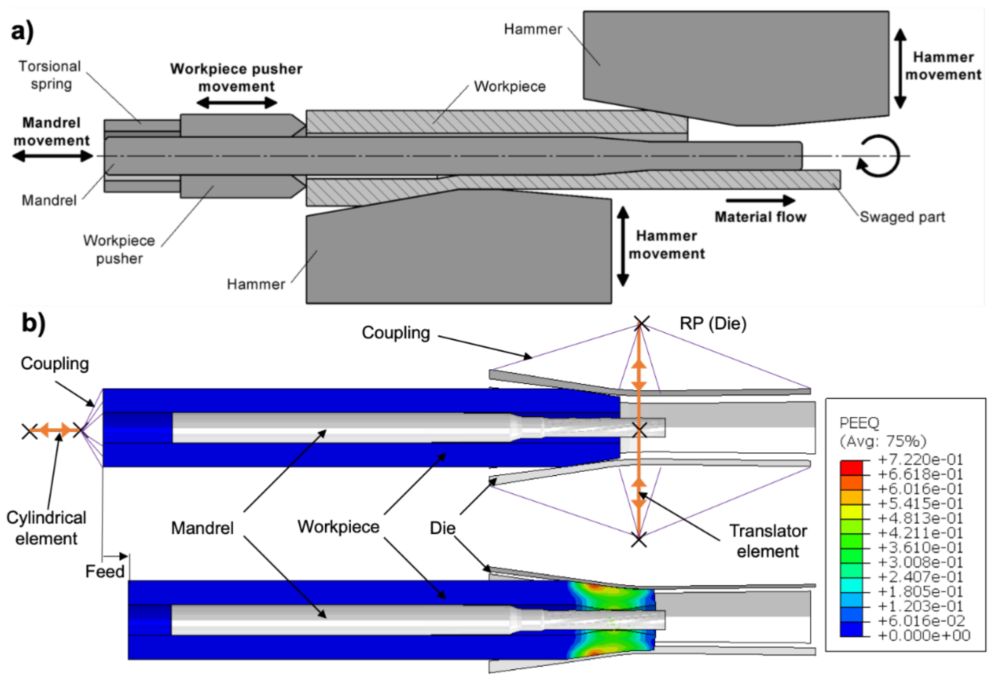

Fig. 2. Rotary swaging analysis model. a) Schematic view of forming section and machine elements, upper and lower die show initial and final position respectively. b) Modelling elements and equivalent plastic strains on deformable body (workpiece) for initial and final steps of the simulation.

Cylindrical element in Fig. 2 represents the workpiece pusher of the rotary swaging machine. Workpiece pusher controls the axial motion of workpiece. Hence, it is exposed to axial reactions. Axial reactions during process simulation are exported from cylindrical element. Fig. 3 shows the load history of the cylindrical connector. When friction coefficient is low (0.1), load profile starts with an increase in each blow. After approximately 2 seconds, a steady load is achieved. This profile is due to entrance tapers of the die and workpiece. Sliding on tapered sections occurs due to low friction. A significant difference is observed for high friction coefficient. During the process, the dies are retracted after the impact. This positive reaction forces prevent the workpiece from escaping back during this retraction. So, upper motion result in a reverse loading with increased friction. The most significant result is the reduction of reaction forces from 12 tons to 7.2 tons when an increased friction is applied between die and workpiece.

Moreover, die torsion force on the workpiece is evaluated for different frictions. Fig. 4 shows relative rotation between the front and rear ends of the cylindrical connector. As can been seen from Fig. 2, during consecutive flows, the contact area between dies and workpiece increases in the tangential direction as workpiece translates into the sizing region. This is the reason behind the cumulative character of the Fig. 4. As the process continues, the contact area between the die and the workpiece increases and the workpiece also takes the shape of the die profile. The change of friction coefficient in forging region introduced only a small amount of increase (0.03). This increase is small as expected since the main contribution comes from sizing region where friction coefficient is the same for both models. Also, by using V-shaped dies the increase of disruptive effects due to friction are prevented. Contact lengths are controlled in axial and circumferential directions by the help of this shape. A final evaluation is made for the translation of dies to observe if increased friction creates any disruptive effect on die actuation (shown on Fig. 4). No significant difference is observed when reaction forces on translator connectors which actuate dies during analyses are compared. This is related to the angle of the entrance taper. Motion and forces mainly contribute in the horizontal direction. Hence, deviations in the vertical results are relatively small.

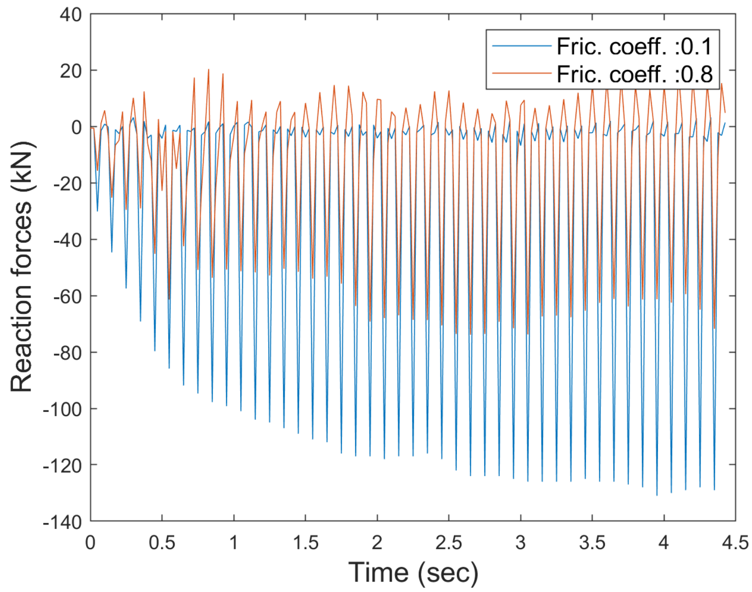

Fig. 3. Reaction forces on workpiece cylindrical connector for different friction coefficients.

The effect of friction coefficient is visualized on Fig. 5 using contact frictional shear pressure outputs. By increasing the surface friction, the contribution of the frictional shearing is increased. During the blow, die pulls the part in the feeding direction which supports the reaction forces created by the tapered section. However, since the die force in vertical direction and contact area are more dependent to workpiece material, contact normal pressures have no significant difference relative to different friction coefficients.

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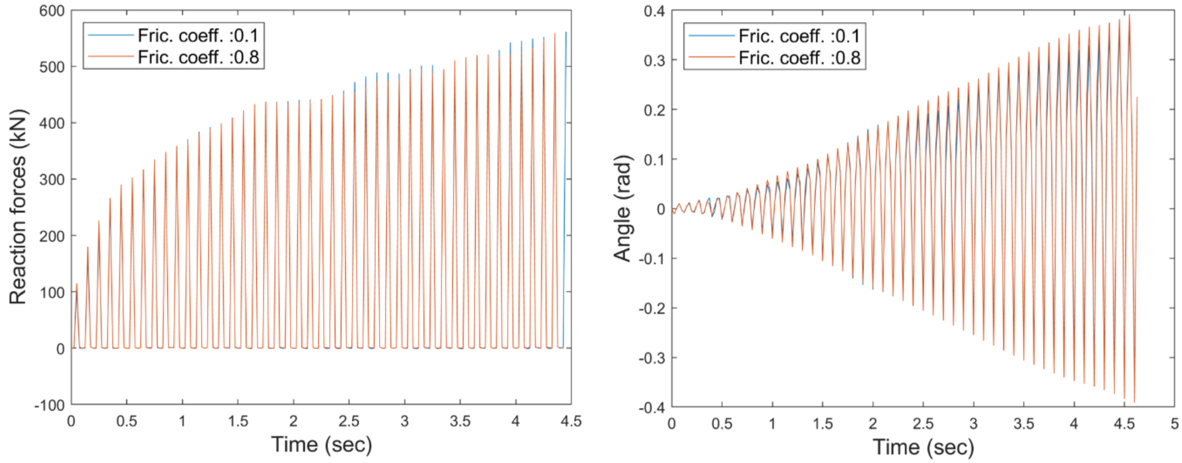

Fig. 4. Reaction forces on die connector for different friction coefficients on the left, Angle between 2 points on cylindrical element for different friction coefficients on the right.

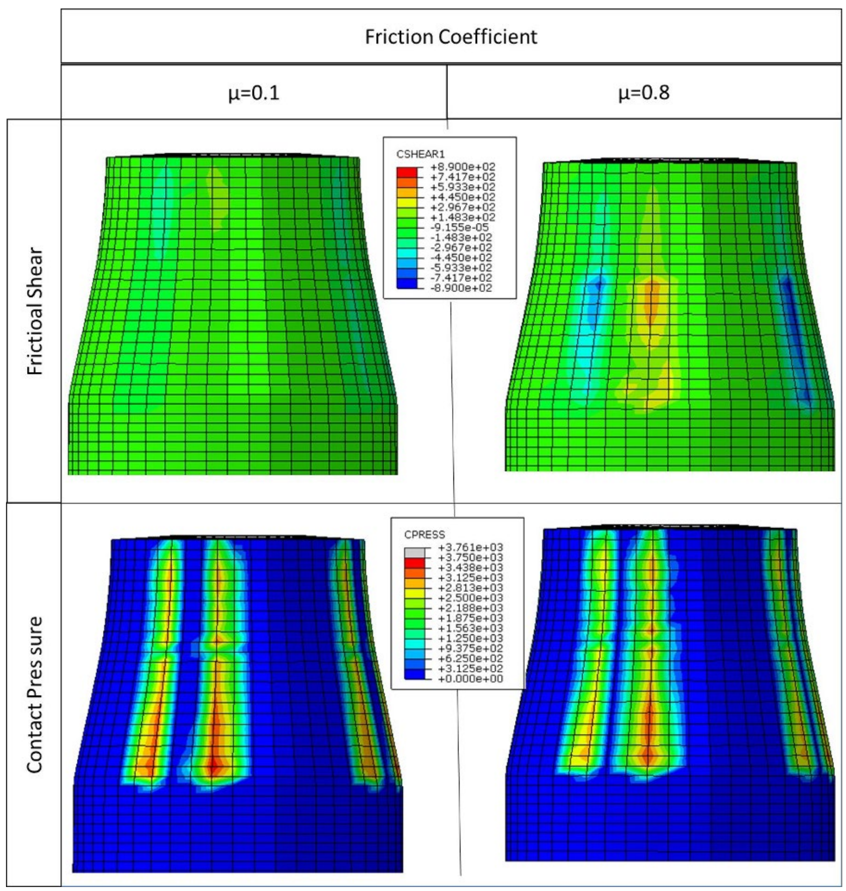

Fig. 5. Frictional shear and contact pressure (in MPa) on the workpiece during forming for different die frictions.

Experimental Validation

In the literature, surface roughening is initially performed using hard facing. Rough areas are coated by hard tungsten layers. During this process, natural pores occur on the surface which creates the necessary roughening. A problem with this method is determined during micro forming studies. During the process, roughening effects disappears as the pores wear out or gets filled by process residues. This problem is especially important for micro forming applications because workpiece easily buckles due to reaction forces. It is solved by machining a wave form to swaging dies using electro discharge machining (EDM) [e.g. 5-7]. EDM is an advantageous method to create accurate and reliable shapes but it requires special tool (electrode) development, which is costly. An alternative method is used in this study to validate the effects of the increased friction. A 20W laser engravement machine (JNLINK/LXF-20W, China) is used to engrave the die surface.

1.2379 is used as the die material for this trial. Using fixed engravement parameters (given in Table 1), a sample engravement pattern is studied to increase surface roughness. Surface roughness is determined using Mitutoyo Surftest SJ210 (Japan). An engraved V-type die is shown on Fig. 6. Section A-A is the schematic cross-section of the wave.

Table 1. Engravement parameters.

Speed (mm/s)	Power (W)	Freq. (kHz)	Start TC (US)	Laser Off (US)	End TC (US)	Polygon TC (US)	Distance (mm)	Depth (mm)
100	20	20	300	100	300	100	0.4	30

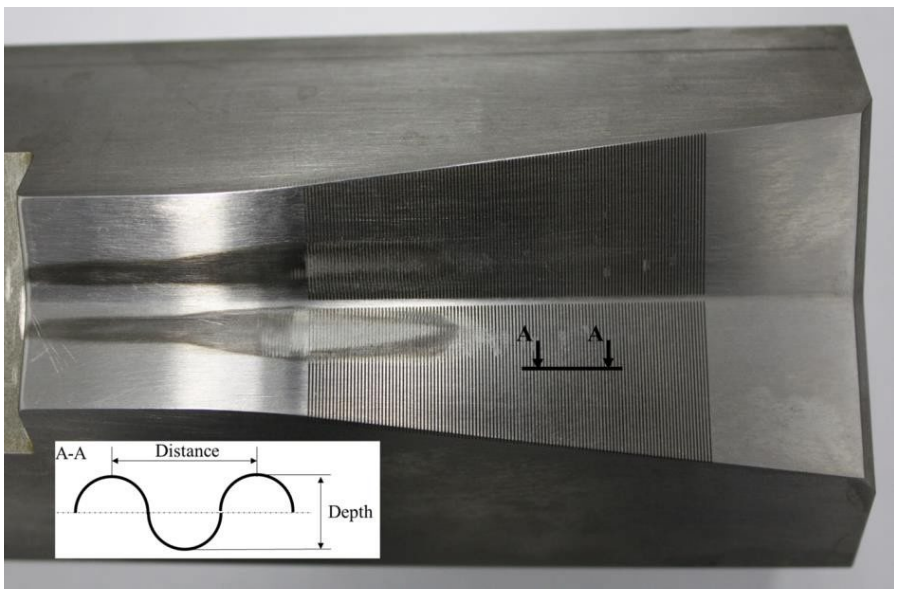

Fig. 6. Engraved swaging die. A-A section shows schematic representation of engravement distance and depth.

V-type dies are composed of 2 sections (left and right) perpendicular to axial direction. Roughness measurements are conducted for these sections separately. Initial and final roughness are presented in Table 2 for 4 dies before and after swaging processes. Initial die geometry is produced using EDM. The difference between the surface roughness parameters for different dies is accepted within tolerances. Surface roughness is measured before and after 3 processes to observe the reliability of the suggested roughening method.

Table 2. Surface roughness of 4 dies before/after engravement and its deviation after 3 processes.

#	Before engravement		After engravement		After 3 processes	
	R_a (right)	R_a (left)	R_a [R_z] (right)	R_a [R_z](left)	R_a [R_z] (right)	R_a [R_z] (left)
1	0.60	0.29	4.37 [43.7]	4.13 [50.0]	3.81 [43.7]	3.00 [39.2]
2	0.71	0.93	3.58 [45.0]	4.03 [40.1]	4.29 [40.1]	3.55 [30.48]
3	0.50	0.69	5.66 [56.7]	6.66 [68.1]	5.97 [33.8]	6.17 [37.56]
4	0.79	0.48	5.75 [58.8]	7.27 [56.7]	8.91 [53.3]	6.09 [48.66]

After the preparation of engraved dies, process trials are performed to evaluate the effects of surface roughness using REPKON RFFM Series, 4-die rotary swaging machine. The hydraulic cylinder, despite the reaction forces generated on the dies, aims to retain its position. As a result, there is a pressure difference at both ends of the cylinder. This pressure difference is then utilized to calculate the reaction force. Since, there was no infrastructure to measure the friction coefficient of the engraved surface in the production facility, it was decided to conduct a comparative study using engraved and non- engraved die sets to verify the analysis concept. During the test, the mechanism that pushes the workpiece into the die set was operated with position control and the reaction forces on the mechanism were measured. Force measurement results are shown in Fig. 7. The introduction of surface roughness on the die has been found to result in a significant reduction of the reaction forces by half. This validates the application of a roughened die surface concept for macro swaging applications. However, a direct correlation is not established due to lack of friction coefficient determination.

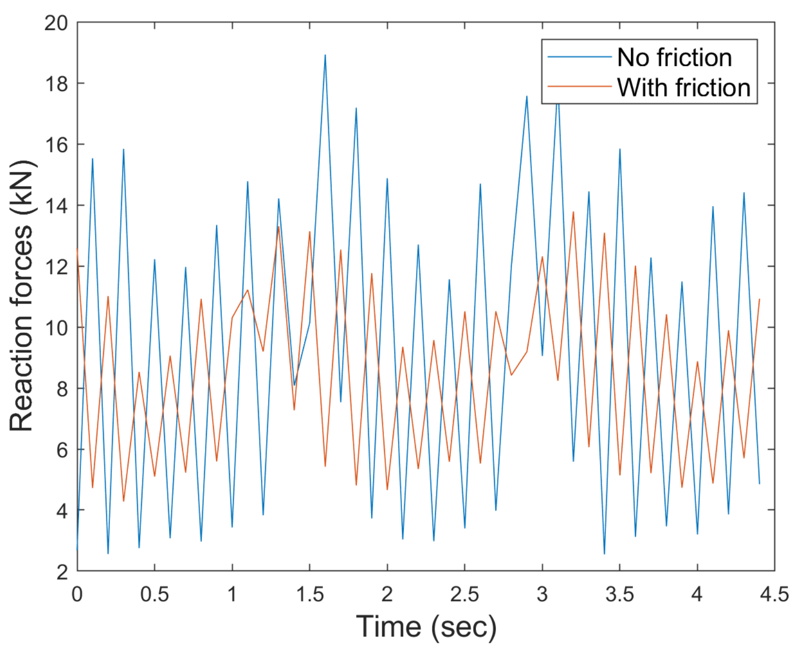

Fig. 7. Workpiece pusher reaction forces during test processes.

Summary

In this study, significant effects of the die surface friction on the rotary swaging process and product quality are determined. Process design requires careful evaluation of benefits and drawbacks for roughened die surface application. Main highlights of the study which construct a base for this consideration are shared below:

- Die surface friction results in frictional shearing between die and workpiece. During each blow, die pulls the workpiece in the feeding direction which supports the reaction forces created by the tapered section. Hence, reaction forces and machine vibrations decrease.
- The geometric precision of the product is increased by the high friction area created on the dies. In addition, a more matt structure is obtained on the outer surface of the product.
- Die shape and contact surface play an important role for the contact interactions and alter the flow of the material. During rotary swaging, dies pull the surface in the axial and tangential direction. Tangential component results in undesired torsion. For V-shaped dies, tangential contact area is significantly smaller than axial. Hence, increased surface friction does not change the torsion on the workpiece.
- The main drawbacks of the proposed methods are the wear of die surface and tearing of the workpiece surface as a result of the increased frictional shearing. Sustainability of the proposed technique for each trial requires a further study to determine optimum surface roughness and lubrication to prevent deterioration of the product surface quality and to increase die service life.

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