DOI: 10.21062/mft.2025.049 http://www.journalmt.com

Novel Multi Levels Tool Based on Rotating Ballizing Technique to Manufacturing the Externally Toothed Components an Experimental Study

Eman S. M. Abd-Elhalim (0009-0003-8710-8160)[1], Emad A. Fahmy (0009-0007-4065-2344)[2], Mohamed N. El-Sheikh (0000-0002-9571-7594)[2], Ahmed M.I. Abu-Oqail (0000-0003-3056-191X)[2], Hammad T. Elmetwally (0000-0003-0234-6104)[2], Ayman Ali Abd-Eltwab (0000-0003-0384-771X)[3*]

[1]Mechanical Eng. Dep., Faculty of Engineering, Assiut University, Assiut, Egypt
[2]Mechanical Department, Faculty of Technology and Education, Beni-Suef University, Beni-Suef 62511, Egypt.
[3]Faculty of Engineering, Beni-Suef University, Beni-Suef 62511, Egypt
[*]Corresponding author Phone: +20-01005728351, E-mail: AymanAli@eng.bsu.edu.eg

Externally toothed components have a very crucial and essential role in all areas of production and manufacturing because they function as away of transmitting motion, energy, and power in all industrial applications, such asmodes of transportation, aviation, aerospace, equipment, and operating machines-like lathes and milling. All machines have a gear box. Therefore, it is receiving increasing attention. This research presents a new multi-stage rotary ballizing technology for producing toothed parts in one stroke. This process has been investigated experimentally. The parameters that were examined experimentally was at the optimal conditions for single stage ballizing were: die rotation speed of 315 rpm; Axial feed rate, 0.13, mm/rev; The interference (cross in-feed) between the balls and the tubular specimen of 5.5 and 6.5 mm is formed by three stages of ball forming of graduated outer diameters and fixed on a single mandrel; Initial tube thickness is 7 and 8 mm. The effect of these parameters on the forming load, filling ratio and quality of the formed part was studied. The finding sindicated that the seideal variables influence the forming load, tooth filling proportion, and product quality. Experimental results proved the success of this novel technique to form toothed tubular components.

Keywords: Multi-stage ballizing, Externally-toothed parts, Ball spinning, Ballizing, Mathematical model, Shear spinning, Coining, Spinning, Gears, Process parameters

1 Introduction

Usually, the movement is transmitted between the rods by belts or gears. Gears are an important and indispensable component in practical life because they are an essential part that is relied upon in all areas of manufacturing and production, such as: military and aerospace industries, and workshop operating machines of all kinds. No machine is without a gear box, due to what distinguishes it from others in transmitting movement and power without sliding (lost in power or speed. In light of the tremendous and rapid technical progress in this era, the methods of manufacturing gears or toothed tubular parts in general have developed and been transformed from traditional methods such as: milling, hobbing machines, and others, to different, Innovative forming methods. Many previous studies were conducted to produce internally splined tubes. The ballizing process enhances the hardness of the premachined holes. Beyond hole sizing and surface improvement, ballizing has a wide range of applications, some of which are challenging or impossible to achieve using other methods. A workpiece was produced through multi-pass single-roller flow forming over a splined mandrel. The results demonstrate that themaximummeasured equivalent true plastic strain waslocatedat the interface of the workpiece and mandrel. Significantly, with the growing workpiece thickness reduction, the greatest equivalent plastic true strain near the workpiece near the nose of the internal ribs alsorose [1]. Processes involving the displacement of material from a region to another on a surface often lead to the formation of topographies defined by three separate layers. Another category of processes yielding similar three-layered topographies involves the addition or removal of material, both above and below the initial surface's average line. In instances of material addition, the resulting topography conforms to the SRR pattern, as peaks are introduced concurrently with the filling of valleys. Conversely, in cases of material removal, the resulting topography follows the RSS pattern, as valleys are augmented simultaneously with the removal of peaks [2]. Utilizing micrography analysis has proven instrumental in enhancing our comprehension of metal plastic flow during the process of backward the ball spinning for thin-wall tubular components featuring longitudinal inner ribs. multi-pass spinning leads to material work hardening, detrimentally affecting formability for inner ribs. The orientation of grains indicates that the metal follows the tangential and radial directions as it flows into the mandrel's groove. Significantly, these simulations illustrate that the three elements of spinning force increasewith growing numbers of spinning passes, indicating the presence of work hardening in the metal throughout the multi-pass spinning process [3]. Practical studies showed a clear effect of feed rate and spindle speed onkeyaspectssuch as inner diameter, wall thickness, and load requirements. Notably, employing slower feed rates and higher spindle speeds led to noticeable expansion of the inner diameter and reduction in wall thickness. Furthermore, elevated spindle speeds were particularly impactful in substantially diminishing the forming load requirements. The material's hardness exhibited a direct correlation with the extent of thickness reduction in the annealed state [4]. Employing a rounded corner design in the transition region between the teeth and grooves results in minimal fluctuations in metal flow and contact force. This design alteration proves advantageous in mitigating defects and averting mandrel failure [5]. Anew analytical method is presented to ascertain the best angle of attack for tube spinning, with the key aim of lessening the resulting spinning force. It was shown that the optimal angle of attack can be numerically calculated via the transcendental equation [6]. During the production of thin-walled tubes with small diameters using Ball spinning. was a critical concern in this process is the potential occurrence of a peeling phenomenon, which arises when factors like the working angle are not suitably chosen. This phenomenon can lead to deformations such as material crashing, curling, and unwanted coverage over areas preceding the ball, sometimes resulting in damage to the working die. concluded that peeling arises when the actual working angle surpasses a critical value αc. Conversely, if real working angle is less than or equal to αc, the material in front of the ball's flows smoothly [7]. During the backward ball spinning process. Experimental findings indicated the presence of a minimum ball diameter essential for ensuring the proper formation of inner ribs. The specific value of this minimum diameter is contingent upon factors like the feed ratio, wall thickness reducing, initial the wall thickness of tubular blank, and the material properties. The size of the ball is a pivotal factor in the backward ball spinning process for thin-walled tubular components with longitudinal inner ribs. It significantly influences both the magnitude of spinning force and various aspects of the part's quality, including surface finish, metal material flow stability, and inner rib formability. the utilization of larger ball sizes contributes for reducing the surface build-up in the spun part and simultaneously enhancing the height of inner ribs [8]. The crucial correlation between axial feed, ball size, and number of balls holds the decisive sway in determining the ultimate surface quality of the produced parts. The configuration and dimensions of the contact surfaces between ball and workpiece exert discernible influence on the components of deformation force [9]. During backward the ball spinning in the thin-walled tubular components with inner ribs longitudinally. The deformation zone in side the spun part assumes a condition of three-dimensional compressive stress. The interior rib region, the deformation zone undergoes tensile strain in the radial and axial directions, as well as compressive strain in the tangential direction. Adjacent to the inner rib, the wall deformation zone experiences compressive strain in the radial direction and tensile strain in the axial and tangential directions. Furthermore, all three spinning force components increase with augmentation of ball's stroke. Among these the force components, radial force component outweighs other two, while tangential force component displays lowest magnitude [10-13]. To enhance rib height, employing large wall thickness reduction and the feed ratio is recommended [14]. The significant influence of two main parameters, namely workpiece diameter ratio (D1/D2) and the feed rate (v), on the damage behavior observed in the ball rotation operations must be taken into account [15]. During the ball spinning to form inner grooved copper tube simulation results have indicated that folding defects occur due to the gap between inner surface of copper tube and plug. To prevent these folding defects, several measures have been proposed based on finite element (FE) simulations: Reducing difference between inner diameter of reduced blank tube and outer diameter of plug, creating appropriate rounded corners between the groove wall of plug and its outer surface and decreasing the roughness value of both plug's groove walls and its outer surface. The microstructure observed on cross-section of copper tubes indicates that folding is formed as a result of multi-track metal flow [16]. During the ball spinning of the thin-walled tubular parts, all three force components increase with an increase in feed ratio and ball diameter. Additionally, in backward ball spinning, each spinning force component is greater than its counterpart in forward ball-spinning [17]. A novel ball set design has been introduced to address multiple issues encountered in the tube spinning process, suchas material accumulation ahead of the shaping spheres, material folding on the tube'sinterior surface, and possible failure of the forming mandrel due to load variations at the base of the forming tooth. Observed that the new design utilizes smaller ball sizes compared to the conventional design, which limits its applicability to tubes with relatively small thicknesses [18]. Tube spinning employs a functionally graded ballizing arrangement. The proposed design consists of four balls, one for each plane. The novel design has shown the potential tolargelysurpassthe pile-up formation in front of the forming balls atcertainball arrangements [19]. The maximum value of strain hardening increased with both interference and wall thickness. The greater the wall thickness, the lower the wall elasticity [20]. At surface roughness increases, fatigue life tends to decrease Notably, when comparing equal surface roughness conditions, it was observed that ballizing yielded the shortest fatigue life for Assab 760 steel, while polishing resulted in the longest fatigue life. The reason behind the reduced fatigue life in the case of ballizing can be attributed to a decline in the material's fatigue resistance when subjected to a certain level of pre-strain [21]. it was established that smaller the ball diameters result in higher levels of stress and strain, along with increased strain rates. Numerical analysis further reveals that reduction ratio plays a significant role in shaping strain state within the inner tube holes after the ballizing process [22, 23]. There exists a critical interference value that maximizes the improvement in microhardness, roundness, and surface finish during the ballizing process. The ballizing process yields favorable surface characteristics, significantly enhancing the average surface roughness by approximately 85%. Moreover, it has a positive impact on the bearing ratio. Precise control over surface characteristics can be achieved by carefully adjusting the interference parameter [24]. Generally, increasing the interference (the gap between the ball tool and the bore) improved surface quality up to an optimal point. However, excessive interference could lead to micro profile distortion and excessive work hardening, resulting in poor surface finish. Themeanouter surface straineescalatedwith higher interference levels. Surface hardnessamplifiedwith higher rotation speed, feed rate, and depth of penetration. This increase in surface hardness is advantageous for the overall effectiveness of the process [25, 26]. Observed that the attack angle resulted in the smallest magnitude of the axial force additionally resulted in the smallest quantity of material accumulation [27]. The substance pushed aside by the ball can bese parated into three parts: elasticshift, plastic displacement, and material compressibility [28]. At predict the ballizing load under both dry and lubricated conditions. Assesses the effectiveness of various common lubricants and compares them in terms of the load reduction and their impact on surface finish. found that can be estimation of loads during ballizing when no lubrication is used, when lubricants are applied, predicting the load becomes more challenging because value of "β" which represents fraction of the load-supporting area where film breakdown occurs, is unknown. This value can then be used to evaluate the performance of a specific lubricant. Among the lubricants examined, a soap solution was found to be most effective. Lubrication, while reducing friction, also diminishes the surface finish improvement achieved through metallic contact and burnishing effect between ball and bush [29]. The length-to-diameter ratio of part to be ballized should ideally be within range of 1/10 to 10 times the bore diameter. The wall thickness of the material should be greater than 1/10th of bore diameter. The material to be ballized should not have a hardness exceeding 45 Rc (Rockwell C scale), while balls used should have a hardness greater than 65 Rc [30, 31]. Durin flow forming procedure used on a lathe to manufacture internal gears. discovered that all factors and interactions affect tooth height, such as attack angle, thickness reduction, interaction among roller diameter and attack angle, and reaction between roller diameter and feed rate [32]. Innovative "symmetric cold expansion" method offers superior control and uniformity of residual stresses, as well as proven enhancements in fatigue life through experimental validation [33]. To achieve the specified final diameter, an oversized ball must be employed, and the extent of oversizing can be estimated from the recovery angle value. Surface hardness increased by approximately 20% in most specimens, and this increase was more pronounced with greater interference [34]. Generally, as the interference is increased, surface quality improves up to a certain optimal point, after which it starts to deteriorate. This is because ballizingprocedureinvolves plastic deformation, and insufficient interference can result insolelyelastic deformation, leading to poor quality, especially for slight inter ferences. Conversely, excessive interference can lead to micro profile distortion and excessive work hardening, resulting in a poor finish [35, 36]. ballizing process is effective for finishing mated holes, even those with slight bends or s-bends, in a single pass. It can handle interrupted areas, such as cross holes and recesses, without difficulty. Ballizing is versatile and can be applied to various materials, including ferrous, non-ferrous, and stainless steels. but it not suitable for materials that have been hard chromium plated. Heat treatment carried out after Ballizing can disrupt the sizing and finishing of the ballized hole, so it should be taken into account when planning the manufacturing process [37]. Ina ball-shaped spinningproceduretoproduceinternally-splined tubes,importantfactorslikemandrel rotationalvelocity, axial feed, and cross in-feed wereobservedto have anotableeffecton both the forming load and the quality of the formed sleeves;the surface roughness of the sleevesdiminishasthe cross in-feed increased. While it increases with increasing axial feed. The filling ratio increases by increasing both cross in-feed and axial feed [38]. (DOE) technique was applied. It was discovered that speed and feed are the most critical variables impacting power usage. The resulting force on the roller is governed by the roller attack angle, roller nose radius, and reduction %. The resultant force consists of three components: axial, radial, and circumferential. Among them, axial force is found to be the largest, followed by radial force, and circumferential force was determined to be the least [39]. In this research suggests a novel design that promises to address all these problems simultaneously using simple tools to produce external gears or any other externally toothed parts. In addition to the formation of tubular sections with relatively large thicknesses compared to previous studies in the spinning of internally splined or non-splined tubes. Also, analytical, and practical work is done to examine the formation of externally toothed components utilizing a new rotating ballizing approach.

2 Experimental work

The multi-stage ballizing depends on dividing the thickness of metal required to be displaced (flowed) inside the cavity of the die teeth into layers that correspond in number to stages of ball bearings used, so that the graduated outer diameters of ball bearings together give a streamlined conical shape, for easy displacement of the metal and the transition of flow from one stage to another gradually with High flexibility.as shown as in Figure 1 and 2 therefore all common ballizing problems such as metal piling up in front of the forming balls, folding, radial and axial load swing result from the metal piling up, are overcome. in addition to overcoming the elastic spring of the metal behind the forming balls in a relatively large amount compared to single- stage ballizing, and the metal peeling phenomenon. Figure 1 and 2 consists of several shots representing the stages of gear formation. In stage (a), the forming tool advances towards the die, while stage (b) is when the forming tool enters the die, forming the gear. Figure 1 (c) is also shown while stage (d) is exiting the forming tool. All that at one time (in one stroke). This gives possibility of obtaining the externally toothed parts with greater thicknesses, speed in forming, saving time, reducing the forces consumed more, and ensuring complete filling of the product teeth. In addition to improving the mechanical properties of the product, such as hardness and others. Figure 2 They explain schematic drawing of multi-stages ballizing process sequence and isometric section of the process and sample ejection mechanism.

2.1 Experimental set-up of the multi-stages rotating ballizing technique

Figure 3 Shows the components of the testing device used in the forming process. The proposed design of the forming tool is a mandrel mounted on it two ball bearings or three ball bearings with graduated outer diameters (multi-stage ballizing process) and each ball bearing has six rotating forming balls with diameters of 13, 14 and 16 mm, respectively. The balls are made of hardened tool steel and are spaced 60 degrees apart to prevent folding of the metal during forming. They were designed to eliminate all the known problems of the ballizing process, which faced many researchers in previous studies, and still are still such as piling up, folding and others. Fig. 4 shows a schematic diagram of the forming tools used to form the toothed parts externally (in one stroke) using the multi-stage pelleting technique. The forming die rotates at an optimum speed of 315 rpm obtained from process parameters for single-stage ballizing, while the rotating forming balls rotate almost at the same speed as the toothed die when it comes into contact with the workpiece placed inside the toothed die. The radial feed of forming balls ranges between (5.5 mm and 6.5 mm). The cross in-feed value (interference between the forming balls and the sample) is changed by changing the inner diameter of the tubular sample while keeping the diameter of the ball bearing constant according to the required diagonal feed value (diagonal interference). The optimum axial feed rate of the mandrill was 0.13 mm/rev (also obtained from process parameters for single-stage ballizing). The toothed die is fixed in the lathe chuck at one end and the workpiece is inserted into it at the other end. The die gap provided axial support for the tubular specimen, while the die teeth rotated it. The tubular sample is made of commercial lead, with a strength coefficient of K=163 MPa and a strain hardening exponent of n=0.49 determined by an experimental pressure test. The lead was bought as scrap, it was melted and purified from impurities. tubular samples were made by pouring in a metal mold, and the casting mold was devised and produced to make the tubular samples in the required dimensions. The spindle is placed on top of a conventional lathe carriage and is set centrally with the centerline of the lathe using a dial gauge with a sensitivity of 0.01 mm. The forming balls approach the sample from the free side of the mold until contact occurs between them without penetration into the sample, then the speed and axial feed of the machine are adjusted. Automatic feeding has been activated. Thus, the sample rotates with the rotation of the mold, while the forming balls move independently and axially along the surface of the sample from the inside.

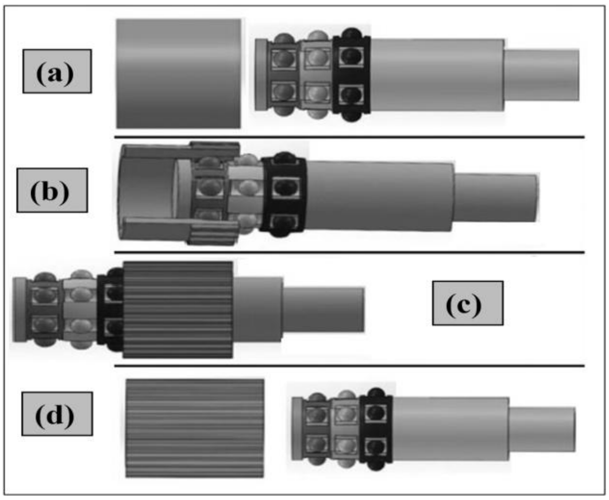


Fig. 1 *Isometric section showing multi-stages ballizing process and sample ejection*

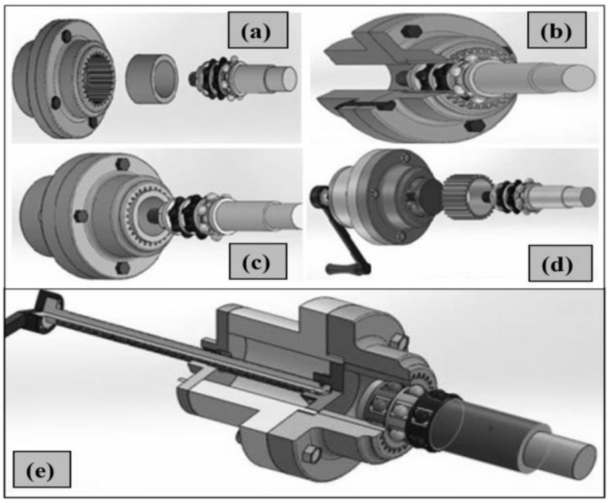
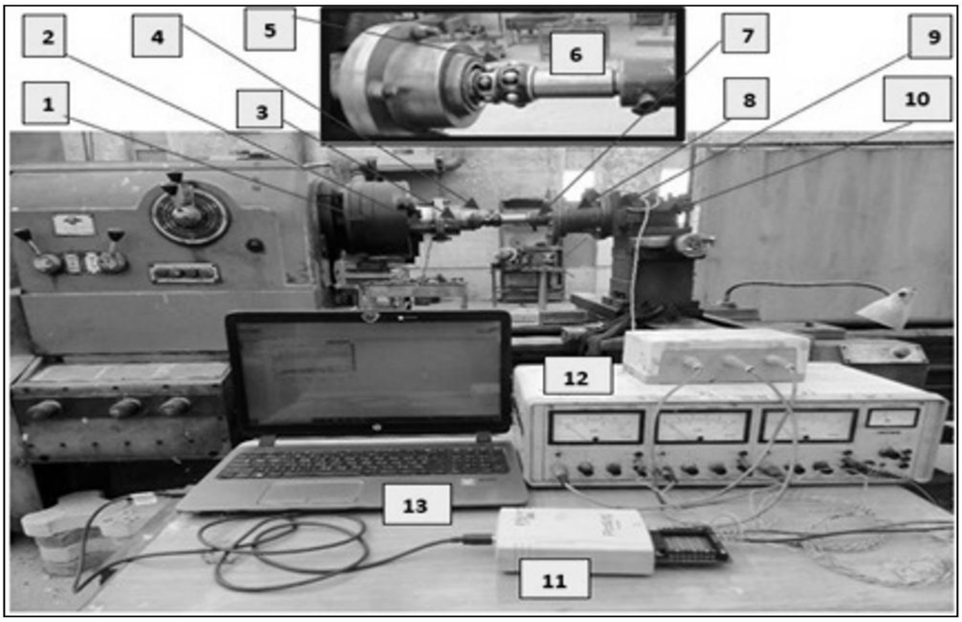


Fig. 2 *Isometric section showing multi-stages ballizing process and sample ejection*



1-Lathe Chuck
2-Product ejection mechanism
3-Toothed Die
4-Specimen
5- Forming Balls
6-Novel Ballizing Tool
7- Tool Holder
8- Dynamometer
9- Holding Jig
10-Tool post
11- Data logger device
12-Transducer Device
13-Computer

Fig. 3 *Experimental set-up of the multi-stages rotating ballizing technique as a novel forming tool*

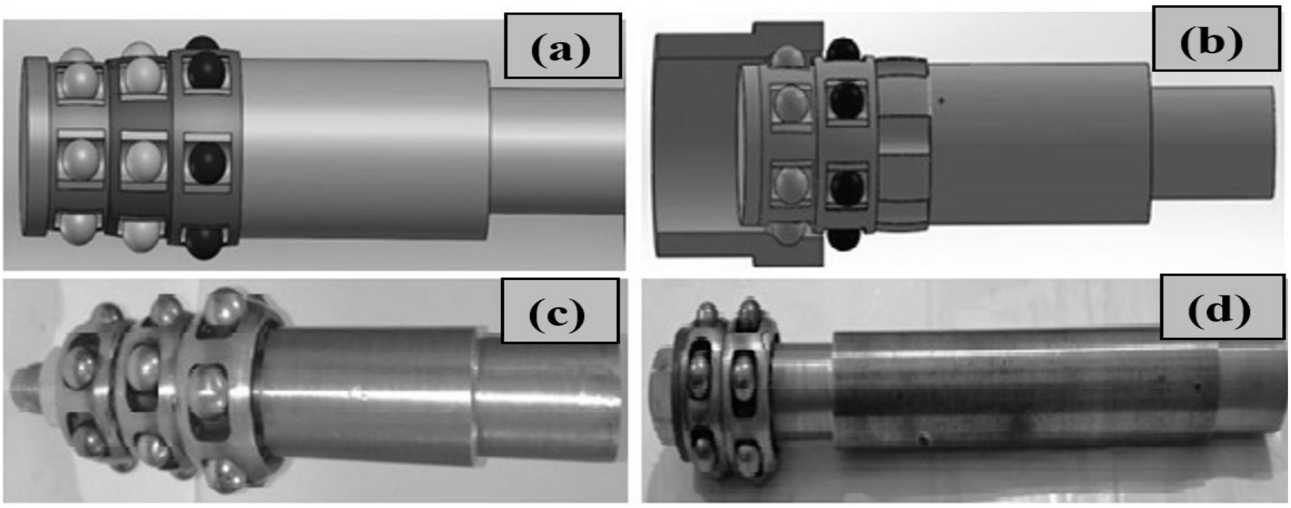


Fig. 4 *Schematic diagram showing the two and three-stage mandrel (multi-stages mandrel)*

ISSN 1213–2489
e-ISSN 2787–9402

2.2 Force, hardness, and filling ratio measurement devices

The deforming loads were gauged by the dynamometer connected with the data logger device through transducer which transfers output signals into volt and received by data logger, the data logger type is PIC OLOG 1000 series. The data logger device is connected with laptop which receives the signals through Pico-log program. The hardness of the product was measured by microhardness tester (Micromet 2001). The filling rate was calculated as follows:

- 1 - The geometry theoretically (complete filling) was calculated from die teeth dimensions.
- 2 - Actual the geometry (contour) of formed parts isenlargedto aprearranged scale utilizing a microscope to figureout the true volume occupied.

2.3 The filling rate is computed as the following

A photo scanofthe die and formed workpiece isshownin Figure 5 No (a) and (b). The real and theoretical areas were calculated using an AutoCAD program. The ratio is the total from the division of the actual and theoretical values.

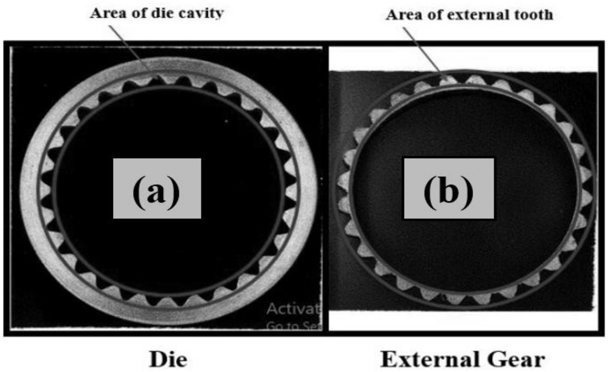


Fig. 5 Photo scan for die and external toothed part to compute the filling ratio

Experiments were done under optimal conditions derived from single-stage ballizing to study influence of process parameters (t, Δt) and machine parameters (f, N) on deformation loads. The influence of the process and machine parameters on product quality, defined by hardness and filling rate of outer teeth of the product, was investigated. Table 2 displays experimental plan and operational parameters.

3 Results and discussions

3.1 The geometry of externally toothed components

Figure 6 shows some the externally toothed tubular products which produced with the new multi stage ballizing technique and Fig. 7 photo scan for externally toothed tubular products at optimum parameters and different cross in-feed. It is obvious that the externally toothed tubular product was perfectly manufactured using the innovative multi-stage rotary ballizing technique with thicknesses 7 and 8 mm. This is a novel, simple, and low instrumentation approach.

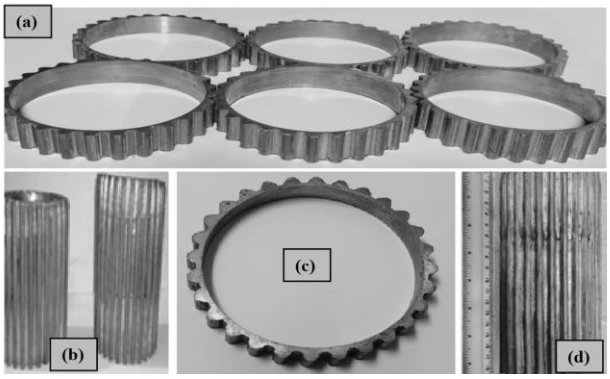


Fig. 6 Shows the ball trace geometry for the multi-stage ballizing process

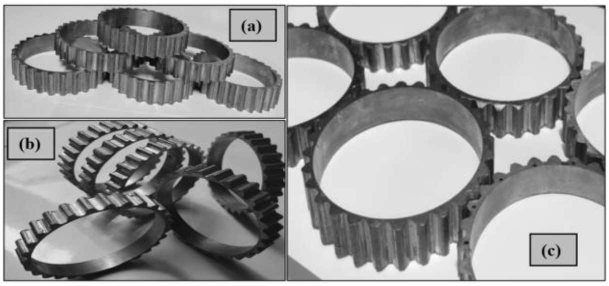


Fig. 7 Some the externally toothed tubular products which produced with the new multi stage ballizing technique

Figure 8 shows the teeth filling ratio against die rotational speed. The filling ratio was enhanced by raising the die speed, as illustrated. This is due to increased metal flow caused by greater die rotating speed. as a result of a rise in the metal's temperature and flexibility caused by fast friction. Furthermore, as the die rotational speed increases, the forming balls force more metal into the front and inner perimeters of the die, resulting in greater filling for the die tooth cavities.

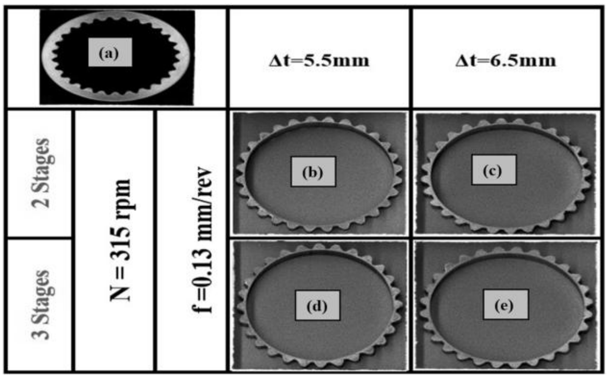


Fig. 8 Photo scan for externally toothed tubular products at optimum parameter and different cross in-feed

3.2 The impacts of die rotating speed and mandrel axial feed on forming loads

Figure 9 illustrates the relation between die rotation speed and forming loads. The graphs show that as the die rotation speed increases, the forming loads drop in three directions, eventually reaching their minimal values at the optimal die rotation speed of 315 rpm. This is due to the metal's plasticization as a result of the higher speed of friction between the balls and the workpiece, which promotes flow, as well as the quick decrease of buildup metal. Figure 9 illustrates that the forming load increases as the axial feed of the mandril increases for cross in-feeds of 5.5 and 6.5 mm, respectively. This is thought to be owing to greater contact area with increased axial feed, resulting in more build-up and greater formation load components.

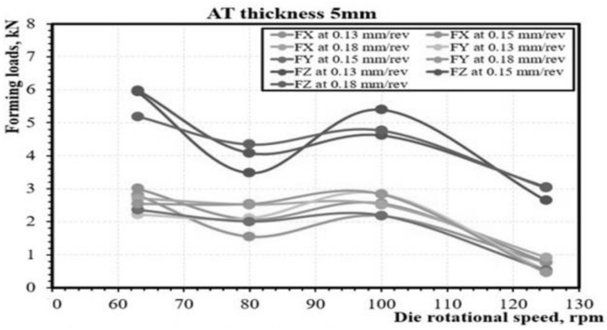


Fig. 9 *Relationship between the rotational die speed and the forming loads at cross in-feed*

3.3 Influence of process parameter on hardness

Figure 10 shows the relation between hardness and die rotational speed, as well as axial feed. It has been revealed that the higher the rotation speed, the greater the hardness, which is caused by the forming balls passing through the same surface area several times. The hardness diminishes as the axial feed rises, which is explained by the growing distance between subsequent ball strikes. As a result, the total impact of repetitive deformation on the part surface is minimized. The product's hardness will be impacted as a result.

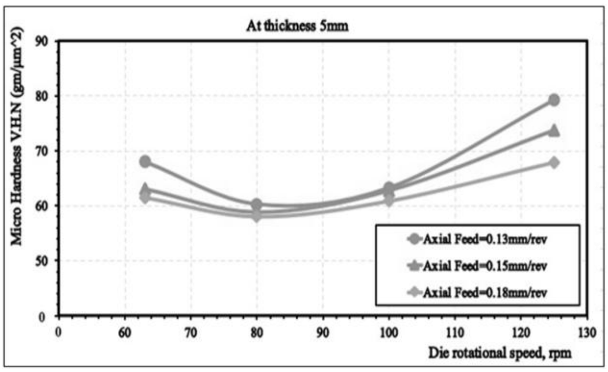


Fig. 10 *Effect die rotational speed on product hardness at cross in-feed 7mm*

4 Conclusions

This study concludes that:

- Multi-stage ballizing process produces superior results, allowing for thicker tubes and reduced forming load components.
- It was discovered that the multi-stage ballizing technique considerably decreased metal accumulation in front of the forming balls by dividing the specimen thickness into three ball bearing stages during forming in single stroke.
- Metal folding in front and behind the forming balls was removed, minimizing load fluctuations caused by metal buildup in front of the balls.
- A scientific expression was developed for predicting deformation loads, and the findings were consistent with experiment.
- The optimal die speed is 315 rpm, and an axial feed of 0.13mm/rev.
- The axial load has the largest value, followed by the radial and tangential loads.
- Ball diameter affects forming loads. When utilizing a big ball diameter, the forming loads rise.
- Increasing axial feed, speed, and cross in-feed leads to higher die filling rates.
- Hardness rises with increased speed and cross feed, but decreases with increased axial feed.

Author Contributions

The authors of this study have made significant contributions throughout the research process. Firstly, Mohamed N. El-Sheikh played a crucial role in designing the main idea of the study. Additionally, Emad A. Fahmy, Essam Khalaf Saied, Ahmed M.I. Abu-Oqail, Hammad T. Elmetwally, Eman S. M. Abd-Elhali and Ayman Ali Abd-Eltwab worked together to prepare the test-rig component, performed, and wrote a draft copy, collected the data and analyzed it. Ayman Ali Abd-Eltwab and Mohamed N. El-Sheikh review and revised the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgement

The authors would like to extend acknowledgement to their research institutions Faculty of Engineering, Faculty of Technology and Education Beni-Suef University and Mechanical Eng. Dep., Faculty of Engineering, Assiut University, Assiut, Egypt, that provided support for this work.

References

[1] HAGHSHENAS, M., JHAVER, M., KLASSEN, R. J., & WOOD, J. T. (2011). Plastic strain distribution during splined-mandrel flow forming. *Materials & Design*, 32(6), 3629-3636

[2] JIANG, S. Y., ZHENG, Y. F., REN, Z. Y., & LI, C. F. (2009). Multi-pass spinning of thin-walled tubular part with longitudinal inner ribs. *Transactions of Nonferrous Metals Society of China*, 19(1), 215-221

[3] MISCANDLON, J., TUFFS, M., HALLIDAY, S. T., & CONWAY, A. (2018). Effects of flow forming parameters on dimensional accuracy in Cr-Mo-V steel tubes. *Procedia Manufacturing*, 15, 1215-1223

[4] LI, Y., XU, Z., TANG, Y., & ZENG, Z. (2010). Forming characteristics analysis of the cross-section of axially inner grooved copper tube. *The International Journal of Advanced Manufacturing Technology*, 47, 1023-1031

[5] MA, Z. E. (1993). Optimal angle of attack in tube spinning. *Journal of Materials Processing Technology*, 37(1-4), 217-224

[6] LI, M., ZHANG, S. H., & KANG, D. (2005). Research on selecting working angle in ball spinning. *International journal of vehicle desig*n, 39(1-2), 73-79

[7] JIANG, S., REN, Z., LI, C., & XUE, K. (2009). Role of ball size in backward ball spinning of thin-walled tubular part with longitudinal inner ribs. *Journal of materials processing technology*, 209(4), 2167-2174

[8] ROTARESCU, M. I. (1995). A theoretical analysis of tube spinning using balls. *Journal of materials processing technology*, 54(1-4), 224-229

[9] ZHANG, Y. Q., JIANG, S. Y., ZHENG, Y. F., & ZHAO, L. H. (2010). Finite element simulation of backward ball spinning of thin-walled tube with longitudinal inner ribs. *Advanced Materials Research*, 97, 111-115

[10] CHUNJIANG, Z., JIE, X., XIAODONG, H., LIANYUN, J., JIEFENG, L., & CHEN, W. (2017). The analytical model of ball-spinning force for processing an annular groove on the inner wall of a steel tube. *The International Journal of Advanced Manufacturing Technology*, 91, 4183-4190

[11] ZENG, X., FAN, X. G., LI, H. W., ZHAN, M., ZHANG, H. R., WU, K. Q., ... & LI, S. H. (2020). Die filling mechanism in flow forming of thin-walled tubular parts with cross inner ribs. *Journal of Manufacturing Processes*, 58, 832-844

[12] KUSS, M., & BUCHMAYR, B. (2016). Damage minimised ball spinning process design. *Journal of materials processing technology*, 234, 10-17

[13] ZHANG, G. L., ZHANG, S. H., LI, B., & ZHANG, H. Q. (2007). Analysis on folding defects of inner grooved copper tubes during ball spin forming. *Journal of materials processing technology*, 184(1-3), 393-400

[14] SHUYONG, J., & ZHENGYI, R. (2008). Analysis of mechanics in ball spinning of thin-walled tube. *Chin J Mech Eng*, 21(1), 25-30

[15] AHMED, K. I. (2011). A new ball set for tube spinning of thin-walled tubular parts with longitudinal inner ribs. *JES. Journal of Engineering Sciences*, 39(1), 15-32

[16] KASSAR, M., AHMED, K., ELSHEIKH, M., & EL-ABDEN, S. (2022). Tube Spinning Using Functionally Graded Ballizing. Available *SSRN*, 3977528

[17] EDRIYS, I. I., & FATTOUH, M. (2013). Characteristics of Finished Holes By Ballizing Process. ERJ. *Engineering Research Journal*, 36(4), 403-415

[18] LAI, M. O., & NEE, A. Y. C. (1989). The effect of several finishing processes on the fatigue resistance of hole surfaces

[19] DYL, T. (2017). The numerical and experimental analysis of ballizing process of steel tubes. *Archives of Metallurgy and Materials*, 62(2A), 807-814

[20] DYL, T. (2017). The Numerical Analysis of the Ballizing Process. *Scientific Journal of Gdynia Maritime University*, (100), 63-75

[21] FATTOUH, M. (1989). Some investigations on the ballizing process. *Wear*, 134(2), 209-219

[22] EL-ABDEN, S. Z., ABDEL-RAHMAN, M., & MOHAMED, F. A. (2002). Finishing of non-ferrous internal surfaces using ballizing technique. *Journal of materials processing technology*, 124(1-2), 144-152

[23] KIM, N., KIM, H., & JIN, K. (2013). Minimizing the axial force and the material build-up in the tube flow forming process. *International Journal of precision engineering and manufacturing*, 14, 259-266

[24] NEE, A. Y. C., & VENKATESH, V. C. (1983). A mathematical analysis of the ball-burnishing process. *CIRP annals*, 32(1), 201-204

[25] NEE, A. Y. C., & VENKATESH, V. C. (1984). Dry and lubricated ballizing. *Tribology international*, 17(1), 25-29

[26] UPADHYAY, P. K., JOSHI, H., & AGARWAL, P. Evaluation of Different Forces for Super Finishing the Internal Surface of Ballizing process

[27] NEE, A. Y. C., & VENKATESH, V. C. (1982). Bore finishing—the ballizing process. *Journal of Mechanical Working Technology*, 6(2-3), 215-226

[28] KHODADADI, M., KHALILI, K., & ASHRAFI, A. (2020). Studying the effective parameters on teeth height in internal gear flowforming process. *International Journal of Engineering*, 33(12), 2563-2571

[29] MAXIMOV, J. T., DUNCHEVA, G. V., & AMUDJEV, I. M. (2013). A novel method and tool which enhance the fatigue life of structural components with fastener holes. *Engineering Failure Analysis*, 31, 132-143

[30] UPADHYAY[1], P. K., AGARWAL, P., & ANSARI, A. Discussion and Analysis of Ball Rolling (Ballizing) Process with Elastic and Plastic Deformation between Ball and Material

[31] ABD-ELTWAB, A. A., EL-ABDEN, S. Z., AHMED, K. I., EL-SHEIKH, M. N., & ABDEL-MAGIED, R. K. (2017). An investigation into forming internally-spline sleeves by ball spinning. *International Journal of Mechanical Sciences*, 134, 399-410

[32] AYMAN ALI ABD-ELTWAB, ESSAM KHALAF SAIED, AHMED MOHAMED ATIA, NOUBY M. GHAZALY, A.A. Gomaa, Karim Mohamed Atia (2024). Investigation of externally toothed parts forming using ballizing technique. *Results in Materials*, 24 (2024) 100640, https://doi.org/10.1016/j.rinma.2024.100640

[33] BHATT, R. J., & RAVAL, H. K. (2018). In situ investigations on forces and power consumption during flow forming process. *Journal of Mechanical Science and Technology*, 32, 1307-1315

[34] DROGE KRAFTE, K., und Material fluss beim Drucken, T.H. Stuttgart, (1954)

[35] HAYAMA M., "Theoretical Study of Tube Spinning", *Bull. Fac. Eng. Yokohama Univ.*, Vol. 15, pp. 33-47, (1966)

[36] RAGAB K. ABDEL-MAGIED, EMAD A. FAHMY, A. EL-SAYED M. HASSAN, MOHAMED N. EL-SHEIKH, ESSAM K. SAIED AND AYMAN A. ABD-ELTWAB, "An Investigation into Forming Externally Toothed Parts using Novel Tool based on Rotary Forging Technique." *International Journal of Advanced Science and Technology*, ISSN: 2005-4238 IJAST, Vol. 29, No.03, (2020), pp. 2194-2206

[37] ABD-ELTWAB, A.A., HELAL, G.I., EL-SHEIKH, M.N., SAIED, E.K., & ATIA, A.M. (2023). An Investigation into Conventional Spinning Process Using Ball Shaped Rollers as Forming Tool. *Manufacturing Technology Journal*, 23(6), 788-800.
doi: 10.21062/mft.2023.084

[38] ABD-ELTWAB, A.A., ELSYED AYOUB, W., EL-SHEIKH, M.N., SAIED, E.K., GHAZALY, N.M., & GOMAA, A.A. (2024). An Investigation into Forming of Gears Using Rotary Forging Process. *Manufacturing Technology Journal*, 24(4), 539-551.
doi:10.21062/mft.2024.068

[39] ABD-ELTWAB, A.A., HAMDY, K., ELSHEIKH, A., SAIED, E.K., GHAZALY, N.M., & GOMAA, A.A. (2024), An investigation into production of double wall tube using squeeze Ballizing technique. *Journal of Manufacturing Processes*, 127 (2024) 545–558. https://doi.org/10.1016/j.jmapro.2024.08.005