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A comprehensive review on incremental deformation in rolling processes

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Abstract

Incremental deformation is a well-known concept among material scientists, when applied with advanced automation it becomes very efficient. It has advanced in leap and bounds over time and has established itself in mainstream industrial applications. Yet, there are a few common problems associated with this technique. Many of these problems are related to predicting material behavior, inaccuracies in setting roller angles and distance, and the velocity of rollers and workpieces. This review paper attempts to concisely present these processes, problems, and the advances that have been made over the years. Firstly, in this review, a detailed overview of the rolling processes, carried out in different academic universities, based on conventional and generic techniques is given. Secondly, an outline of various rolling techniques like thread rolling, incremental rolling, shape rolling, and some other advanced techniques like corrugated rolling, riblet rolling, and symmetric and asymmetric rolling, are discussed in detail with their merits, demerits, and applications. This is followed by a study of recent reports on the finite element methods (FEM), consisting of work on numerical methods by research scholars and practical experiments such as experiments based on the topic like specific material usage or the enhancement of the rolling process through different methods. Finally, a decisive summary of the challenges behind the novel concepts, and the specific domains requiring further enhancements are mentioned.

Keywords: Incremental deformation, Finite element methods, Forming, Rolling

Background of incremental deformation

The history of metal applications dates to the late Neolithic age, where development in farm tools, hunting weapons, and ornaments started [1]. Since then, the progression of metallurgy has spread like a wildfire. Elementary metals such as copper, silver, and gold were predominantly used in the past. Improvements in the field of metal processing have led to further discoveries of novel metals such as bronze, iron, different alloys, and alloying techniques. Even though the availability of such resources was limited due to the extraction processes, the hotspot for different metals was determined by explorers which aided in the discovery of new metals and non-metals, as seen in the periodic table now. The advancement in the production of iron was started by Hittites in 1200

BC, which was later improved by the Greeks, Romans, and finally by the Chinese with the invention of the blast furnace which was substantial for the beginning of the iron age [2]. New techniques for metal production were invented over centuries, among which the twentieth century was considered to be the most significant. Both the world wars had a great impact on this industry, which led to myriads of manufacturing, production, and sheet metal forming processes/techniques for the rapid fabrication of a variety of products.

Over time, more and more scientists and scholars have begun research in materials and their properties from the physical surface to the molecular level, which helped in determining the mechanical properties of metals, the foundation of alloys, and their roles in our daily lives. This knowledge especially about cold, warm, and hot forming conditions, for different sheet metal forming techniques, has aided in modifying the solid metals into their desired shapes for implementation. These processes initially consisted of external tooling techniques and loading cycles, which were associated with factors affecting the workpiece properties by compression and friction [3]. Later, rolling mills were introduced in the market, which provided the accurate shapes that forging could not and were significantly economical. Subsequently, other rolling techniques were then introduced to cater to the needs of the industry. For example, the ring rolling and tube piercing process met the demand for accurate rings and tubes for boilers, reactors, bearings production, and the underground pipe industry. Furthermore, with the advancements in the transportation industry, demands for gears and shafts grew which led to the formation of gear and threaded rolling [3]. Due to the complex kinematics of such procedures, a great deal of research and experiments were conducted for these processes to promote their implementation in special applications like rocket parts, shafts, and pipes for power plants, large vessels, alongside other heavy machinery parts that must withstand excessive stress and cyclic loading. Additionally, the increase in demand for such machinery led to huge pressure on the manufacturers for making machines specific to industry applications.

Thus, incremental deformation provided a simpler solution to this problem. The incremental deformation method is based on flexible and locomotive external tooling which permits localized plastic deformation at the required areas for fabrication of the desired product while reducing wastage of raw material. This deformation initiates strain hardening of the area by highly induced stresses through external tools which increases the slip planes in the workpiece [4]. The rise in friction and temperature furthermore makes the workpiece workable. The residual stresses which add up in the material are released by annealing [5], hardening [6], and finishing processes to further improve workpiece quality [7]. However, certain boundary conditions must be heeded to reduce and prevent any material or tooling damage. Even though incremental forming techniques optimize grain structures, tooling conditions may result in low or high friction production which can either damage or deform the workpiece causing early failures and quality issues [8]. This resulted in severe problems that obscured the industry. Several scientists indulged themselves to solve this problem through research in the predictive behavior of grains in varying external conditions like temperature, friction, forces, and then numerically modeling the formability. Ma and Sugitomo in 2011 coined a simulation program and software called LS-DYNA capable of emulating the response of materials under the application of high forces. The subroutines like contact pressure, plastic strain, changing coefficient of friction, frictional work, and temperature were experimentally verified through long rigorous testing. This led to the dynamic development of 2-D and 3-D numerical modeling simulations [9]. An extensive list of programmable systems like finite element method (FEM) [10], multi-grid and meshing method, computational fluid dynamics (CFD) [11], boundary element method (BEM) [12], fast Fourier transformations (FFT), and many more were used to predict material behavior. The principal emphasis of all systems focuses on optimizing procedures for complex processes and exacting material description and behavior from the macro-to-micro scale on the modeling framework of crystal plasticity theory.

Since the last decade, improving the predictive ability of numerical simulations has been a great task due to many constraints in real-life scenarios. These predictions include phase transformations, stress distributions, change in sheet thickness, spring back, buckling, cracking, temperature distribution, material deformation, and forming limit diagrams. A major drawback of these predictions is the behavior of material microstructures of different lengths, as deformation is not steady-state and elastic zones are closely adjacent to forming zones in the structures [13]. Additionally, due to cyclic loading and continuous contact points during the processes, the modeling becomes strenuous. Hence, predicting change in material behavior at the succeeding loading cycle is difficult. Tackling these through the radical 3-D adaptive remeshing technology combined with FEM numerical simulations gave a breakthrough in optimizing material flow and crack occurrences in sheet metal forming procedures (including thick and high strength steel) [14]. This technique is the baseline of much-advanced simulation software programs like Forge, Ansys, and Simufact.

The objective of this review paper is to summarize recent trends and experimental findings in major sheet metal forming processes and to outline the use of simulation-based numerical modeling and FEM (2-D and 3-D) simulation of optimizing materials and processing quality. In the following sections, selected rolling processes, in which incremental deformation plays the role of a governing factor, and the research done by several institutions and personnel concerning these processes are mentioned. Subsequently, the findings are presented in a tabular form and the fields in which more research is required are stated. Lastly, a discussion on several applications based on methodological developments in the conventional incremental rolling process is carried out.

Incremental rolling

Incremental rolling is a process in which a metal is deformed, using circular rolling dies which have a special tooth profile, that is adapted on machines [47]. Furthermore, there are several ways in which incremental rolling techniques are utilized in industries. In this section, a review on the advantages, disadvantages, applications, and evolution is done, and along with it a detailed view on various types of incremental rolling processes like corrugated flat rolling, flat rolling, shape-forming, ring rolling, periodical straining to roll, and skew rolling is presented (refer to Table 1).

Table 1 About processes in brief

Process	Material	Common uses	Typical tooling\equipment required	Challenges
Ring rolling	-Metals and metal alloys depending on the purpose.	-Railway tires [15, 16] -Rockets -Turbines [17] -Pressure vessels [18] -Gears -Pipes [18] -Bearings [17]	-The preparation of the workpiece includes shearing and flattening the billet, which was later punched to form a ring. The process requires a driven roll, idler roll, and two edging rolls, all of which control the diameter and thickness of the final ring product.	-In hot rolling, the final grains and microstructure are not as tough as the cold cold-rolled rings. -The outer surface of hot rolled structures required heat treatments for increasing strength and surface finishing techniques. -Asymmetrical parts are very difficult to produce [19].
Thread/gear rolling	-Stainless steel [20] -Non-ferrous metal [21] -Cast iron -Carbon steel -Alloy steel	-Gear manufacturing [22] -Worm wheels [22] -Screws [23] -Bolts [24] -Screw machines -Flat and cylindrical die types	-Workpieces are placed and compressed against two or three hardened dies, which are rolled against the workpiece to imprint the thread/gear profile onto the workpiece.	-Synchronizing the rolls -Feed rate and penetration rate should be checked after every operation -Gauging problems -Mismatched helix angle which creates screw jacking -Surface finishing at tooth surfaces
Shape rolling	-Steel [25] -Carbon steel -Stainless steel -Non-ferrous metal -Alloy steel depending on the application [26]	-Bridges -Railroads -Roller coasters -Home appliances -Structural beams for constructions -Architectural applications	-A strip of metal (workpiece) is passed through a series of rolls in different angles/positions to the workpiece, varying on the final cross-section profile is achieved.	-Microstructure deformations are less refined at the flanges [27] -Position of rolls should be in perfect alignment for production otherwise defects and further complications occur
Skew rolling	-Alloys of titanium and steel [28] -Aluminum [29] -Nickel -Magnesium [30]	-Springs -Railway bars [31] -Rods [30] -Reinforcement products -Grinding mill balls [32] -Roll bars	-An input feed of metal stock is directed toward two specially designed skewed rollers, which roll in opposite directions. The wedges in the skew rollers help to cut the stock metal for creating metal balls.	-No hollow parts can be formed -Wear in the rollers cause voids in the final product [33] -Rollers should be parallel -The temperature of rolls should always be lesser than the feedstock [34] -Point of contact between rollers should be avoided

Table 1 (continued)

Process	Material	Common uses	Typical tooling\equipment required	Challenges
Tube piercing	-Stainless steel [35] -Carbon steel -Steel alloys [35, 36] -Aluminum -Aluminum alloys -Nickel alloys -Brass -Titanium alloys [37]	-Pipes in automotive, and aerospace [38] -Electrical and nuclear industries [39]	-Long input billets are pierced through plugs in the middle of two or three rollers with the presence of a guide wheel. The temperature of the process is quite high, as a lot of deformation takes place at the center when the plug pierces to make tubes.	-Velocity and angles of the rollers should be carefully controlled [37] -Internal cracks and voids [40] -The plug should be extraordinarily strong and surface hardness should be high -Guide rollers should be aligned and controlled properly so that there is no variable thickness in the tube.
Periodical straining rolling	-Metallic alloys of aluminum and magnesium	-Automotive -Aviation -Marine -Wind energy industries	-First small, periodic rack rack-like groves are made on the metallic sheet by a worm gear-like grooved roll and then in the second stage, these groves are flattened using conventional work rolls.	-Types of grooves must be carefully monitored. -Final smooth surfaces can have problems in strain distribution. -Changes in microstructural and texture gradients must be carefully studied.
Flat rolling	-Steel [41] -Stainless Steel [41] –Aluminum [42] -Brass -Copper	-Refrigeration [43] -Home electric appliances [43] -Aircraft -Subways -Bullet train cars	-Working rolls are fed with the material having a rectangular cross-section.	-Space between two rollers must be carefully maintained along the process [44]. -Roll slips can happen in certain conditions especially when thickness change is too large [44].
Corrugated flat rolling	-Metal-based composites [45] -Galvanized Iron -Iron	-Rural and temporary military building setups to build rooftops -Manufacturing wrought iron sheets	-With the use of a combination of corrugated roll and flat roll, the composite plate is rolled. Then in the next step, flattening of the resulting waved plate is done with the traditional flat roll.	-It alters bending strength hence it must be keenly monitored. -The two-dimensional strain distribution model for the initial corrugated rolling process highlighted severe plastic deformation [45]
Riblet rolling	-Ti-6Al-4V [46]	-Wind tunnel [46] -Aircraft [46] -Aviation	-Profiled rollers with a diameter ranging from 115 to 25 mm are grooved with a negative riblet geometry. -The rollers are mounted on an axle and are rolled over the workpiece surface under the influence of a constant rolling force	-Producing a negative riblet structure on rollers is challenging [46] -Effects of mispositioning of the riblet roller on the workpiece are critical. -Roller angles must be precise [46].

Flat rolling

Flat rolling [6] is one of the most basic forms of rolling and it is extensively used to produce flat sheets and strips. As depicted in the book, "Cold Rolling of Steel" [48], it was first used by Leonardo Da Vinci to roll lead by employing a hand-cranked mill. Even after several decades since its introduction, the fundamentals of rolling for the production of flat pieces of materials are the same. However, there has been a significant evolution in dimensions, materials, precision, speed, mechanical, and metallurgical quality of the final product [49]. Most importantly, the mathematical analysis and the control of the process have evolved along with modern technological advancements and now these are considered as one of the most successful "high-tech" processes, for efficient, modern, and productive applications.

Methodology

In the flat rolling process, two rollers called working rolls are fed with the material having a rectangular cross-section. The space between the working rollers is adjusted such that it is less than the thickness of the input material. When the workpiece is fed into the rollers as shown in Fig. 1, the deformation of the material [50], as the reduction in thickness, happens due to the friction generated at the interface of the material and the working rolls. Further, the material elongates evenly too; this is due to even stress distribution and a decrease in material thickness. However, the amount of deformation possible due to the friction between the working rolls is limited, as sometimes the rolls slip over the material if the thickness change is very large [51].

Along with the development of new incremental flat rolling processes, many empirical and numerical approaches [52, 53] have also been introduced by various institutions focusing on improving existing areas of application, and simultaneously developing new methods of incremental rolling processes.

Corrugated flat rolling

The conventional process of flat rolling has evolved significantly over the last decade. Especially, with the introduction of new metal-based composites [45] and with

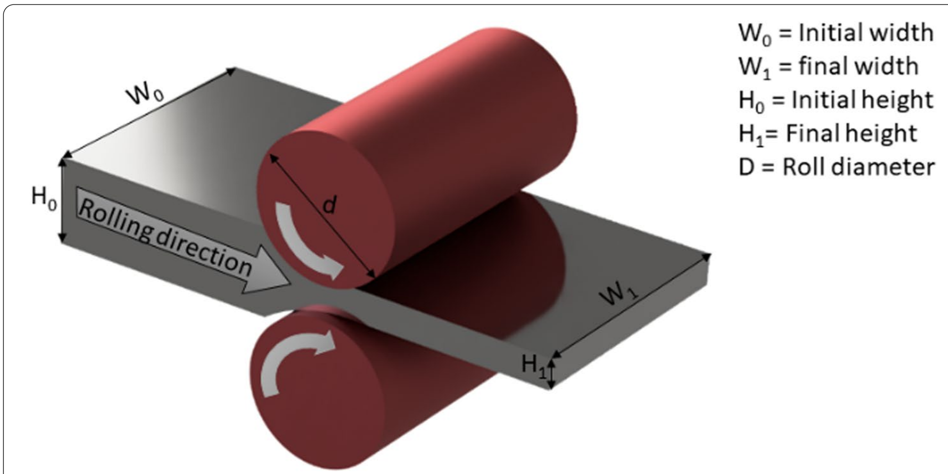

Fig. 1 Reduction in thickness of a workpiece by flat rolling process

demand for a change in traditional manufacturing practices for these composites and particular complex shapes led to the introduction of corrugated flat rolling. This process has been developed, based on the traditional flat rolling process along with the advent practices targeting enhancement of the grain microstructure that improves the mechanical properties of the material.

Methodology data overview

The College of Mechanical and Vehicle Engineering of the Taiyuan University of Technology, China, came up with an unprecedented rolling method based on the corrugated rolling process, called as corrugated + flat rolling process (CFR). In this process, the Cu/Al laminated composites with appreciable mechanical properties and a low reduction ratio, up to 20% per pass at room temperature, were manufactured with the use of the proposed CFR process [54]. Later, Taiyuan University used this novel technique to successfully manufacture Mg/Al laminated composites at 400 °C with reduction ratios of 35% and 25% followed by subsequent annealing treatment at 200–350 °C [55].

Simulation methodology overview

As per the methodology adopted by the Taiyuan University of Technology, the corrugated process comprises two stages of deformation. As depicted in Fig. 2, the initial stage comprises the rolling of a composite plate simultaneously with both the corrugated roll and the flat roll. The next step involves the flattening of the resulting waved plate with the traditional flat roll. Finally, we get the flattened and laminated composite with a corrugated bonding interface after the process of flat rolling. The first CFR pass in this method results in the preliminary combination of the substrates of the composite plate, and the second pass provides the final combination with a reduced reduction ratio.

The corrugated bonding interface formed in the process does not include an intermetallic phase, but grain refinement of the interface is observed after the CFR process as remarked in Taiyuan University's research [54, 55]. The two-dimensional strain distribution model for the initial corrugated rolling process highlighted extreme plastic deformation established at trough positions. This deformation at the trough contributes to severe bonding and refinement of grains as compared to that in the peak or top positions. The analysis performed was used to study the mechanical properties and the interfacial microstructure of the laminates of the flattened composite along both, rolling direction (RD) and transverse direction (TD). For the flattened as-rolled sample, the interfacial intermetallic compound (IMC) layer formed was observed to be continuous along with the TD while it was discontinuous in the longitudinal direction. The resulting composite laminate exhibited excellent tensile and tension-shear properties in both RD and TD because of the refined microstructure and a well-bonded interface [55]. Transverse tensile properties were observed to be higher due to the microstructure spatial distribution and the IMC's layer along with different directions. Therefore, a novel CFR process was projected successfully to manufacture bimetallic composite laminates with outstanding mechanical properties.

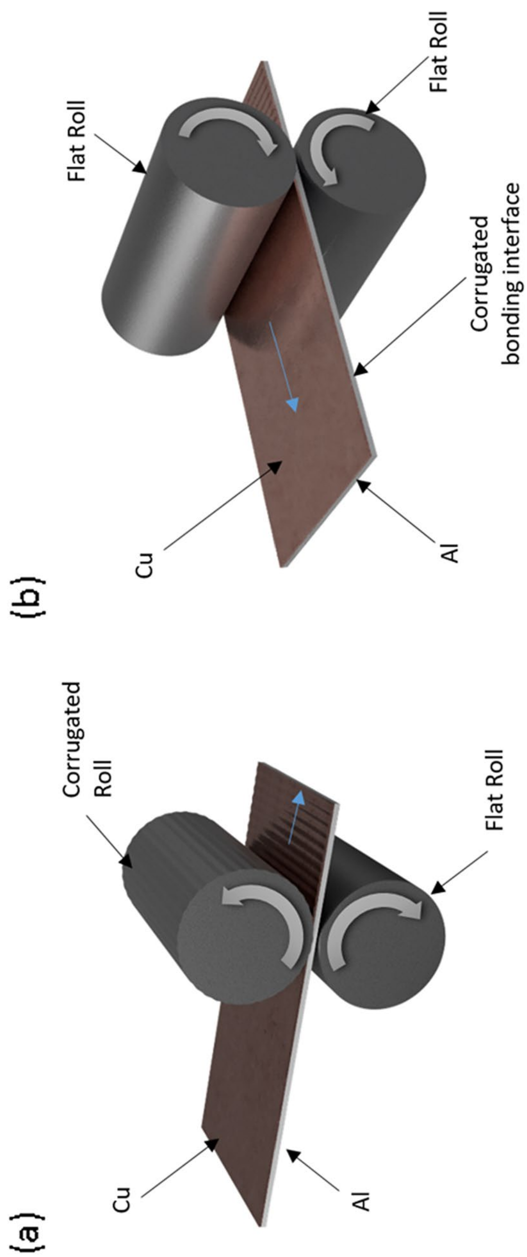

Fig. 2 The Cu/Al plate was fabricated by corrugated flat rolling

Riblet rolling

The longitudinal structures called “riblets” have been researched extensively as they result in the generation of Cataclysmic variables in the boundary layer. A theoretical investigation of the characteristics in the viscous zone of the turbulent boundary layer of V-shaped and U-shaped riblets has been reported by Tullis et al. from Canada. An experimental study of the characteristics of a turbulent boundary layer using a heat-loss anemometer was performed by Choi et al. in the UK [56]. By using smoke visualization, various patterns of longitudinal vortices in the viscous sublayer of the boundary layer were observed above different forms of riblets. Wallace et al. from the USA obtained experimental data [57] on the flow over riblets in a way similar to Bechert et al. [58]. In the late 1970s, Nakamura et al. investigated the structure of a turbulent boundary layer over rectangular riblets in a wind tunnel [59]. In the 1990s, Kasagi et al .[60] was involved in numerous research projects on the characteristics of flow and patterns of streamlets, hence establishing velocity vectors above riblets. Later on, Bechert et al. also performed research analysis on various forms of riblet, developing sharp scales lookalike of riblets along with different simple riblets, modeled on elements of shark scale. Some of the major research findings by a few key institutions of the riblet rolling process have been briefly explained below.

Theoretical modeling overview

Under the “RibletSkin” research cooperative project, “RWTH Aachen University’s Institute of Metal forming” (IBF) presented insights [61] on the relevance and importance of surface structuring on part components and large semi-finished products. In this study, riblets or other defined surface structures were aligned parallel along the direction of flow contrary to flat surfaces. These fine ribs tend to decrease the shearing stress on the walls of bodies due to the turbulent flow since the airflow is either around them or through them. In the periphery region of the structured surface, the wall friction is further reduced by the inter-exchange of impulse caused due to a reduction in lateral movement of turbulent flow. An optimum structure of riblet setup decreases up to 10% of wall friction [46, 58, 62–64].

Riblet geometries as represented in Fig. 3 also play a critical role in reducing wall friction as per Bechert et al.’s investigation. The type of riblet and the ratio of riblet height (h) and riblet width (s) are the decisive factors in wall friction reduction [58, 62, 65, 66].

Simulation methodology

In the riblet rolling process, profiled rollers with diameters ranging from 15 to 25 mm were grooved with a negative riblet geometry as shown in Fig. 4. The rollers are then mounted on an axle and were rolled over the workpiece surface under the influence of a constant rolling force. To provide an adequate airflow structure to the component surface, the lateral offset of the forming roller was used to generate additional surfaces upon rolling path completion as shown in Fig. 5.

The process of incremental rolling in riblet structures is evident, as the negative riblet structure on the roller deforms the workpiece material; however, the specifications and boundary conditions are difficult to determine. Accurate positioning of the riblet roller

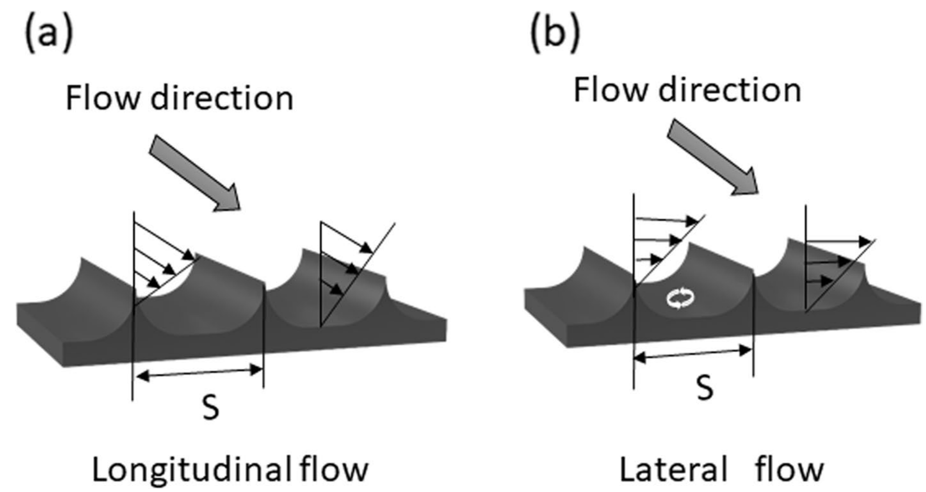

Fig. 3 Viscous flow (longitudinal and lateral components) across riblets

on the workpiece is critical since even the slightest of deviations in roller angles can lead to inconsistent riblet forms. Furthermore, current research work does not offer any clear explanations on how to tackle the difficulties in the rolling process of large riblet fields which are filled with complex contours.

Another study related to manufacturing process feasibility enhancement is also being conducted by the Institute of Aerodynamics (AIA) of the RWTH Aachen Institute (Germany) in which they are working in the direction of optimizing and enhancing the dimensional aspects of riblet geometry for further applications and use by analyzing and monitoring the reduction in friction experienced by the test body structures under the actual flow conditions.

Shape rolling

Since the last century, many industries have relied on metal sheet forming. Huge demand for beams and sections for the construction sector are statutory, thus the formation of a process devoted to thick metal sheet working was a necessity. Hence, the “shape rolling process” was developed which consists of passing structural metals through a mill for deformation according to the desired shape. The most commonly formed profiles are H beam, I beam, U beam, T beam, a railroad rail, and bar stock [67]. Just as the other rolling processes, shape rolling is divided into 2 major categories: hot and cold rolling. Even though the deformation and quality of cold-rolled materials are better, the cost factor for this process is extremely high. With the current trends of technology automation, a significant amount of research has been conducted in the methodology and optimization of shape rolling [67, 68] and how its deformation should be done, by applying enough force and torque by the rolls.

Current research

Considering the present advances of technology, more interest has been inclined toward technical considerations in forming accurate shapes as efficiently as possible. This is done through various findings and formulas in shape deformation with controlled

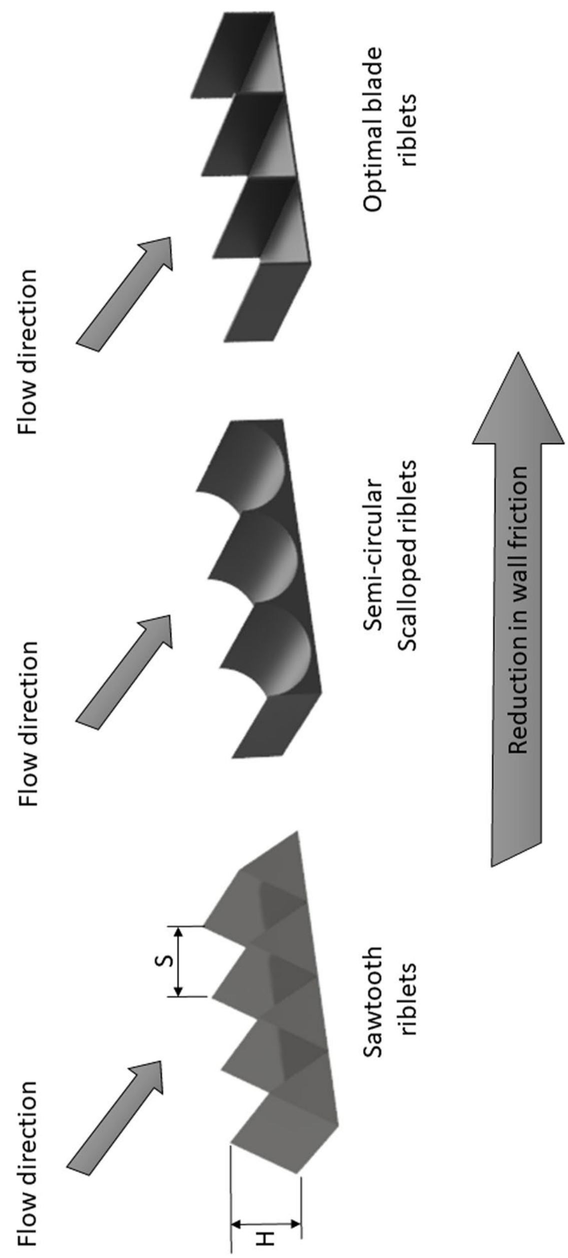

Fig. 4 Riblet geometries and their reduction in wall friction of a turbulent flow

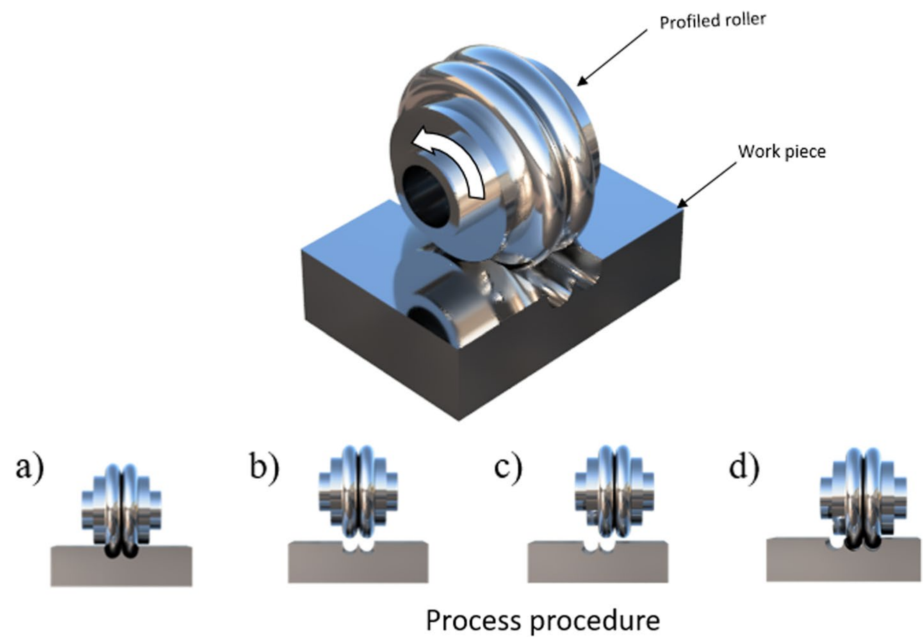

Fig. 5 Isometric view of the profiled roller and process of Incremental riblet rolling. **a** The grooved roller is rolled over a workpiece surface. **b** Roller is moved up. **c** Roller is positioned for next grove. **d** Roller is rolled over workpiece again producing defined riblet structures

variables in force, torque, temperatures, and other conditions. Incremental deformation taking place in the microstructure (grains), during the rolling process, is produced by strains in rolls that occur in the perpendicular direction to tool travel and are negligible in the parallel direction which makes the grains finer and compact for strengthening [69]. Furthermore, many researchers have conflated and derived empirical formulae on stress-strain graphs, shear strain, grain texture, and deformations which has further aided in automating rolling procedures and generating quality products.

Theoretical modeling

Shivpuri et al. from Ohio State University in 1992 devised three key factors for successful shape rolling: roll separating force and torque, spread and elongation, and the geometry of roll grooves [70]. These were incorporated in technical software with known formulae, and are called computer-aided manufacturing [71], finite element methods, and TASKS code. This software helped in estimating the metal flow, deformation, and grain texture based on the input of forces and torque of the rolls and other temperature conditions to find optimal performance. The prime focus of the study was to minimize the count of the rolls and to produce the aimed microstructure deformations with the required shape and size.

On the other hand, professors Glowacki et al. (1995) established an integrated data model to predict plastic flow, microstructure evolution, and heat transfer during shape rolling [27]. The formation of this has aided in significant cost reduction and gave estimates for heat readings to produce the required microstructure for good decent quality products. FORTRAN 77, a computer program was made to incorporate this mathematical model created by them, which also used finite element modeling in 2-D and 3-D planes using a generalized plane strain method. Major microstructure evaluation models were taken from Roberst et al. [72, 73] during the ASM International conference (1983) for changing the rate of austenite grain growth in the reheating process. This required many static and kinetic equations for grain growth which were experimented with again by the University of Mining and Metallurgy in Poland and the results agreed with previous data.

Additionally, another important use of simulation was performed on the Q235 steel for thermo-mechanical modeling through shape rolling and the results were conclusive, as determined by The China University of Petroleum. The formation of austenite grains in microstructure predicted theoretically was closely achieved in the stock however grains were less refined in the flanges [74]. Further models of recrystallization after heat treatment showed only an inhomogeneous grain structure at the starting area of the stock where the largest deformation happens. However, after computing all mill rolling velocities and other forces, the mean values of displacement of grains were close to the predicted ones [75]. The forces cause all the slip systems to align in a way that strengthens the material as a whole. Hence, making steel-based products a good utility for shape-rolled products.

Ring rolling

The process of ring rolling [75, 76] had a major development in the twentieth century, that consisted of bulk metal shaped in a 3-D formed ring with its inner diameter and circumference being increased and height adjusted to the desired requirement of the manufacturer [77]. Essentially, for basic ring manufacturing, the process requires 3 rolls: a forming roll (generally driven), an edge roll (driven), and a mandrel roll (idle) [78]. The forming roll acts on the outer surface of the ring causing it to decrease the cross-sectional area whereas the mandrel provides a support fixture to provide force indirectly during the pulling process. The edge roll works on a different axis to control the height and directionally pull the ring to get the required inner diameter [79]. The entire process is set at a specific temperature at which the microstructure quality of the ring is restored. As the need for better airplane engines grew during the Second World War, ring rolling was used in fabricating the fan case of these engines for enhancing the flow of air of the fan engines used in large commercial planes and aircraft.

The mid-nineteenth century was the beginning of the industrial revolution around the world. The manufacturing of cars [80], trucks, trains, and many more required precision-cut wheels which were extremely difficult to produce due to their circular nature. Regular hot rolling and forging could not produce impeccable wheels that were appropriately heat-treated too. In 1842, Bodmer et al. devised a hydraulically operated design for rolling large rings which were then constructed by A. Krupp et al. in 1849 [81]. This ring rolling process provided an economical alternative to all other techniques on account of lower material loss, smoother texture, better grain orientation, and minor deformations. Additionally, as technology ensconced on getting diminutive while offering the utmost possible features, products like small bearings and gear blanks became vital. The invention of bearings allowed minimal friction while granting maximum free rotation as its design imparts the use of perfect grooves in which spherical balls locomote [82]. Hence, ring rolling was utilized for the fabrication of numerous components, from large fan engines to small bearings in food blenders, accurately.

Current research

Researchers at Ohio State University found that the grain boundaries align with the surfaces of the ring, while deformation follows the curvature creating a matrix that is resistant to cracks and improves machinability. They discussed the efficiency of factory designs like the seamless rolled ring forging process that encompasses building the ring from a block to a fully heat-treated quality ring [81]. The radial-axial ring rolling process uses an oil hydraulic system that is fast, efficient, and is economical as it saves time, energy, and material usage. Improvements in this technology later triggered unique product-specific processes like ring gears, asymmetrical parts, different grooves in mandrels for complex shapes, an increased number of rollers contact points for dimensional accuracy, and miniature products.

Meanwhile, the Manchester Institute of Science and Technology experimented on a new successful process for cold ring rolling to make rims and gears of exceptional strength and different alloys. The procedure incorporated an enclosing die with lubricant distributed copiously around the part to minimize die wearing and stresses induced in the teeth, hence saving cost and time [77]. The utilization of a multi-step process allowed for stability and control of the diameters and other allowances in the ring. The incremental deformation of the grains in a particular direction increased strength based on the plastic deformation through stresses induced by the rolls. Thus, making the grains finer, lattice stronger, and augmenting the quality of the metal. Further study in the theoretical analysis of pressure forces to be given on axes of the ring (both on the axial and radial axis) aided information of a new control system that predicted torque, rolling force, and power dissipation by the apparatus used [78]. With this, the segregation of ring rolling was done into 2 origins: single mandrel and multi mandrel.

Theoretical modeling overview

Material enhancements, in the following years like alloys and composites, have established rampant growth. The Wuhan University of Technology, Chongquing University, Xi'an Jiaotong University, and Northwestern Polytechnical University have researched many alloys and processes regarding ring rolling processes. Their findings in 2019 have highlighted alloys like GCr15 bearing steel of high wear resistance and hardness and workability due to good carbon gradient after ideal austenitizing and other heat treatment processes. Additionally, AZ31 (Mg-3Al-Zn) alloy used in hot ring rolling produces a refined ring, grain size, and texture. The final product displays anisotropic properties with high ductility and double-peak texture and tilted basal poles from the center. Northwestern Polytechnical University developed a polycrystal plasticity model for cold ring rolled products which predicts the texture of microstructure/grains after deformation. A VUMAT model was incorporated in a 3-D finite element simulation producing approximate stress-strain and shear strain models for deformation during the rolling process. Additionally, Xi'an Jiaotong University proposed an improved rolling process for spline shafts countering the pre-existing problems like disorientations in the tooth. Enhanced tooth divided flow method (TDFM) while processing is used to negate the effects of large rolling blank diameter on tooth filled quality, loading the rolls, and error on the pitch.

Increasing demand in aerospace engines parts, gear sprockets, nuclear reactor parts, pressure vessels, bearing brushes, and other important industrial applications has made ring rolling processes pivotal. Though some applications like rocket parts require extensive investigations and mandate high accuracy, hence the development of the finite element method of simulation software of exceptional performance and reliability can aid. The basic computation of this software is governed by various formulas that simulate working performance in different situations under stress with the use of mesh algorithms. Computer-aided design/manufacture software programs [83, 84] such as Q form and Simufact provide optimal working conditions to reduce the cost for development. In addition to these, the advantages of the software include full simulation of the ring and rolling process with the prediction of final shape by setting parameters and the approximation of fiber and macrostructure and temperature profile on the ring surface.

Periodical straining rolling

The evolution of gradient structures in metals have made it possible to attain extensive properties in the same materials itself and currently, as reported by XiaoLei et al. [85], the gradient microstructures are being pioneered in engineering metallic materials such as steel [86], aluminum [87], copper [88], and other alloys, which resulted in a significant enhancement in the ductility and other mechanical properties of the processed materials. Xiao Lei et al. explained that the macroscopic strain gradient is particularly induced when the grain-size gradient is applied with uniaxial tension. Now, the conversion of the induced uniaxial stress to multi-axial stress is preferably there due to progression and propagation of unsuited deformations along with the depth of the gradient [85]. Hence, concluding that the mechanism or technique of creating gradient structures is monitored by the resulting severe plastic deformations with predetermined strain gradients, which results in an up-turn in strain hardening rate [89, 90].

The demand for lightweight materials is ever increasing due to their wide range of applications in the automotive, aviation, marine, and wind energy industries. The lightweight materials such as metallic alloys of aluminum and magnesium have gained worldwide attention because of their extremely striking characteristics such as high specific strength, recyclability, and lightweight. Efforts have been made to further enhance the strength of these metallic alloys by forming an ultrafine grain structure, which is not attainable by conventional operations and is done by the use of severe plastic deformation (SPD) methods. These SPD techniques, as sliding friction treatment [91], surface mechanical attrition treatment [92], surface mechanical grinding treatment, high-pressure surface rolling [93, 94], skin-pass cold rolling [95], equal-channel angular pressing (ECAP): severe plastic deformation to produce very fine-grained material, and multidirectional forging [96–100] have been examined. However, accomplishing enhanced strength by the use of SPD methods comes at a cost of reduced ductility of materials in the process. Therefore, a new and unconventional method was required to produce a more efficient amalgamation of high strength and good ductility. This ductility and strength combination in the gradient structure could be attained by the evolution of grain structures achieved by a systematic change in the grain size along with the depth on a macroscopic scale from micro to the nano-scale structure throughout the thickness of the processed metallic material [101]. Strain hardening is extremely critical for enhancing the ductility of the material, hence a special rolling technique, namely the incremental rolling process, is used to attain the desired strain gradient through a given sheet thickness.

Simulation methodology

In general, the PSR process has two stages of deformation as depicted in Fig. 6 below. At the first rolling stage, the metallic sheet is made to roll with pinion-like or worm-gear-like grooved roll and flat roll, resulting in the periodical formation of rack-like small grooves on the metallic sheet in the process. At the subsequent rolling stage, the previously formed rack-like metallic sheet with microscopic grooves is flattened by the use of conventional smooth-work rolls as in Fig. 6. Hence, the final smooth surface sheet with localized strain distribution because of the indented small grooves of the periodical straining roll shapes is obtained.

In the papers [102–105], the authors have devised a novel incremental rolling process called "Periodical Straining Rolling" (PSR) that generates strains in the microstructure and texture gradient of the metallic sheet in the process. Shimo et al. periodically localized plastic strain in the processed metallic sheet by the use of a pinion-like or worm-gear-like grooved roll. The PSR process is aimed to radically control the strain distribution. Yama et al. from the Metallurgy Department of Tohoku University proposed unique insights [102] on how to seek an optimal tool design for strain distribution on the microstructure and texture gradient evolution by examining the effect of various tools profiles of the PSR process. Recently, Nosov Magnitogorsk State Technical University under the Russian Federation also performed an experimental study suggesting the combined use of symmetric rolling with microscopic grooves of work rolls, and asymmetric

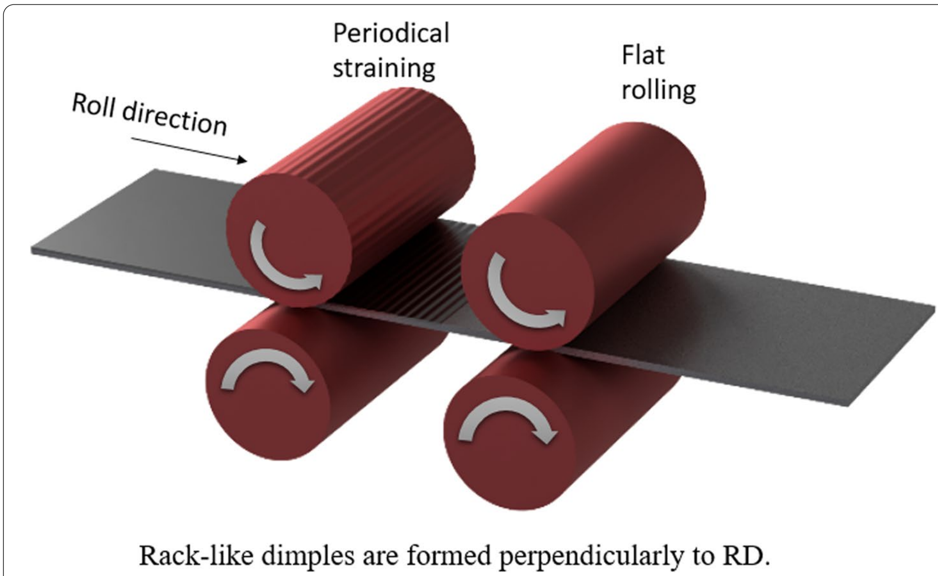

Fig. 6 Schematic illustration of the two stages of periodic straining rolling (PSR) process

cold rolling, to stimulate extremely high strain gradients in the aluminum sheets [105]. Studies have been conducted to investigate the thickness reduction per pass, effects of microscopic groove rolls, roll speed ratio, contact friction coefficient, etc., by the use of rigid-plastic finite element analysis [102–104]. By replacing the conventional smooth roll profiles with worm-gear-like grooved roll profiles, the PSR process can be adapted in the prevailing strip rolling mills with great ease.

Research studies have proved that the PSR process has sufficient potential to control the microstructural and texture gradient of metallic alloy sheets. Spatial microstructure distribution and texture evolutions in the longitudinal, as well as the direction of thickness, can be provided by the roll profile design of the PSR process. Therefore, the PSR process can be deemed significantly effective in improving the mechanical properties like larger elongation to failure, reduced yield stress, etc., as compared to the traditional flat rolling process [104, 105].

Skew rolling

The manufacturing of steel/metallic balls has escalated considerably due to the rise of automotive and robotic technology during the Industrial Revolution [47]. According to the American Bearing Manufacturers Association (ABMA), bearings serve as the main component of many mechanical systems to translate motion smoothly. For a bearing to function correctly, all the balls must be of the same size, shape, and material as they must withstand an equal force without being deformed or cracked. Uneven sizes may result in improper and wobbly motion that may damage other connecting parts. With the current standard of technology, skew rolling mills are a dominant industry in this market where material wastage is minimum [32] and the product formed is semi-finished with slight to no imperfections. This process is done through two specially designed rollers shaped like large threads (helical-shaped grooves) that rotate continuously in opposing directions. As the hot red stock enters at one end of the roll, they are cut into equal round pellets by the crests of the roller and form a spherical shape in the grooves as they keep on passing through the rotating threaded rolls before they eventually come out [32]. The crests of the threaded rollers have no contact points to each other; however, they are remarkably close to cutting the stock bar into equal pieces and moving them forward due to the opposing motion provided by the rollers. Skew rolling exhibits the qualities of both metal forging and metal rolling.

M Bellman et al. patented this skew rolling process in 1971. One of the main breakthroughs of this setup was the helical flanges, which were altered in their width and height when the billet progressed with the motion of the roller at the ends [86]. The final flange is more protruded with knife-like ends that disconnect the balls into individual pieces. Secondly, the design allows the constant volume of the material to be closed for rolling, with precise shape and stroke of helical grooves at the rolls in obliquely inclined axes consistent with the lead angle. In this process, through Fig. 7, we can observe that a lot of strain and heat acts on the flanges with the cutting necks as the reduction ratio is interdependent on it. In case of the reduction ratio not being followed (when billet diameter is greater than required), the deformation causes ovalization at the cross-section and, hence, the formation of internal cracks.

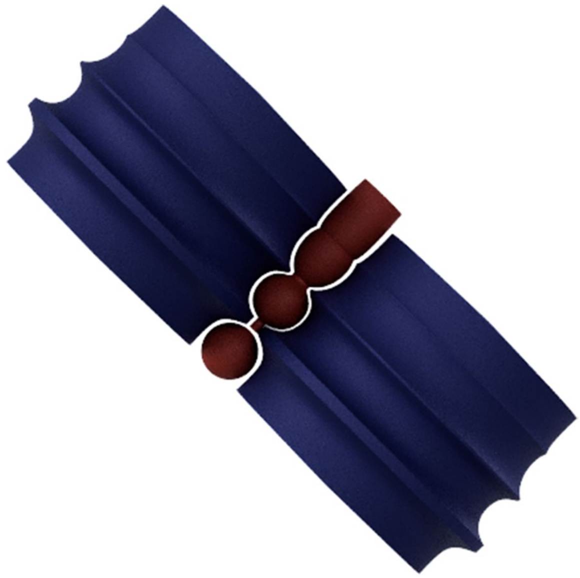

Fig. 7 Illustration showing strain on the flanges in the skew rolling process

Theoretical simulation overview

J. Tomczak et al. presented their research results (2018) in skew rolling of balls under multiple helical impressions, both theoretically and experimentally [106]. Simufact forming software was used for three-dimensional numerical analysis based on FEM under complex thermal analysis. Analyzation of metal flow at different periods under rolling, strain, temperature, and forces of the ball were studied. Results were experimentally tested in the laboratory, taking into consideration the same process parameters including temperatures and strain distributions that were defined. The results highlighted maximum deformation in connector areas due to elongated contact time at heated temperatures allowing the hardening of the skew balls after the process. The arrangement of material and tools was determined to be an especially crucial factor in the quality and precision of the balls up to ± 2 mm. The internal deformations of the ball were not uniform due to the disparity in tool and ball temperature (the tool is colder) thereby causing heat transmission [88]. Another research displayed the lowest strain in the center of the balls with temperatures around 940–1040 °C, whereas pre-calculated values were observed to be around 860 °C [89]. This paper suggested a 2-roll based process that successfully simulated crack-free, precise balls with better uniform deformation than the 3-roll helical process but at higher temperature and radial force.

Moreover, the University of Science and Technology in Beijing examined the stress in skew rolling to characterize material AISI-1045 and deformation behavior using ANSYS/LS-DYNA. Rotation around the major axis of the helical tool caused the workpiece (billet) to deform plastically and reduction increased slowly from the surface to the center areas. The forces at the beginning of the roller to the end changed from compression to tensile at the center area and in a transverse direction (for the ball), the tensile stress erased the residual stress due to counter-movement in the radial direction that finally produced a hydrostatic tensile stress state [90]. Similarly, the Kushan University of Technology in Taiwan performed a numerical analysis for the rolls of the skew rolling, and the results matched with all other previous studies. A major improvement in this process was done using the parametric equation of forming rolls which emphasizes the relation profile and wear of the roll. This, including a suitable selection of materials, results in an improved design of the roll; hence, leading to better quality products.

Thread/gear rolling

A gear is a mechanical device, having an equally cut teeth-like structure that meshes with other gear structures in rotatory motion allowing motion and transmitting torque [37]. Gears have existed for a long time in human history, especially since the advent of clocks. With the progression of years, gears have been a part of most mechanical devices and given has inspiration to many other applications like threading [107]. However, for devices like these to function, the fabrication of threads and gears should be much more accurate. Hence, for fabrication, several modern approaches like subtractive methods (cutting, grinding, etc.), forming methods (forging, rolling, molding, etc.), and additive methods (3-D printing) are in use [108]. Even after this, due to the current situation of shortage of materials and environmental factors, it is necessary to maximize the usage of raw materials. Taking that into consideration, deformation methods too, like hot and cold rolling, are majorly used in the industry to use material efficiently and save expenses [106].

In 1910, Harold Anderson et al. invented a full-fledged industry-purpose deformation the rolling machine that could make gears and thread by the application of compression and stress using 3 rollers and would also include finishing off the final part [85]. In this cold forming process, a cylindrical blank (having a diameter between the major and minor diameter of the expected thread) is inserted between 2 rotating disc dies with the reverse thread pattern so that the required thread pattern is mirrored on blank as depicted in Fig. 8. Rolling dies are used to penetrate the blank surface with compression stress and displace the surface radially outward to form the pitch and crests without wasting any material. Here, the grain structure is not severed but is deformed to the unbroken grain contours of the thread. Additionally, grain density at the roots is exceedingly high, increasing strength and wear resistance in the threaded and lower regions as well, as many slip planes are close to each other in this region. The later stages involve finishing the threads at roots, crests, and flanks to eliminate surface imperfection. Which could be the cause of failure later, since compression at the roots is maximum.

Current research and simulation results

The research scholars at Fraunhofer Institute for Machine Tools and Forming Technology (Germany), especially Dr. Reimund Neugebauer, have expansively examined the gear rolling processes. In many research articles, different rolling processes have been compared, and a benchmark has been declared for this rolling process bridged into 3 major steps: rolling phase, penetration phase, and calibration phase [86]. Two materials, 16MnCr5 and C15, were analyzed due to their wide practice in this application. In the initial rolling phase, the threads of the tool rollers rotate in the opposite direction and pitch into the workpiece diameter to set up controlled points.

During the penetration phase, compressional forces are radially applied by the tools into the workpiece for deformations and obtaining the required parameters. The calibration phase includes tuning the finished gearing, to acquire uniform tooth filling and roundness. Among all of these processes, FEM simulations and analysis were also carried out using Transvalor software Forge. Now, these simulation results displayed higher stresses and bending load in rolling tools and other concerning supporting components, which gave tolerances due to repeated oscillations. However, induced stress in the workpiece ranged from 200 to 950 N/mm^2 that was lesser than that of the rolling tool [87]. Further, the grain contours (orientation) and density for both materials were high at the crests, flanks, and roots. Thus, providing excellent strength properties and making both highly recommended for such applications [88].

Tube piercing

A substantial rise in demand for pipes began between the early to mid-twentieth century, where Mannesmann's invention of seamless tube production in 1885 became prevalent and was in heavy demand [109]. In this technique, the rotary tube piercing process is used. This consists of creating tubes through compression, in a way that stresses are concentrated at the center of the solid, then penetrating it from the center using a mandrel which opposes the forward motion of the solid as shown in Fig. 9. The compression is usually done using rollers that apply stresses causing crack propagation at the center. Thus, make the piercing processes easier and with lesser force [110]. Furthermore, the shape of the mandrel used is tapered-conical, with the pointed area directed to the solid tube for penetration with additional pressure, and

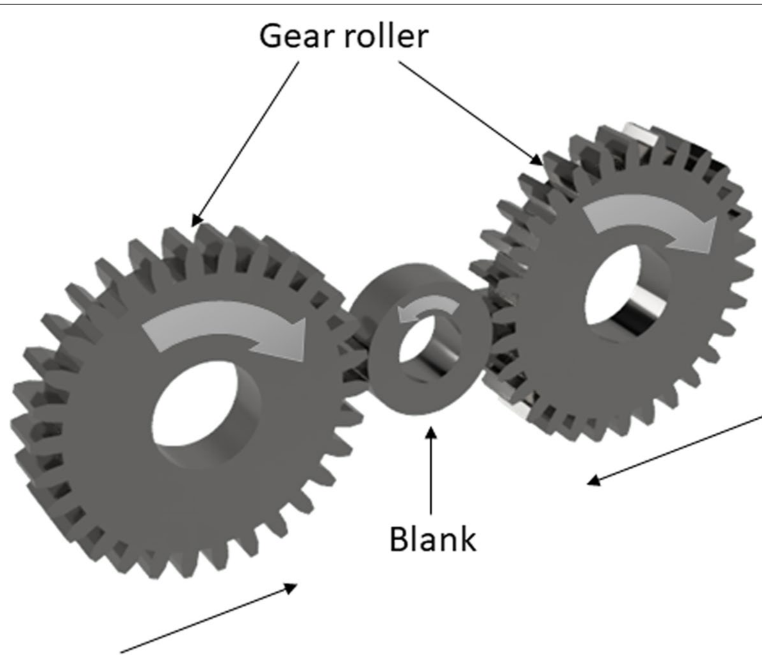

Fig. 8 Cold forming process illustrating reverse threading pattern on blank

its end diameter is equal to the inner diameter of the tube to be produced. The rolls are usually set at a derived angle with contact points to provide enough rotation, translation, and friction for the billet so that it undergoes circumferential and central deformations and cracks through the longitudinal axis to form a void which is then pierced [111, 112].

Theoretical modeling

Mannesmann-Stefiel piercing process is also known as tube piercing. This piercing process first elongates the grain through the rollers by compressing them and then the mandrel penetrates the cracks in the grains. This makes the grain anisotropic due to the dislocations based on the plasticity of the metal. The strain is maximum at the internal and external diameter of the tube just after piercing by the mandrel and the metal temperature is maximum at the contact area of the roll/disc and just before penetration at the center of the workpiece. Further annealing and strain hardening processes are performed on produced tubes for strengthening and improving grain quality [111]. Taking all of this into consideration, many improvements have been made in the past 50 years including formulating stress, strain, and temperatures using finite element method analysis.

New simulational data analysis and results

Professors at the Northwestern Polytechnical University in China performed a rotary tube piercing (RTP) process on a bi-modal microstructure titanium alloy (Ti-6Al-4V). This research pertained mostly to thick-walled tubes as they have many drawbacks in regular forming processes [109]. The main advantages of this include high material utilization, low forming loads, and good fabrication efficiency. The process involved finding an optimum feed angle (8°–15°) and cross angles which affects the piercing speed and speed of the billet. Furthermore, XRD microscopy results analyzed and represented through Image pro-plus software had highlighted 3 different microstructures in the tube at different contact points that include a primary alpha phase, a lamellar alpha phase, and a beta matrix by the isothermal compression and by slip plane deformations in the

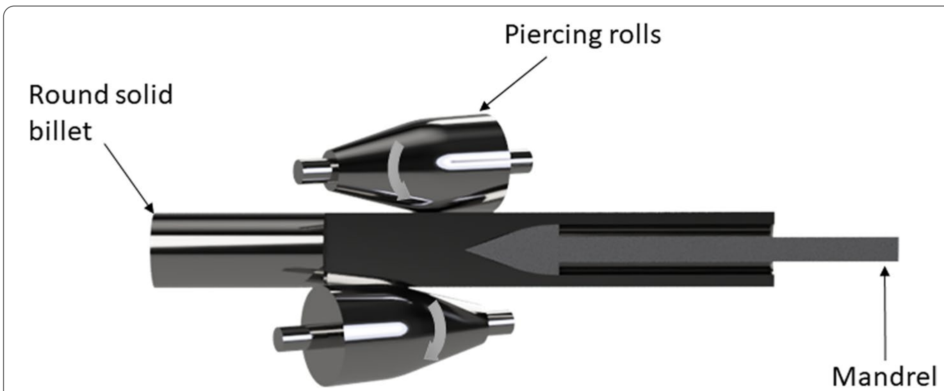

Fig. 9 Cross-section view of the tube piercing process depicting the roller compression and mandrel insertion in the workpiece

inner part of the workpiece. FEM is used to display the material flow and temperatures during the RTP process and torsional deformation is exhibited at the outer surface (by the rolls) which is directly proportional to axial velocity. The outcome given for the best quality titanium alloy was at a reduced rate of 6% or higher for the smooth progression of the piercing process and a roll speed of 30–60 rpm as higher speed corresponds to temperature rise which additionally will not provide the required bi-modal microstructure for maximum strength.

Alternatively, the Lublin University of Technology conducted an extensive analysis of tube piercing processes in 2 roll and 3 roll mills in 2019. All of this was performed using the Forge NXT software which helped in analyzing the distribution of torque, rpm, axial stress and loading, strain, and temperature between 2-roll and 3-roll piercing processes [110]. This FEM-based numerical modeling was inspired by Urbanski et al. in their research on rolling mills by FEM in 1993. However, in most calculations, the friction coefficient is governed through the Coulomb model, whereas in practical conditions, the observations differ and temperatures are slightly higher than those theoretically calculated. Feed angles on the rolls were between 8° and 16° determined by Zhao et al. in 2014. Through the experiment, Pater et al. found 3-roll mills were 30% faster than 2-roll mills to produce thick tubes as the circumferential flow is increased in 2-roll mills at the surface layer, consuming more time and affecting both strains and energy consumption. Furthermore, 2-roll piercing gave a higher probability of cracking due to material racking, causing added tensile stress in the axial area and ovalization of the cross-section of the workpiece.

Challenges or limitations associated with incremental rolling

There has been a surge in the research related to the applications of incremental deformation due to the ever-increasing needs of the industry. The concept of incremental deformation is incorporated in most of the rolling processes in diverse ways and has helped in the development of these processes over the years. Yet, these processes have not been perfected and there is room for further improvement.

In the case of ring rolling, which is used for manufacturing bearings and turbines [17], the parts manufactured from cold rolling have a tougher microstructure and grains than those which are produced by hot ring rolling. Moreover, these components made with hot rolling also require heat treatment and post-processing to improve their strength and surface finish. Additionally, it is difficult to create asymmetric parts using ring rolling with the existing techniques [19]. Thread/gear rolling also has a few challenges such as roll synchronization, gauging problems, and bad surface finish of the gear tooth. And sometimes, the helix angle is mismatched due to which the problem of screw jacking is created. Regarding shape rolling, the major problems are that the microstructure deformations are less refined at the flanges [27] and the rolls need to be aligned perfectly to avoid defects. In the skew rolling process, which is used to manufacture springs and rolling bars to name a few, it is impossible to make hollow parts [113]. A lot of precaution is taken to make sure that the rollers are wear-proof and placed parallel to each other to prevent voids in the final product [33]. While the tube piercing process is prone to internal cracks and voids [40] so the plug used needs to be extraordinarily strong and surface hardened, and the guide roll should also be aligned properly to avoid variable thickness of the rollers. In the case of periodical straining rolling, the changes in the microstructural and the texture gradient can affect the properties of the final product and have to be monitored carefully.

To summarize, every rolling process has challenges that are specific to them, but some, for instance like the alignment of rollers as well as their velocity, angle, temperature, and roller health, play a vital role in every rolling process and affects the final product manufactured, and it is difficult to monitor them efficiently using the traditional mechanical technology and gadgets. Although there has been significant development in this field every year, there is still a need for more research and studies to develop these processes further.

Conclusions

Incremental rolling processes allow localized plastic deformation based on flexible and locomotive external tooling and the friction thus generated during the process causes the temperature rise to further increase the workability of the metals used. In this review paper, we discussed a variety of rolling processes and how incremental deformation plays a vital role in modern manufacturing techniques. As established before, certain boundary conditions have to be maintained to reduce and prevent any material wastage or tooling damage. Hence, this process is widely studied to check for operations where improvements can be made to make them more efficient.

1. *Flat rolling* is the oldest rolling process and hence forms the basis of various new techniques that have been developed over the years. The fundamentals of incremental rolling remain the same in these processes but they are altered either by changing a few steps or replacing certain components for targeting specific applications.
2. *Corrugated flat rolling* process includes modification of the rollers which induces grain refinement and enhances the mechanical properties of the material. This process is used largely to join two different material plates along with their thickness reduction and the resulting output has increased tensile and tension-shear properties owing to the well-bonded composite interface. CFR has replaced the conventional flat rolling process as it has a wider range of materials and better bonding.
3. *Riblet rolling* is a unique incremental deformation process that uses an irregular-shaped riblet roller to transform flat surfaces into a shark-fin shape in order to reduce the wall friction by increasing the surface area. Although there is still room for improvement in this process when using it for large riblet fields with various contours.
4. *Shape rolling* was developed in the last century to assist in the huge demand for beams and sections in the construction sector. Over the years, studies at various universities have led to the development of empirical formulas for force and torque to be applied during this process to get accurate shapes efficiently and get a better understanding of the grain microstructure that is achieved. Research has improved this process greatly and the simulation results almost match the real-time tests, which widens the applications of this process.
5. *Ring rolling* process was developed predominantly to manufacture circular and cylindrical components which were costly and difficult to produce by existing processes

with precision. Studies depicted that in this process, the grain boundaries of the material align with the surface of the ring which makes it resistant to cracks and also improves its machinability. Ring rolling has become one of the most commonly used processes and has its applications in the aircraft, aerospace, and railway industries to name a few.

6. *Periodic straining rolling* technique involves the formation of gradient structures by sharp plastic deformation and enhanced strain hardening rate. Unlike many conventional processes, PSR increases the strength of lightweight materials without reducing their ductility.
7. *Skew rolling* is a very important incremental deformation process that is mostly used to produce the balls in the bearings. Research in this technique has shown that the internal deformation in the ball is not uniform owing to the difference in the ball and tool temperature at different regions which resulted in the lowest strain at the center of the ball. The deformation was more uniform when a 3-roll helical process at higher temperatures and radial force was performed.
8. *Thread/Gear rolling* which as the name suggests, is used to produce threads and gears with a rolling process that is cost-effective and has less material wastage. This process produces strong edges which have increased wear resistance due to high grain density. This is essential in the applications of these components.
9. *Tube piercing* technique is used to make hollow pipes or tubes. Various studies have been performed on this process over the years using simulation software to find the right machining parameters for different materials to get the best output with the least material wastage, high strength, and low cost. Later studies also suggested that a 3-roller technique is more preferable to a 2-roller since it has a lesser probability of material cracking, reduced ovalization of the cross-section of the workpiece, and is 30% faster when producing thick tubes.

Efforts are still being made to improve these incremental deformation processes further and develop new techniques for specific applications. Most of this experimentation is done through the use of CAM, FEM and simulation software to save time and money.

Abbreviations

FEM: Finite element method; CFR: Corrugated + flat rolling; RD: Rolling direction; TD: Transverse direction; IMC: Interfacial intermetallic compound; SPD: Sever plastic deformation; CFD: Computational fluid dynamics; BEM: Boundary element method; FFT: Fast Fourier transformation; CFR: Corrugated flat rolling; IBF: RWTH Aachen university Institute of Metal Forming; AIA: RWTH Aachen Institute of Aerodynamics; TDFM: Tooth driven flow method; PSR: Periodical straining rolling; CAM: Computer-aided manufacturing; RTP: Rotary tube piercing; ECAP: Equal channel angular pressing.

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Authors' contributions

P.A., S.A., N.B., U.S.S., and A.K. contributed equally to this work. P.A., S.A., N.B., U.S.S., and A.K. wrote the whole manuscript. U.S.S. and A.K. drew all the figures and tables. P.A., S.A., and A.P. reviewed and edited the paper. P.A. and A.P. conceptualized the work. All authors read and approved the final paper.

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