ANALYSIS OF PROFILED RING ROLLING

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MEHMET HALİL AKCAN

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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ABSTRACT

ANALYSIS OF PROFILED RING ROLLING

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Bearing outer rings are aimed to be produced by profiled ring rolling instead of turning. Bearing rings produced by profiled ring rolling as a cold metal forming operation, is anticipated to have longer fatigue life. Material hardness, resistance to dynamic loading and surface quality are good advantages for cold formed products. These advantages shall lead to longer life for bearings. Application of cold roll forming to the final shaped product includes studies such as creation of simplified simulation models, making three dimensional simulations and experiments to verify the results. Details of the bearing ring is a challenging process to be directly filled by workpiece during rolling. Therefore, a special shaped preform is needed for each final product. This preform shape is to be manufactured by turning by shape and dimensions acquired from trials made with simulation models. Production of full profiled bearing rings will be an original production method.

Keywords: Finite Element Method, Profiled Ring Rolling, Ring Rolling, Bearing, Metal Forming

ÖZ

PROFİLLİ BİLEZİK OVALAMANIN ANALİZİ

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Tez Yöneticisi: Prof. Dr. Erman Tekkaya

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Tornalama ile üretilen rulman bileziklerinin ovalama ile yapılması amaçlanmaktadır. Soğuk metal şekillendirme prosesi olan profilli ovalama ile imal edilen rulmanın ömrünün daha uzun olacağı tahmin edilmektedir. Soğuk metal şekillendirme proseslerinin genel bir özelliği olarak malzeme sertliği, dinamik yüklemelere dayanımı, yüzey kalitesi daha iyi olacaktır. Bu özellikler sayesinde ömrünün uzayacağı düşünülmektedir. Soğuk şekillendirmenin nihai ürüne uygulanmaya çalışılması, basitleştirilmiş simülasyon modelleri ve üç boyutlu profilli ovalamanın simülasyonu ile yapılan deneylerin sonuçlarının karşılaştırılası çalışmalarını içermektedir. Ovalama işlemi ile profildeki kapak yuvası gibi ayrıntıların doldurulması çok zordur. Bundan dolayı profile uygun bir ön şekil verilmesi amaçlanmıştır. Tornalama ile yapılacak olan bu ön şekil, sonlu eleman analizleriyle bilgisayar ortamında denemeler yaparak, tespit edilecektir. Çalışma sonucunda soğuk ovalama ile nihai profil şeklinin verme işlemi özgün bir üretim prosesi olacaktır.

Anahtar Kelimeler: Sonlu Eleman Yöntemi, Profilli Ovalama, Ovalama, Rulman, Metal Şekillendirme

To My Parents

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CHAPTER I

INTRODUCTION

1.1. Definition of Metal Forming

Metal forming is a kind of manufacturing process that the part attains a specified shape by permanent deformations through applied forces and impellent boundaries such as tool and dies. The external forces can be in the form of compression, tension, torsion, shearing, bending, drawing or a combination of the various forces. Usually ingots from simple shapes are formed using tools and dies. Shaping of the metal stock means plastic deformation throughout or some parts of the material stock. Plastic deformation is strain values due to stresses above elastic limit. Reason for this aforementioned plastic deformation is slips occurring between crystallographic planes of the metallic structure.

Metal forming processes are being widely used since early ages. Starting with hammering iron to make tools, war equipments such as swords or blades, metal forming has an immense history. Many advantages of metal forming processes are listed:

1. Utilization of metal is very high in some cases 100% material is used directly as final product.
2. Fatigue life of the formed products compares very much to the conventional production methods such as casting or cutting.
3. It is not affected with cutting tools' shorter life and risk of changing dimensions because of abrasion or breakage used in machining processes.
4. It is a robust process that can give same final shape and dimensions for high amounts of production.

5. Production cycle time is very low compared with chip consisting and many casting processes, since casting requires higher temperatures compared to hot forming in case heating is much significant in casting.

Metal forming technology is used in following areas; Aerospace, Appliance / White goods, Construction, Medical equipment manufacturing, Military, Rail car and rail car component manufacturing and Automotive...

1.1.1. Classification of Metal Forming Processes

In general terms, metal forming processes can be classified in terms of type and shape of formed parts and deformation zone. Classification is bulk-forming and sheet forming at first sight. Afterwards these also have minor branches as seen on Figure 1.

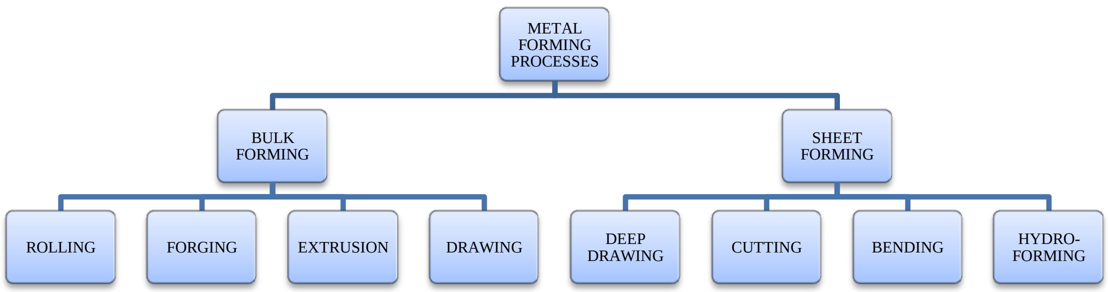


Figure 1 Classification of Metal Forming Processes [1]

Bulk Forming Processes involve large amount of plastic deformation. The cross-sectional area of workpiece changes without volume change. Shape of the deformation zone that covers the cross-section changes during forming of the material. The ratio cross-section area/volume is small. For most operations, hot or warm working conditions are preferred although some operations are carried out at room temperature. Subheadings are briefly defined as following;

Rolling: Compressive deformation process in which the thickness of a plate is reduced by squeezing it through two rotating cylindrical rolls [1].

Forging: The workpiece is compressed between two opposing dies so that the die shapes are imparted to the work.

Extrusion: The work material is forced to flow through a die opening taking its shape.

Drawing: The diameter of a wire or bar is reduced by pulling it through a die opening (bar drawing) or a series of die openings (wire drawing).

In Sheet-Forming Processes, the cross-section of workpiece does not change, the material is only subjected to geometry changes. The ratio cross-section area/volume is very high. Sheet metalworking operations are performed on thin (less than 6 mm) sheets, strips or coils of metal by means of a set of tools called punch and die on machine tools called stamping presses. They are always performed as cold working operations. However, there are new trends to warm the sheet before forming

According to working temperature forming operations are also classified as seen on Figure 2 where T_m is the melting temperature of the solid metal;

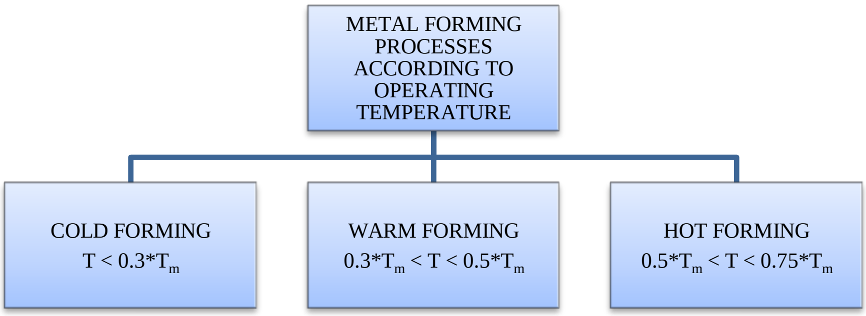


Figure 2 Operating Temperature Ranges of Metal Forming Processes [1]

Cold Forming, is a metal deformation process performed at room temperature namely below the melting and recyrstallization temperature. Advantages are dimensional accuracy, better surface finish, high strength and hardness of the finished part. Whereas; there is need for higher forces and power in addition sometimes annealing before process.

Warm Forming, is metal deformation performed at temperatures above the room temperature but below the recrystallization one. Advantages are lower forces and power, more complex geometries and no annealing process. However; another heating process is required before forming.

Hot Forming process involves deformation of preheated material at temperatures above the recrystallization temperature. Advantages of the process are forming of the large geometries being possible, requirement of lower forces and power due to low flow stresses and occurrence of no work hardening. However, process gives lower dimensional accuracy and surface finish, higher production cost and shorter tool life.

1.2. Definition of Roll Forming Process

In Rolling Process, thickness of the work is reduced by compressive forces exerted by two or more opposing rolls. Process produces continuous strip of metal through a series of contoured rolls. Accordingly, cross-section of the metal part is formed into a pre-determined shape.

Cross-section area of the rolled material is decreased in single direction or both directions while passing through the rollers. Aforementioned change leads to elongation in the rolling direction.

The nature of roll forming when cold rolling is applied; allows the finished part to be within very tight tolerances. Roll formed sections have an advantage over extrusions of similar shapes due to being generally much lighter and stronger, when having been work hardened in a cold state. Exclusions are observed when hot rolling is applied.

Roll forming has extended usage in areas such as the aircraft industry, architectural industry, electronics, and the automotive industry.

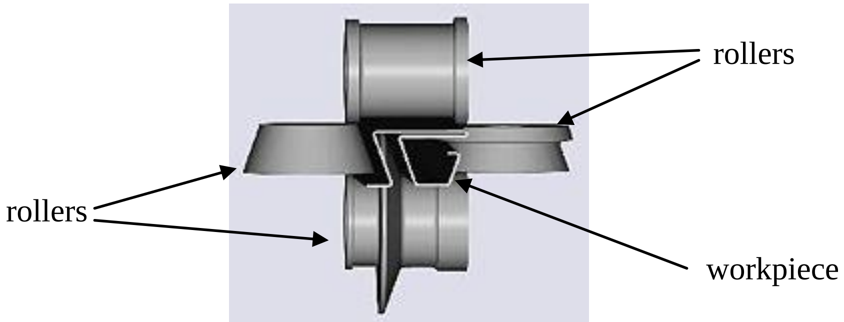


Figure 3 Roll Forming Stand [2]

1.2.1. Classification of Roll Forming Processes

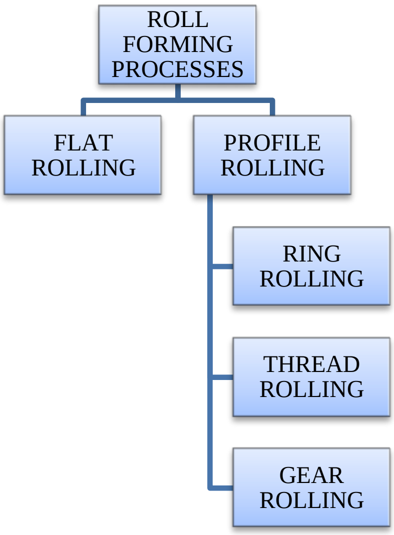


Figure 4 Classification of Roll Forming Processes [1]

Flat Rolling is used while rolling sheet metals or any cross-section without boundaries at prependicular direction to both rolling and rollers axis. At the same time; the rollers have no contours along their movement axis.

In Shape Rolling; the workpiece is deformed by a gradual reduction into a contoured cross section (I-beams, L-beams, U-channels, rails, round, squire bars and rods, etc.).

Ring rolling means, thick-walled ring of small diameter is rolled into a thin-walled ring of larger diameter. Thread rolling is used to form threads on cylindrical parts by rolling them between two thread dies. Gear rolling is similar to thread rolling with three gears (tools) that form the gear profile on the work.

In addition to the former classification, there is cold and hot rolling cases applicable to roll forming processes. Same benefits and unfavorable properties exist for each rolling case as told while classifying general metal forming.

1.2.2. Ring Rolling Definition as a Metal Forming Process

Ring rolling is a metal forming process that is being used for ring shaped industrial parts' production. Rolling processes generally involve area of the cross-section decrease while the total length of the product increases. Flat rolling processes need subsequent operations to obtain desired cross-sections after rolling process. In ring rolling process, as similar to the native rolling process, there is cross-section shrinkage and also increase in length resulting diameter enlargement in a ring.

As blank material, there is a ring; that normally has a constant cross-section around whole circumference. This cross section is also generally symmetric about the axial central plane. For specific final shapes forming cases, this initial cross-section might have special edge profile. In Figure 5, representation of blank ring and rolled workpiece is given. In ring rolling process, a ring blank is squeezed between two cylinders, one or two of which are rotated at the same time. A smaller cylinder is placed inside the workpiece ring. That means the diameter of the small cylinder should be smaller than the hole diameter of the initial blank ring. Another large diameter cylinder is placed at the axes of the blank ring and smaller diameter cylinder are in parallel while positioned at the same line. These two smaller and large diameter cylinder shaped tools used in the process are called as mandrel and form, respectively. Rolling relatively light pieces requires one large cylinder is rotated and the other is rotated by the effect of the workpiece. Whereas, larger diameter and heavier workpieces require both cylinders are rotated at the same time. Figure 6 dictates the rolling process with roll tools' movements.

Figure 5 Final ring workpiece (right) rolled from the blank ring (left)

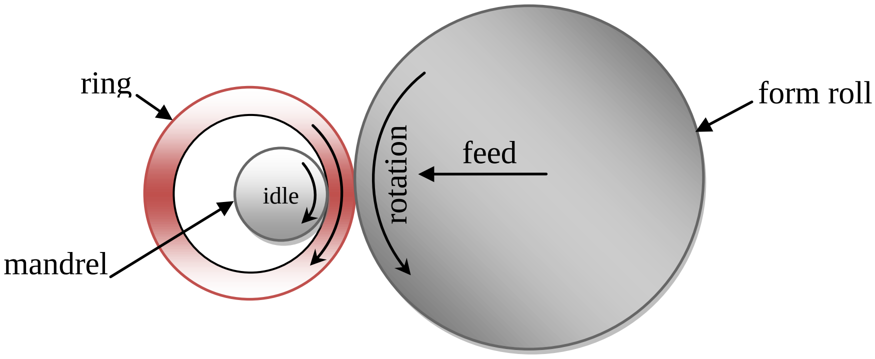


Figure 6 The rolling process with roll tools' movements

1.3. Motivation of the Study

Recent developments lead to usable results for ring rolling process. These developments can be grouped in two ways, one of which is the shape of the final formed part and the other is the type of additional cylinder tools used in the process. Final formed rings can be symmetric and asymmetric about the axial plane. Also final formed rings can be flat or can have profiles as a result of investigations being made. In accordance with the tolerance class of the blank workpiece, ring rolling can be classified as rough forming or final shape forming. Rough formed parts usually require subsequent processes as to catch the required dimensions and related tolerances. Investigations also led to additional tools to be used in the process as to improve process stability, quality of the formed shape, decrease ovality of the formed ring, eliminate surface or inner defects that can occur during the process, affect the final shape in a way that filling defects are minimized for profiled ring rolling and at last make the forming possible. Additional tools can be listed as side rollers and backup (guide) rollers. Side rollers are used to decrease chip forming on lateral surfaces of the rolled ring workpiece. Backup rollers are placed parallel to the axis of the workpiece at angular locations to decrease ring ovality. These additional tools are shown in the Figure 7.

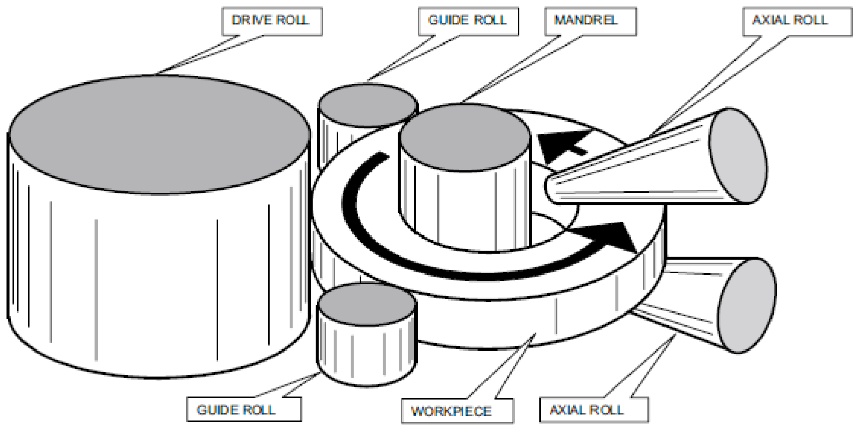


Figure 7 Additional tools in the ring rolling process [3]

1.4. Aim and Scope of the Study

Work in this research aims to apply profiled ring rolling in the production of bearing rings. Application of profiled ring rolling comprises near net shape forming. Therefore, forming tolerances are required to be compatible with machining (turning) process tolerances. This issue requires the blank material tolerances to be tighter than the final requirements. Conventional production of bearing rings include flat (non-profiled) ring rolling and then turning of the details that include bearing raceway and seal groove. Raceway and seal groove with all the surfaces turned during the process cuts off 60% of the material. This huge amount of material loss should be somehow eliminated. Therefore, main investigation results should look for both improvement in quality and reduction in cost.

By profiled ring rolling both the bearing raceway and seal groove shall be formed to the final shape details. This forming process requires a special shaped blank. Dimensions of the blank could be determined by trials at the shop floor. To find an alternative to this costly and time consuming process, work in this research aims to determine this blank shape by finite element simulation technique. Turning process does not require special tooling to produce the blank material for profiled ring rolling of bearing ring. On the other hand, turning of the details seal groove and maybe raceway requires special ground cutting tools. Therefore, overall cost reduction is also affected due to aforementioned benefits of profiled ring rolling.

Specific research is concentrated on finite element modeling of the profiled ring rolling. Several literature resources are investigated and coverage of them is reported. Application of profiled ring rolling in the production of bearing rings is studied and several experimental tests are performed. Design of preforms has been accomplished by simulations, to obtain ring profile completely filled with material. Test results and simulation results are compared in terms of residual stress and profile dimensions. The test results are also compared with the conventional manufacturing method of turning process. Experimental, simulation and conventional manufactured rings' profile measurement results are compared with nominal dimensions in detail and reported.

CHAPTER II

LITERATURE SURVEY

2.1. General Information on Profiled Ring Rolling

This chapter gives information about ring rolling for both modeling and application areas. Investigation subjects can be listed as; products manufactured by ring rolling, tools used, manufacturing technology by ring rolling, imperfection occurring, modeling techniques, possible results obtained from models, process design and parameter definitions.

Ring rolling technology was invented in Britain for producing railway wheels. Later, seamless ring producers applied the process to more kinds of products such as bearing rings [4].

Technique in the process is squeezing the ring in radial direction by decreasing gap between roll shaping tools as seen in Figure 8. Other selective tools are guide rolls and axial rolls. Guide rolls control the circularity and axial rolls control the ring height during the rolling process [5].

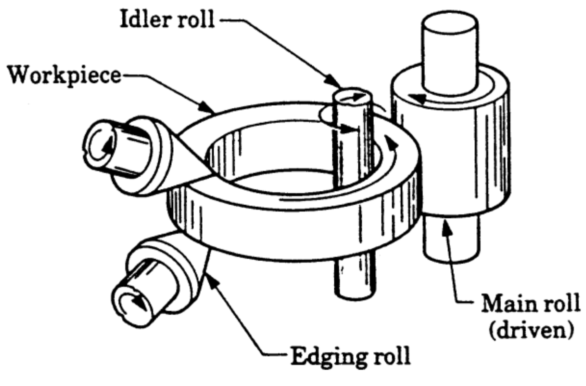


Figure 8 Schematic of a radial-axial ring rolling mill [5]

Authors mention about their research to verify comparison of product fatigue life between metal formed and machined bearing rings. They claim that bearing service life is improved by a factor of two in profiled ring rolled part. They state the reason as streamline layout differences in the final product. During turning the raceway, streamlines are being cut where in opposition to that profiled ring rolling helps to make streamlines positioned along the edge of the raceway resulting in anti-corrosion effect and fatigue life improvement with the aid of contact fatigue strength increase [6].

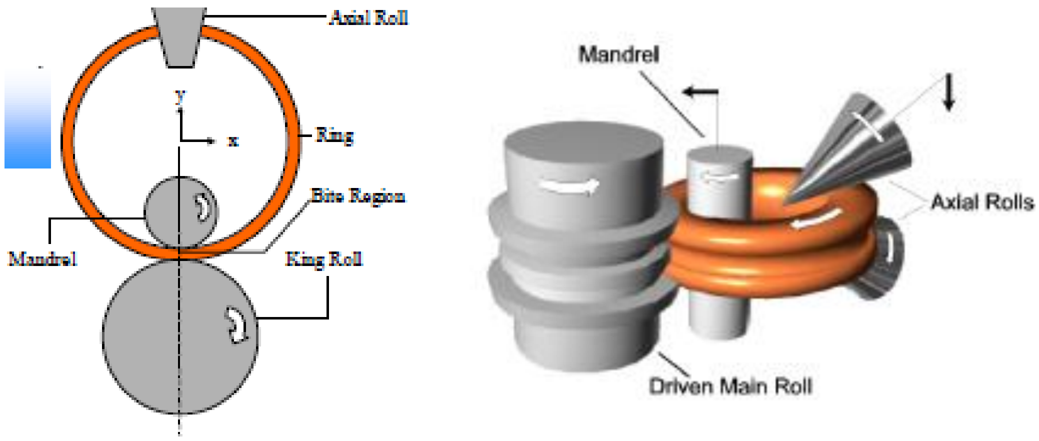
Wen et al. [7] gives similarities between rolling and ring rolling process as both have passes between rollers. Whereas flat rolling has number of rollers as number of passes, ring rolling process has only a set of roller. Authors also mention about ring rolling process having between five and fifty passes. It is also dictated that “The rolled section has a slimmer waists and the rolled section has more spread near the roll surface (top or bottom)".

Joun et al. [8] applied an axisymmetric finite element modeling approach to ring rolling. The aim was to design shape and dimensions of the blank workpiece used to form bearing rings by ring rolling process. That design process is mentioned to be a critical step in process planning since dimensional accuracy and surface quality is required while preform shape and dimensions may lead to unfilling defects, excessive burrs and immature tool fracture. Authors define a design parameter that is ratio of spread to diametrical expansion. Ring rolled products and their preforms are generally axisymmetric workpieces.

Song et al. [9] described the ring rolling process as small deformation along the radial thickness with larger deformation along the circumferential direction occurring. Accordingly, inner and outer surfaces of the ring achieve higher level of strain than the mid-plane of the ring section. In addition, the inner surface achieves higher strain than outer surface due to smaller diameter of the mandrel. Thinking about temperature coupled effects gives an observation of temperature drop at the outer surface is greater due to larger area of contact between the ring and the form roll and the larger thermal mass of form roll.

Sun et al. [10] gives the fact of guide rolls' controlling the ring circularity and stability of the ring rolling process.

Alfozan and Gunesakara [11] talks about the main process advantages of the ring process; that it gives uniform quality, smooth surface finish, close tolerances, short production time and relatively small material loss. And other general process conditions are two set of rolls requirement of which are a radial set to form the ring material and an axial set of rolls which need to exert sufficient force to enable rings' position fixed. Ring rolling process is schemed in Figure 8.



(a) (b)

Figure 9 (a) Schematic of Ring Rolling Process (b) 3-D View of Ring Rolling Process [11]

Wang et al. [12] talks about the fishtail defect which occurs along the circumferential sides of the ring as seen in Figure 9 that means the sag region at end-plane. That region is placed at side faces of the ring that is not touching mandrel and form rolls. This defect is found to occur without usage of axial rolls. Outer diameter growth rate of the ring increases with rolling progression due to fixed feed rate of the driver roll. Rotating cylindrical tools are also driven at constant velocities are the things also mentioned by the authors.

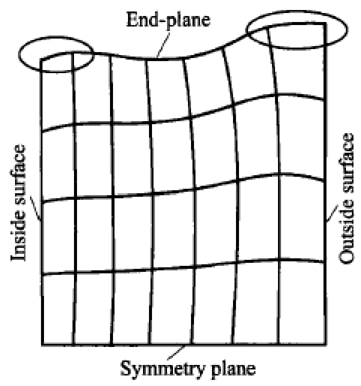


Figure 10 Cross-section of final ring [12]

Utsunomiya et al. [13] gives the clue that the ring vibrates irregularly only at the beginning of the rolling then stabilizes.

Friction effects are studied by Boman and Phontot [14]. They found that minimizing friction is good to reduce force and energy in ring rolling but sufficient amount of it is required to have ring rotated between rolls. Effective lubrication improves product quality without surface defects and tool life is extended with the help of wear reduction and insulation effect.

Adoption of process design software for ring rolling is established by Szabo and Dittrich [15]. The software calculates blank dimensions, rolling sequences, NC codes for designated machines. The main aim is to think up the manufacturing process in an industrial viewpoint so calculation, scheduling and quality control may all be adapted in a single program.

Tiedemann et al. [16] describes the process is flexible since parameters such as ring/tool geometry, feed rate have effects on formed shape and forming force. Profiled contours can be processed with rolling so that machining can be cut off to some extent. Forming forces are small with the aid of partial forming zone. Authors also complement the process against casting, closed-die forging and machining. But it is claimed that large quantity of workpiece is required to compensate tool costs and set up time. Tangential flow is more effective than other directions.

Han, Hua and Lan [17] tried to apply ring rolling to a conical ring with inner steps. But less-profile filling and shrinking-drawing defects were observed. Therefore, they acknowledged the process could be still implemented by forging, flat rolling and machining due to too many defects occurring during rolling trials.

Yan, Hua and Wu [18] think about the feed rate determination during rolling and put up a theory of ring outer diameter growth rate to be constant. First of all, they determined the extrema of these rate values. Then the authors made mathematical models to obtain nonlinear relationship between feed rate, ring thickness and ring outer diameter growth rate. So that they could obtain feed rate values as a table in terms of ring thickness and as a result outer diameter growth rate is kept constant. Figure 11 shows graph of feed speed values in terms of thickness of the ring under constant outer diameter growth rate.

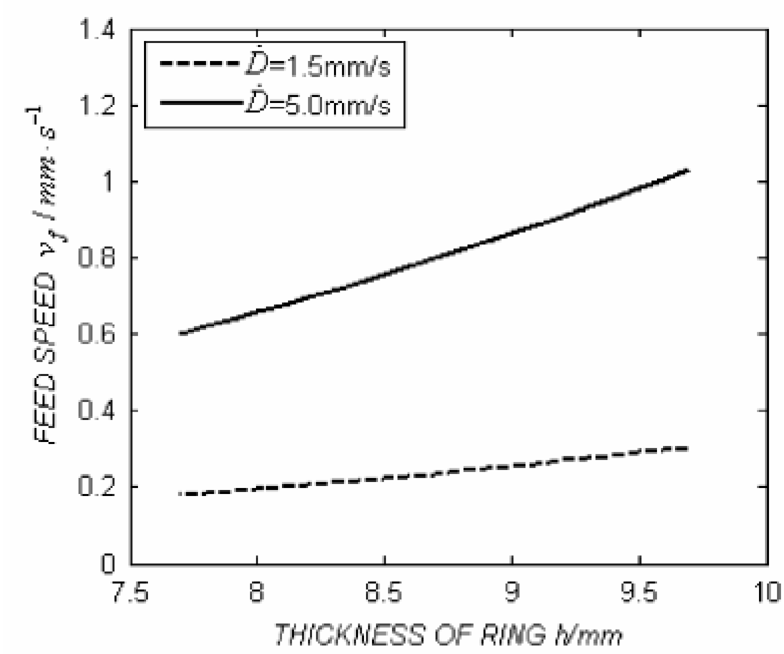


Figure 11 Variation curve of the feed speed with ring thickness under constant ring outer diameter growth rate [18]

Yea et al. [19] studied on plain and t-shaped ring rolling by simulations. They tried to observe side spread changing due to changing feed-rate and groove factor.

General application of ring rolling is limited to plain ring rolling than machining the parts having profiled contour. Yeom et al. [20] intended to obtain these complicated cross-sections through profiled ring rolling by making simulations. Authors called this as near-net shaping technology so that material consumption and subsequent machining cost could be saved. A mathematical model is suggested to prevent surface defects as seen in Equation 1 and 2;

$$h_1^2 - b_1^2 = h_2^2 - b_2^2 \tag{1}$$

$$\frac{h_1}{h_2} = \sqrt{1 - \left(\frac{b_2}{h_2}\right)^2 + \left(\frac{b_1}{h_2}\right)^2} \tag{2}$$

Subscripts 1 and 2 are for blank and rolled ring respectively. *h* means thickness of the ring and *b* means the width.

Souza et al. [21] mentions about the most important parameter in the profile ring rolling which is the preform. Required tooling is defined as king rolls and different mandrels due to steps in the process. Hot ring rolling requires reheating between steps applied to the process instead of conceiving it as a whole. Profiled ring rolling is mostly affective to reduce material consumption. Authors deal about a jet engine part that requires 12 to 14 unit volumes of initial material for a single unit part produced as seen on Figure 12. Process engineers try to design the process with a larger envelope in case of the risk that is rejecting the part due to unfilling defects. The entire die designer, operators and machining people when combined brings a result with high material consumption. The main study should be focused on to roll a near-net shape during profiled ring rolling so that cost-reduction result is obtained. Ring rolling process is a typical three dimensional forming since ring growth occurs in axial, radial and circumferential directions. Circumferential flow causes ring diameter increase but this flow cannot be homogenous around the cross-section of the ring. Design of preform is the most important stage that one has to try calculations by constant volume and some ring rolling principles. Another fact is that one may obtain precision in the final workpiece as the preform material has.

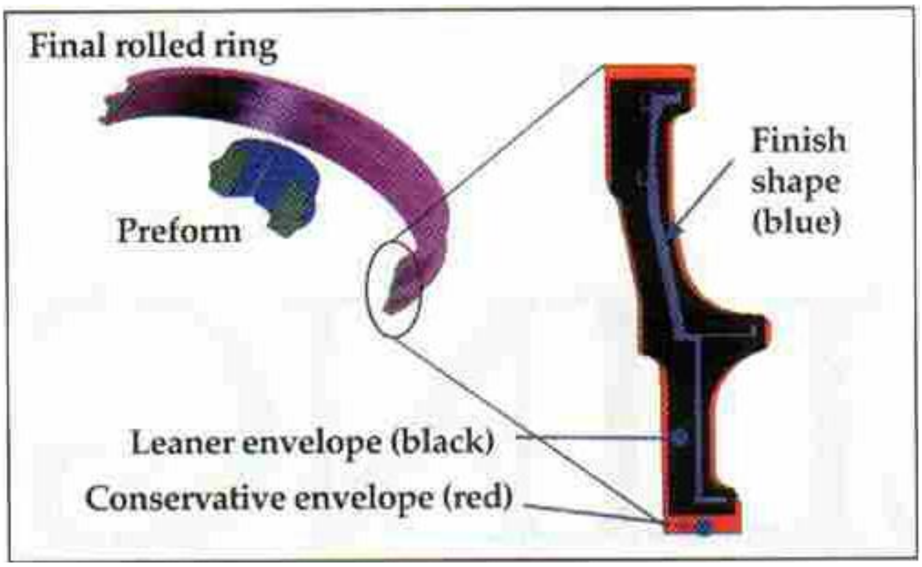


Figure 12 Typical forged envelopes in profile ring rolling of engine cases [21]

Bruschi et al. [22] applied a model to determine geometrical distortions of hot ring rolled workpieces during cooling to room temperature. Their model included both microstructural and material elasticity. Application is made by monitoring dimensional change and accordingly gives feedback to change required process parameters.

General intention to study at ring rolling is to save material by applying a "near-net-shape ring rolling process". As an action to accomplish that, preceding forging operations shall be optimized accordingly. Tani et al. [23] applied the process to achieve a 35% material saving. Importance of process design is dependent on the shape of rolls and preforms.

Main advantages of ring rolling are efficient material usage, surface quality, favorable grain orientation, low cost in terms of labor, cycle time, scrap amount and energy. Process stability is the most favorable result so that rapid failures are avoided with respect to machining is described by Allwood et al. [24].

In hot ring rolling operation the most undesired defect after unfilling is the geometrical distortions during cooling. Casotto et al. [25] defined drawbacks in calculating dimensional changes due to the effects of both non-uniform cooling conditions and microstructural phase transformations.

2.2. Needs for Simulation of Profiled Ring Rolling

As a metal forming operation, there is need for estimating forces, torque values, crack forming, metal flow, lapping and unfilling defects before mass manufacture of the designed parts. These needs can be estimated via simulations or one needs to make experiments to determine process-working conditions. Experiments bring about the industrial case trial and error at the shop floor. This procedure results in both time consumption and money loss. Simulations help to select correct capacity of metal forming machine so that one also saves the environment from the accidents due to overloading.

Guide roller motion is an unknown parameter in radial-axial ring rolling. The motion track needs to be controlled by given inputs so you need to optimize it. Pan, Hua and Lan [26] accomplished this need via finite element simulations, so that one obtains a reasonable motion track for guide rollers to have a more stable and better circularity. Researching by reiterative practical experiments would lead to high material and energy consumption due to large dimension and long rolling time is stated.

Ring rolling process is unsteady-state so that a full ring mesh analysis requirement is claimed by Lim et al. [5]. Authors needed to study on plain and V-shaped rolled sections from rectangular cross-section.

Wen and Petty [7] comment on the large amount of time needed for a full three dimensional finite element analysis of ring rolling. So that they believe in there should be alternative methods, maybe statistical neural networks or some sort of simplified models accompanied by full mesh analysis. An axisymmetric finite element model is proposed to predict cross-section of rolled workpiece. Authors' model is claimed to have accurate results and fast solution time enabling to make parametric study at the design stage.

Simplifications in metal forming simulations help to minimize solution time since large deformations and changing contact conditions lead to higher computation needs. But general simplification procedures cannot be applied to ring rolling is declared by Davey and Ward [3]. Authors claim to test the rate sensitivity if their material model by using different feed-rates in ring rolling operation. However, different feed rates do not only change axial flow by the effect of material rate sensitivity, the effect comes from changing deformation zone due to feed rates. They aimed to see fishtailing defect disappear by axial rolls in the simulation and obtained this result in their study. It is agreed that material flow is constrained by axial rolls and accordingly their model can predict ring growth and flow around profiled roll.

Davey and Ward [27] signify that different contact models used in the simulation effects the material flow behavior resulting different predicted ring profiles. Simulation model should give good results of all radial, axial and circumferential flow of the material.

Rolling processes take a risk of failing due to excess thinning at one edge. Sheikh and Palavilayil [28] studied this case and decided to look for the reasons for failing and found that the strain values are very high at those regions and piercing occurs accordingly.

Song et al. [9] tried to obtain roll load and surface temperature from simulations. Their objective was to compare these simulation results with experiments and the outcomes were affirmative as seen on Figure 13. Moreover, simulation results give the mechanics of the process and defect formation in the ring product without the need of for experimental trials.

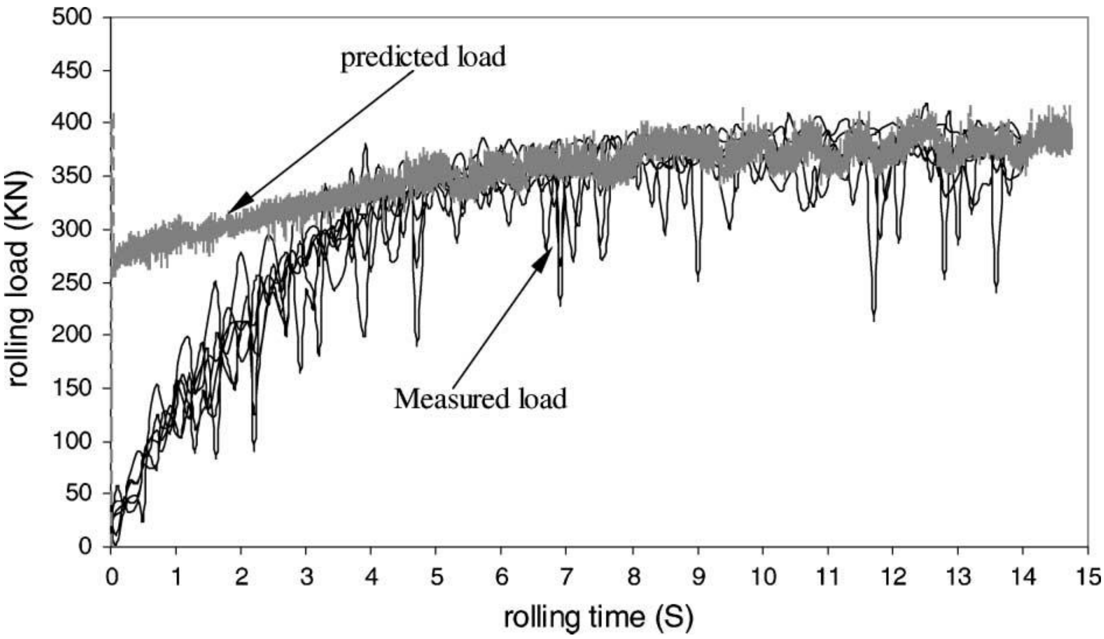


Figure 13 Comparison between predicted and measured loads [9]

Alfozan and Gunasekera [11] defined the needs for simulation as the adequate filling of profile details. It is mentioned that, decrease in ring thickness tends to deform the ring in circumferential direction rather than in axial and radial directions. Authors also mentioned about existence of equations to determine the roll force and torque in ring rolling.

Results that may be obtained from simulations are spread degree in axial direction, fishtail occurrence, degree of inhomogeneous deformation, force and power parameters. Guo and Yang [29] agree on analytical and experimental methods are not feasible for ring rolling in comparison with finite element simulations. Authors defined an average spread parameter and results are shown on Figure 14 in terms of process parameters that are sizes of forming rolls.

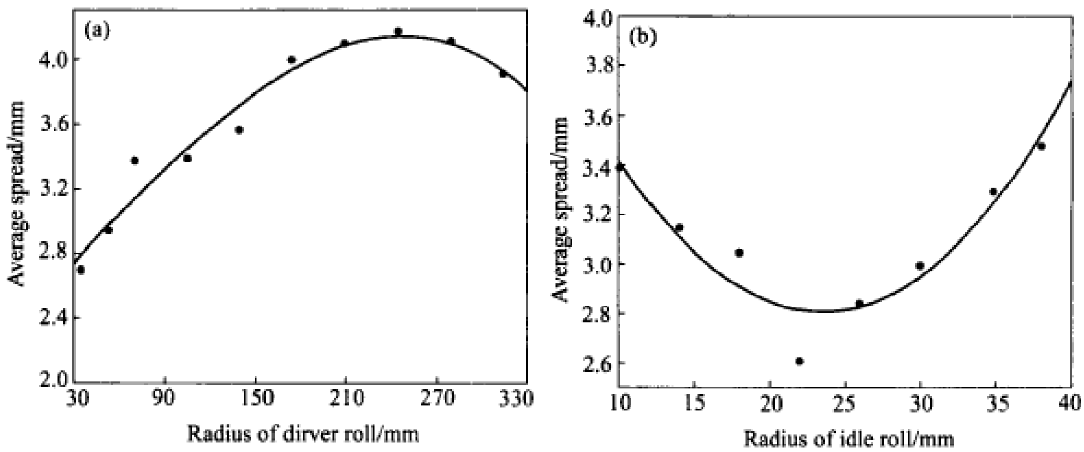


Figure 14 Influences of radius of forming rolls on average spread [29]

Boman et al. [14] states the need for lubrication models to be improved whereas there are complicated models for material and finite element large deformations. Only conventional Coulomb and Shear friction models takes part in finite element models for rolling. This is contradictory to make satisfactory large deformation modeling lacking reasonable frictional force values.

Han et al. [17] researched on profiled ring rolling of a "Conical Ring with Inner Steps". Studied profile is inconvenient to have good results since less profile filling and lying to one side are two main defects that usually occur. Profile ring rolling requires optimized shape and dimension of blank material as the most important parameter to care for.

Feed speed is an important parameter in ring rolling so a model should be defined to determine the most convenient feed speed rather than making trial and error studies. Yan, Hua and Wu [18] decided to make a feed rate calculating mathematical model based on ring outer diameter growth rate during rolling. One obtains a table of feed rate values in terms of ring thickness between rollers. This sort of tabled values can be input to a numerical controlled ring rolling mill that controls the movement of main roll. Feed rates directly affect the quality of the formed ring by material defects, surface quality and dimensional accuracy. In contrast to use a mathematical model for feed speeds, one may lose a great amount of material and time trying to find a reasonable feed speed from experimentation. Yan et al. [18] also made an argument about effectiveness of feed speed calculation model.

Moon, Lee and Joun [30] talk about the need for ring circularity results acquisition from finite element simulations. Authors could observe the practical polygonal-shaped defect arising during experiments, from their simulations. Simulations are prepared for hot ring rolling of a ball bearing outer race. Figure 15 shows the results of simulation and experiment with enormously high circularity values.

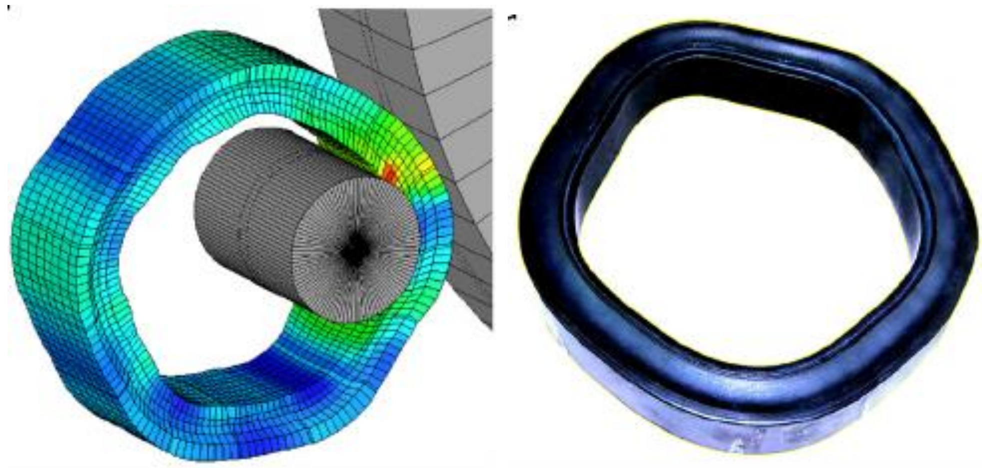


Figure 15 Analysis and experimental result of polygonal shape formation in hot ring rolling [30]

Yeom et al. [20] tried to specify a design criteria based on uniform distributions of strain and temperature for ring rolling. They also wanted to apply a new material model named "Dynamic Material Model" with stable or unstable forming criteria, so that would obtain material defect results. Acquired simulation results were strain and temperature distribution across the ring cross-section. Strain level is higher at the inner and outer surface than inside. Temperature level is lower at the surfaces than inside.

Cost-reduction strategies lead researchers to use profiled ring rolling for closer to net shape. This technique should be applied to both new ring parts and existing products for efficiency improvement. Souza et al. [21] also mentions about ring rolling deformation is three dimensional in cylindrical coordinates. Simulation model should include all these flow phenomena since circumferential flow varies along the cross section affecting filling of the dies. Intention is to have decreased number of shop floor trials by the help of simulations. Authors attempted to make a three-dimensional simulation model but does not contain full 360 degrees of the ring. So only a segment of the ring is simulated to decrease solution time. Simulation models should help the process engineer on adjusting preform and die shapes, material positioning and making several iterations for these aims. Models should also supply results at starting point of the design not taking so much time for the feasibility of procurement.

Bruschi et al. [22] characterized the ring rolling process with a risk of rejecting already produced parts due to dimensional needs of subsequent process. This risk includes inaccuracy of measurements so that a large envelope around finished profile cross-section is generated. This results in material allowances up to 50% for profiled ring rolling. With reference to possible dimensional errors, all the thermal, mechanical and metallurgical coupling mechanisms should be included in finite element simulations. According to authors, cooling effects should also be taken account to determine ring distortion values. Intention of the research was real time prediction of ring distortion. At first, a database should be completed to enable neural network in the model. Succession of the model was to obtain accurate temperature and geometry data after hot rolling operation.

According to Takizawa, Matsui and Kikuchi [31], microstructure after ring rolling should be predicted since mechanical properties are affected. Authors also wish to have deformation, load properties similar to experiments. As outcomes from finite element simulation, underfill of material and distribution of strain would be predicted.

Reasons for making finite element simulations in profiled ring rolling are defined by Yeom et al. [32]. They defined design criteria to achieve minimal forming loads, uniform distributions of strain and temperature and no-existence of defects. Modeling of ring rolling process defects such as the flow localization, instability, shear bands and surface cracks need usage of a "processing-map approach considering flow instability (Figure 16)" included in finite element simulations.

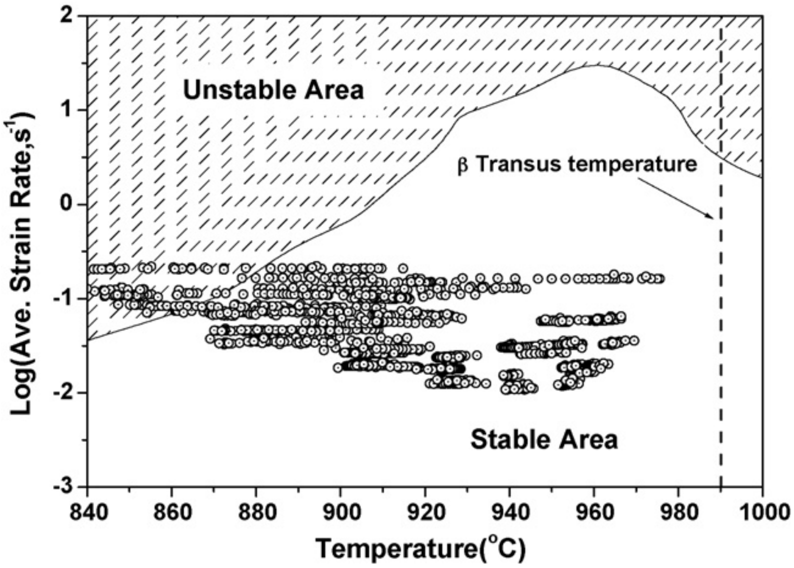


Figure 16 Flow instability maps at a true strain = 1.0 to determine the deformation stability at T = 950 °C and f = 0.5 mm/s [32]

"Thermal spokes method" is a method developed for finite element simulation of ring rolling to keep ring circularity by additional elements connected radial to the inner surface of the ring during ring rolling operation. Forouzan, Salimi and Gadala [33] claim that, accurate predictions of the lateral spread and flow patterns are obtained by the aforementioned method. Authors also want to attract attention to tilting to sideways of the ring during forming. This generally occurs at axial errors between mandrel and main roll, improper loading or in absence of axial rollers as stated by the authors. Process parameters of which are rolling force, torque and spread will be directly affected in the condition of ring tilting due to change in contact between workpiece and rolls.

Stanistreet and Allwood [34] had proposed a new ring rolling technique that may be used to roll different profiles using same tools. That requires changing positions for mandrel meaning tool paths for mandrel. Therefore, one needs to examine the effect of different tool paths. Areas of investigations are defined by the authors as, instability due to asymmetric forming, residual stress distribution, material structure, forming limits, machine complexity and process cycle time. They need to find appropriate tool paths via simple finite element simulation models to form required profiles.

2.3. Simulation Models Created for Profiled Ring Rolling Analysis

Simulation of profiled ring rolling includes nonlinear effects as contact nonlinearity, geometric nonlinearity and material nonlinearity. Contact nonlinearity occurs due to rotating workpiece between rolls. Geometric nonlinearity occurs due to 360 degree rotating finite elements and shape degeneration due to large deformations in elements. Material nonlinearity occurs due to plastic effects inherent in the process. These reasons all make the simulation of profiled ring rolling so much time consuming and bring instability due to simplifications and nonlinearities. All researchers tried to make the simulation more effective, stable and less time consuming.

Wang et al. [1] worked on a three dimensional model to simulate ring rolling of a rear axle gear blank, an aero-engine turbine casing blank and a great conical ring of a nuclear reactor shell. Authors dictated that computing time is higher than other metal forming processes due to smaller increments needed. Authors realized that main investigation in ring rolling should be reducing simulation-solving time. Explicit finite element technique is used during the simulation studies. Largest possible time increment is determined by stability problem. Increasing deformation results in smaller time increments so it becomes unfeasible to achieve solution. Mass scaling function can be used in LS DYNA explicit code to decrease the solution time. In the ring-rolling model used, Wang et al. are unsure how to calculate the unknown velocities for the guide and axial rolls. Afterwards the authors embedded a code in their simulation to calculate the velocities for the rollers at the end of each time step. The solution of conical ring from the explicit model is shown at Figure 17.

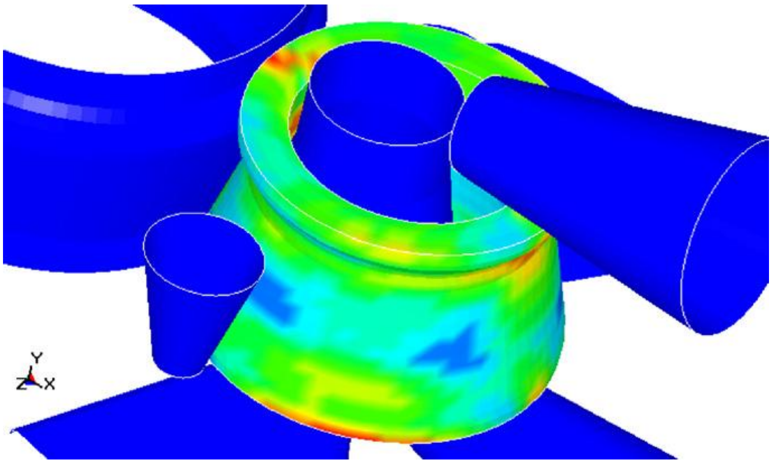


Figure 17 Picture of the ring and rolls at the final state [1]

In another work, Wang et al. [12] also used explicit finite element method with ABAQUS software. Full three-dimensional ring was modeled with elastic-plastic material model, dynamic explicit approach and coupled thermal-mechanical effect.

Pan, Hua and Lan [26] applied the dynamic explicit approach for modeling ring rolling to avoid the huge computation time and convergence problem of the implicit procedure. Reduced integration elements were used to make the computation faster and adaptive remeshing method was used to have more accurate results and less convergence problems.

Another finite element simulation also included full ring mesh with elastic-plastic material model. In the model, a new meshing technique was proposed with two sets. Authors named it as “Hybrid mesh technique” with material mesh and computational mesh system. Material mesh is used to save strain data and computational mesh uses this data to have overall displacement results. The model also used a contact algorithm that is when a node goes inside the roll surface; it is pushed back to surface achieving a more accurate solution [5].

Wen and Petty [7] supposed to make a simplification for ring rolling simulations as axisymmetric ring expansion. They found that only one hundredth of computation time is necessary for such an axisymmetric formulation. Since a rolled ring comes into deformation area between five and fifty times, there is a need for supplementary or simplified methods for finite element models. Authors also know the fact that elongation in the rolling direction occurs and accordingly reduction in cross section area is observed. Their axisymmetric model produced results in a small amount of time but one percent of error takes in place for each pass. This error can accumulate to 7% for the whole process, which becomes unacceptable. Even though they know remeshing is applied in three dimensional models, they even did not use remeshing in their simplified model.

Davey and Ward [3] observed that finite element formulation should be examined in order to reduce computational need. They mention that the conventional Lagrangian codes are not effective for fast solution times due to large number of increments. Their suggested solution technique is new finite element flow formulation called "Arbitrary Lagrangian Eulerian" update strategy with an iteration method called "Successive Preconditioned Conjugate Gradient Method". Authors also collected reducing solution times in a list as; plane strain assumptions, pseudo-plane strain assumptions, 3D simulation in the roll gap only, full 3D analysis with elements concentrated in the roll gap and using double mesh for data and compute stiffness matrices. These were the simplification methods in terms of element network. Coupled Arbitrary Lagrangian Eulerian method does not need interpolation between the meshes but this brings the increase in the number of unknowns. Authors also applied a method "Operator Split Approach" so it is claimed additional unknowns are not introduced. Their outcomes from the method are that identical results gathered with Lagrangian or Arbitrary Lagrangian but just a quarter of solution time by the new method.

In another paper by Davey and Ward [27], Arbitrary Lagrangian Eulerian method is described as combination of Eulerian and Lagrangian formulations. Flow formulation used is created aiming to minimize velocity functional. Authors define the solution method as non-uniform mesh could be used so that dense mesh region is kept always at the roll gap.

Another axisymmetric model is tried to be justified as the cross-sections of perform and rolled workpiece are axisymmetric. A design parameter, ratio of spread to diametrical expansion, is defined by Joun et al. [8]. Rollers in the process are assimilated to be infinite dimensional roll pairs. Authors needed to input relative velocity of tools and they accomplished this by calculation with force equilibrium between elements.

Song et al. [9] included all nonlinear effects without any simplifications while simulating ring-rolling process. Marc/Mentat software was used with full ring mesh, thermal-mechanical coupled effects, heat transfer between tools and workpiece and at last deformable tools. Anyhow, authors could not perfectly model heat transfer. Another exactness applied in the model was a constant dilatation formulation in order to avoid ring volume growth due to coordinate transformation in rotation.

Backward simulation technique was applied for the design of preforms. Alfozan and Gunasekera [35] tried upper bound element technique instead of finite elements for computational and too many trial and errors for assessing preform shapes. They actually defined their method by “The ring was progressively released from the main and mandrel rolls by increasing the cross-sectional area of the ring and reducing its diameter at each time step using condition of volume constancy”.

Kim et al. [36] used MSC.Superform program that uses nonlinear Marc finite element code for modeling ring rolling.

Wang et al. [12] referred the need for improving computational efficiency with an elastic-plastic dynamic explicit model. Anyhow, authors included thermal-mechanical coupled effect and full three-dimensional ring whether these two can increase computing needs. Model was prepared with ABAQUS/Explicit and details were three-dimensional deformation, high nonlinearity, continuous forming, asymmetric conditions and being in an unsteady state. It is admitted that dynamic explicit approach saves time and makes convergence easier. Authors wanted to compare explicit and implicit methods so a two-dimensional thick plate rolling is solved by two methods. It is claimed that explicit method requires only one thirteenth of solution time in comparison with implicit method. Coupled thermal mechanical methods are obtained simultaneously without need of iterations. Rigid tool surfaces, reduced integration elements and adaptive meshing are used during the explicit finite element analyses. Approximating a dynamic analysis to quasi-static metal forming analysis is a favorable part of the explicit method owing to no importance of dynamic mass effects during metal forming operations. In this case, one has the ability to increase the mass density of workpiece and accordingly increasing the stable time limit to obtain a faster solution.

Utsunomiya et al. [13] used implicit finite element codes with an elastic-plastic material model during their ring rolling simulation. Authors used the “mean normal technique” to verify their model.

Reproducing Kernel Particle Method (RKPM) is a method that includes arbitrarily placed nodes without the need of finite elements. Shape functions, boundary condition application and frictional force application are reconstructed for the method. Xiong, Rodrigues and Martins [37] convinced that RKPM and FEM solutions are reasonable when compared for metal forming simulations. Authors give information about shape functions derivation like having linear continuity of variables. However, they found that solution time is increasing with the method they proposed due to increase in bandwidth of stiffness matrix. Authors also mention that solution time can be decreased with worked up nodal integration schemes.

Finite elements near the roll region, that is deformation zone, should exist for obtaining reasonable results in ring rolling process simulation. Moon et al. [30] applied the hybrid mesh approach for improvement in computation time and a new nodal integration code for the benefit of volume change phenomena during the ring rotation. Their model included fine elements near the roll region and coarse elements in other areas. Moon et al. [30] also described the already known cases of nodal update methods as calculation of nodal points by displacements interpolation or need for instantaneous constant velocity not to make nodal points move outward from the center of rotation. Authors completed their simulation with 16,500 increments and 225 remeshings for 15 ring revolutions.

Yeom et al. [20] simulated ring rolling by finite elements method with a deformation process map applied so that material failures could be predicted.

Computational accuracy could be obtained by already proved methods such as elastic-plastic finite element method. Cold ring rolling as being a metal forming process is a quasi-static event without inertial effects. Guo, Yang and Zhan [38] could apply explicit elastic-plastic method for these aforementioned trivial subjects. Computation time should decrease and convergence should be easier according to the Authors. Elemental technologies applied were reduced integration, adaptive remeshing and hourglass control so that elemental shape deformation and zero energy modes were avoided.

Yang et al. [39] also used elastic-plastic dynamic explicit method for three-dimensional simulation of ring rolling by ABAQUS software.

Takizawa et al. [31] studied on modeling only a section of the ring with a rigid-plastic material model to simplify the process of ring rolling. Angular segment requires a starting and ending plane that needs to have essential boundary conditions defined on them. Authors defined these boundary conditions as nodal velocities in terms of increasing rate of ring radius, angular velocity of the ring and translational velocity of the ring center. In addition, microstructural analysis techniques have been introduced into the model so that mechanical properties could be predicted in the final product. Authors achieved a success in computational time of one tenth and a good agreement in the calculated velocity field with respect to a full three dimensional model.

Xie et al. [40] investigated lateral spread in the ring versus feed speed with their rigid-viscoplastic material model. Some information on their findings is that Lagrangian multiplier is the hydrostatic stress parameter, required energy functionals could be used to develop rigid-viscoplastic material model and penalty method being more efficient than Lagrangian multiplier method.

Ring rolling simulation model may include increased feed rate as a simplification tool so that number of rotations in the simulation has a smaller amount. In addition, mass scaling of the explicit method is applied in order to further decrease solution time. Explicit method has a benefit that solution time is first order proportional to the number of nodes whereas implicit method is second order. Sawamiphakdi et al. [41] completed a ring rolling simulation with aforementioned simplifications and used 810,000 time increments.

Li et al. [42] simulated ring rolling process with dynamic-explicit finite element code and a worked up incremental model of rate dependent crystal plasticity (RDCP). Authors prepared three-dimensional model of ring rolling with ABAQUS software and claim that their material model bring in anisotropic and rate sensitive deformation characteristics.

Pauskar et al. [43] tried to compare static-implicit and dynamic-explicit finite element modeling for ring rolling analyses. Ring rolling process modeling requires very small time increments due to always changing contact conditions. According to the authors, static-implicit codes should have decreased solution times to be feasible while solving enormous forming problems. For each time step set of equations is to be solved for static-implicit method giving more accurate results with respect to dynamic explicit method is defined. They found that dynamic-explicit code in their comparison gave results that are more accurate, wherefore fewer nodes comprised in the static-implicit method applied simulation.

Wang et al. [1] used ANSYS LS-DYNA explicit code for ring rolling simulation. Explicit method is used with mass scaling function. Authors included guide rolls and axial rolls in their simulation by defining their motion with ANSYS Parametric Design Language program.

Davey and Ward [44] worked on contact modeling for ring rolling simulations. Steps are defined as detection of contact, imposition of contact boundary conditions and control of contact after time integration. Contact algorithms include projection to the contact surface for every coming into and out of contact state resulting volume loss problems. Authors claim that corrections to this case are uncommon. Arbitrary Lagrangian Approach that was applied by the Authors has led to run time benefits and allows a nonuniform mesh so that fine mesh does not need to be regenerated every rotation of the dense mesh segment in case of the standard updated Lagrangian approach. It is convinced that simplified methods of contact results in different final ring profiles. Authors could obtain smaller solution times by applying “operator split Arbitrary Lagarangian Eulerian” formulation and “SPCGM” solver.

Casotto et al. [25] applied all coupling effects of thermal, mechanical and metallurgical into their cooling simulation of hot ring rolled products. Simplified axisymmetrical model by LAGAMINE code is prepared. The aim was to predict phase transformations resulting from cooling conditions. It is stated that theoretical information about material germination and growth of grains was needed to correctly model the process. Simulation model by finite elements includes effects of phase transformation, phase plasticity and temperature dependent material properties to predict final ring deformations after cooling to room temperature. Cooling results are shown on Figure 18 with center of the rings at left side.

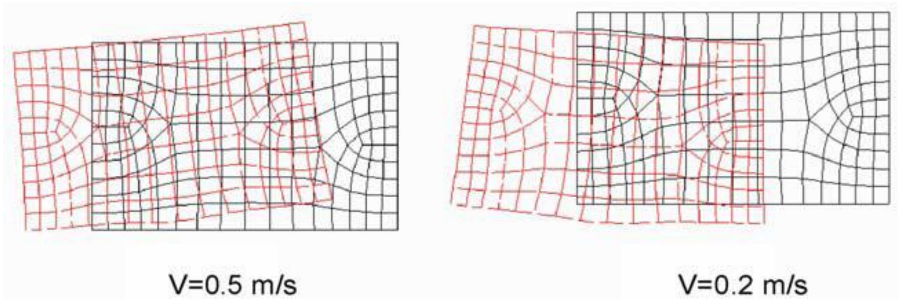


Figure 18 Ring distortions for two different cooling rates (disp. x10) [25]

Forouzan et al. [33] improved a finite element model able to predict tilting of the ring with elastic truss elements added between the inner diameter and center of the ring. It is claimed that temperature increase effect is also included by adjusting link lengths in the model. Authors created the model by ANSYS software and assert the reliability could only be achieved by thermal spokes method. Namely, guide rolls effect is incorporated by thermal spokes method in the model defined.

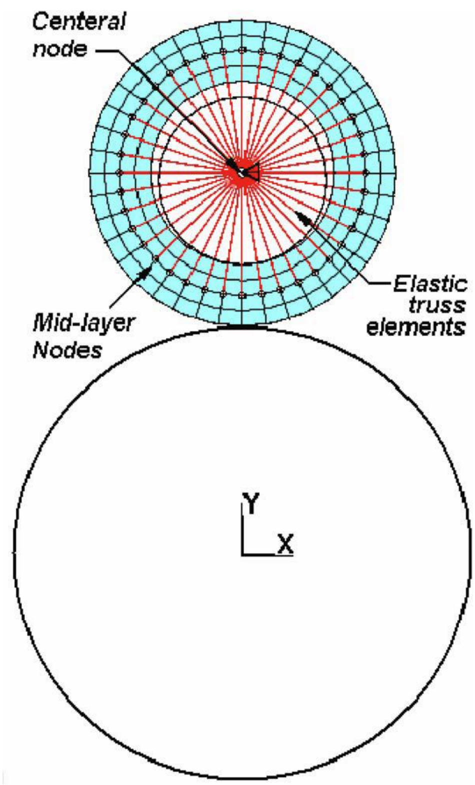


Figure 19 Thermal spokes method [33]

Ranatunga et al. [45] developed a three dimensional UBET (upper bound element technique) simulation for ring rolling of complex profiles. The gap between two rolls is discretized and material flow is observed.

Two simplified models are created and applied to ring rolling by Stanistreet and Allwood [34]. These models are axisymmetric and a ring segment squeezed between rolls. Dynamic explicit method is used with ABAQUS software. Authors claim that contact boundaries are more easily treated by explicit method. It is also mentioned that large number of iterations required by explicit method results in inaccuracy, since errors accumulate with ring rolling process evolving.

2.4. Comparison of Simulation Results with Experiments

Davey and Ward [3] worked on material flow phenomenon on both simulation and experiments. They investigated different feed rates and their effects on radial, axial and ring growth. As a consecutive measure on axial flow (spread) is fishtail defect that can be observed by both simulation and experiments. As a result, authors found that higher feed rates induce more spread in radial ring rolling. Authors complain about asymmetry raised in ring rolled workpieces during experiments that probably caused by erroneous initial positioning. Simulation model results were in good agreement with experimental results especially at lower feed speeds.

Finite element simulation was applied to profiled ring rolling of bearing race by Joun et al. [8]. Authors have also prepared experiments to verify simulation results and deformed shapes showed that simulation results are reasonable. Therefore, it is possible to make conceptual design of preforms by simulation tool.

Finite element simulation of hot ring rolling was prepared by Song et al. [9]. Authors investigated rolling force and surface temperatures. It is dictated that experimental measurements and simulation results are in good agreement.

Kim, Suk and Huh [36] studied on profiled ring rolling simulation with a round groove located on outer diameter surface. Simulation software was MSC.Superform and experiments were conducted on an industrial ring-rolling machine. Afterwards, the simulation and experimental results were compared with each other.

At first Wang et al. [12] simulated ring rolling by both explicit and implicit methods. Comparison of explicit results with respect to implicit results, gathered no unfavorable case. After that, authors could observe the same fishtail defect formation by both explicit finite element simulations and experiments.

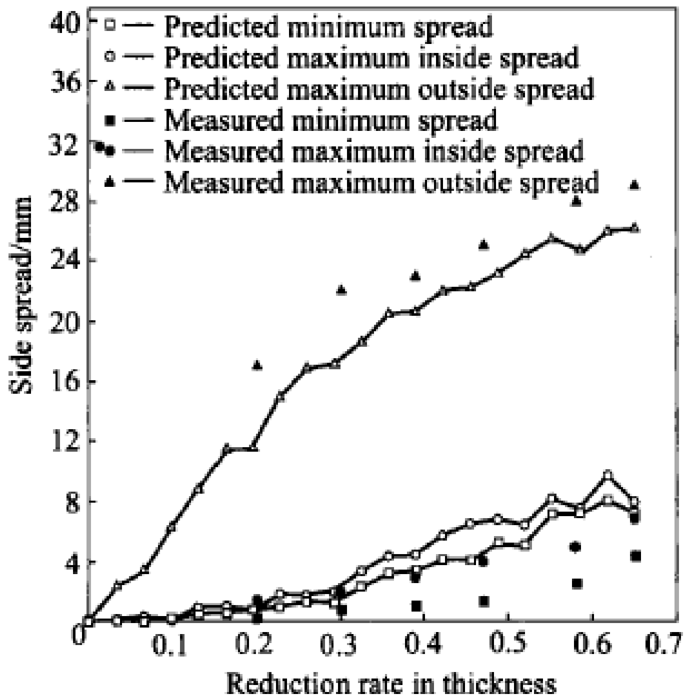


Figure 20 Measured and predicted side spread histories [12]

Obtained results from the finite element simulations with thermal spokes approach are in good agreement by experimental results. Therefore, Forouzan et al. [46] convinced the validity of their thermal spokes approach and modified lever arm principle. Driving torque of the main roll is compared with experimental values and shows to be in good agreement in Figure 21.

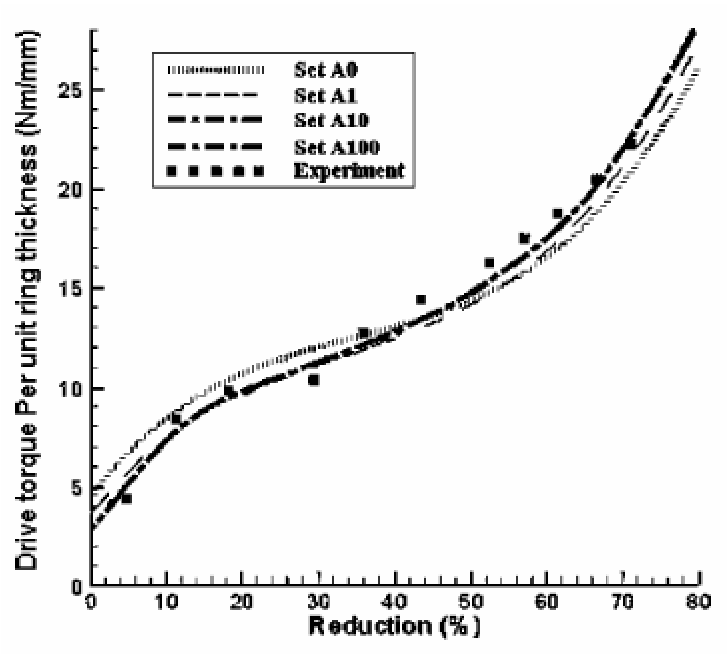


Figure 21 Drive torque versus reduction [46]

Guo and Yang [47] tried to compare rolling force, roller torque and geometry formation in ring rolling, between simulation and experiments. Their three-dimensional elastic-plastic dynamic explicit model was found to deliver accurate aforementioned results and accordingly reliability was happened to be convinced.

Finite element simulation of both conical and inner diameter profiled ring rolling process was accomplished. Conical ring is a challenging process by itself and when it combines with a profiled ring section this case is much harder to be studied. Han et al. [17] could simulate and experiment profiled conical ring rolling.

Xiong et al. [37] compared rolling torque, rolling force and spread results, between their simulations and already completed experiments from the literature, after all agreed on their similarity. They explained that the accuracy of the simulations is higher when the width to thickness ratio of the ring is smaller. At higher values of the ratio, predicted torque values become higher and force values become lower than the actual values. The reason for this case is claimed to be from the rigidity assumption of rolls. Since when the actual force increases for higher width to thickness values, elastic deformation occurs in reality. However, the simulations do not include elasticity for rolls.

When the feed rate is much smaller from the required feed rate values in a ring rolling process, polygonal shaped defects occur. Moon et al. [30] observed this case in both simulations and experiments carried out. It is said to be good qualitative agreement has been captured between model results and experimental results.

Axial flow pattern, pressure distribution and rolling force values were acquired from simulation results. Yea et al. [19] have prepared simulations for experiments found from literature. Authors also compared aforementioned values by changing feed rate, groove factor, and accordingly obtained acceptable accurate simulations results.

Cooling process after hot ring rolling is a challenging case that also needs trial and error. So that, Bruschi et al. [22] resolved to simulate real-time of geometrical deformation for ring rolled rings, since finite element models could not be used during continuous production. Real-time modeling needs neural network with a database. The database could be completed by numerical simulations of cooling phase. Authors produced that model and used for the neural network database. In the real environment, inspections are made randomly with a high risk of rejecting so many parts. Accordingly process planners use larger material allowances. Experiments were conducted after all and the real-time modeling was just validated. Validated results are geometrical distortions after cooling and required inputs were dimensional data and surface temperature at the exit from the rolling mill.

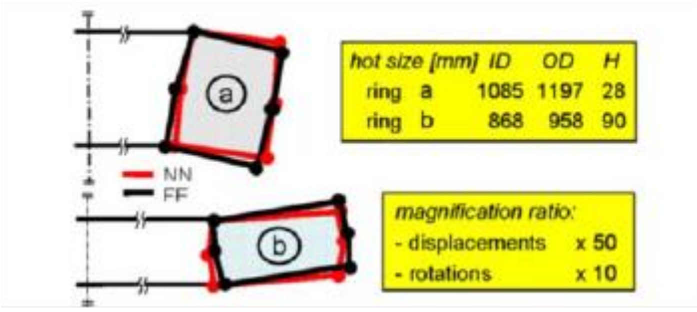


Figure 22 Neural network predictions and FE simulations [22]

Takizawa et al. [31] could obtain simulation results similar to their experimental ones. In ring rolling, deformation and load properties could be calculated from the finite element model, particularly underfill of the material and distribution of plastic strain. Authors mentioned simulation tool might be used for optimization of ring rolling.

Casotto et al. [25] insisted on material deformation of ring rolling was studied extensively but there was no evidence of sufficient interest on cooling case after the process.

2.5. Application of Profiled Ring Rolling to a Specific Product

Initially rectangular cross-sections could be used to roll plain and V-section profiled rings. Lim et al. [5] investigated plastic strain distribution of ring rolled products and observed that plastic strain is concentrated on the inner and outer diametrical surfaces. Authors also experienced strain localization on the inner diametrical surface due to profiled mandrel surface.

Davey and Ward [3] defined the problems of the ring rolling, as simulation simplifications are not adaptable with respect to other rolling processes and it is not possible to control the symmetricity of the rolled product probably due to initial positioning. Another problem of ring rolling was fishtailing but that one is said to be avoided by the use of axial rolls.

In a publication for ring rolling simulation by Davey and Ward [27], there is a complaint about contact boundaries applied by simplified models result in different predicted final ring deformations.

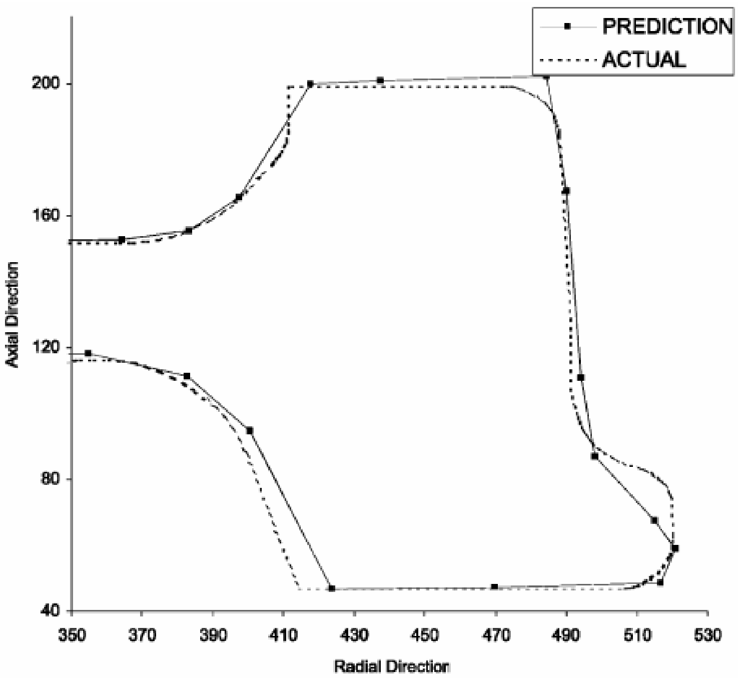


Figure 23 Comparison of predicted and measured wheel rim geometry [27]

When ring rolled products are formed using high reduction rates, there is a situation of unpredictable ring deformation. Alfozan and Gunasekera [35] defined the characteristic property of profiled ring rolling that cannot be easily simulated via forward or backward methods. Authors thought up of backward simulation technique that recovers possible foldovers, local deformation, internal cracks and not filling case of material. It is claimed to have the chance of final ring shape and diameter could be easily attained by the proposed method.

Alfozan and Gunasekera [11] knows the fact about profiled ring rolling may not fill the profile sections with material even the final diameter is reached. Authors observed that the feed rate has an effect for material filling and they claim that lower feed rates are more successive at profile cavity filling. Profiled ring rolling is more effective with the aid of finite element or upper bound element technique.

Kim et al. [36] applied profiled ring rolling process to an asymmetric profiled ring that has outer grooves. Authors used a preform that has a wider width than the product and controlled/decreased the width by conical rolls during forming. This process was a hot ring rolling of a heavy ring in horizontal direction. Authors observed upper portion of the ring tilts outwards when the groove is located at vertically upper position. By virtue of the observation, they could only recommend placing the groove downwards.

Tiedemann et al. [16] described the profiled ring rolling as a flexible process. Authors realized that the large number of products could decompensate high tool and setup costs. They investigated different feed rates for mandrel and upper taper roll in their experiments with a wax based material. That was an illustration of hot ring rolling of steel.

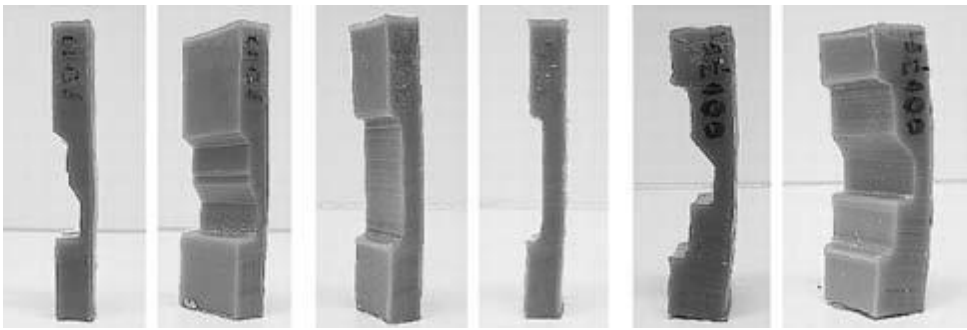


Figure 24 Radial flexible rolled multi-step profiles [16]

Profiled ring rolling was combined with conical ring rolling in a study by Han et al. [17]. Authors realized that this process is a challenging one. Two main problems were more material filling and ring tilting. Smaller side on the section height experiences more tilting.

Profiled ring rolling can be a successive operation when uniform strain and temperature distribution and defect-free ring production are achieved. As Yeom et al. [20] mentions, profiled ring rolled products are included in power generation plants, aircraft engines and large cylindrical vessels.

In a study by Souza et al. [21], an engine part was ring rolled and machined to required shapes, since profile filling defects and heat treatment deformations lead engineers and operators to create a greater excess material. Therefore, profiled ring rolling should be modeled for guessing the ideal shape of the preform. The material loss could reach up to 13 times the final product mass. So that, authors explained a firm strategy for profiled ring rolling that rolling closer to net shape is required to improve material utilization and that could be achieved by modeling techniques.

Bruschi et al. [22] defined a cooling simulation after hot ring rolling could help hot ring rolling process design by revealing deformation data of rings during cooling.

Process condition, initial blank dimensions were determined for plain and profiled ring rolling with Ti-6Al-4V material both experimentally and by modeling. Kim et al. [48] has obtained simulation results that were strain, strain-rate and temperature. Cross-section of the rolled ring with microstructure evaluation is seen in Figure 25.

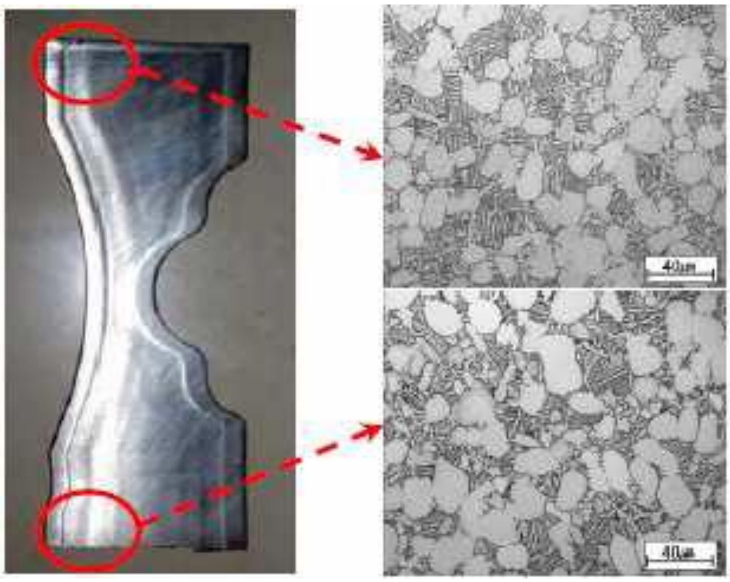


Figure 25 Microstructure evaluations of profiled Ti-6Al-4V alloyring [48]

Stanistreet et al. [49] complained about high costs for tooling in profiled ring rolling. Authors mentioned expensive shaped rolls are needed for variable ring profiles. They tried to define a process that uses same rolls incrementally floating over the product so that different ring profiles could be obtained.

"Near-net-shape" ring rolling process was defined in a study by Tani et al. [23]. Authors' aim was to reduce forging weight of a ring rolled fan case. They defined the success condition by a 35% material save. During the study, authors faced up with cylindericity problems probably because of blank and roll shapes. They defined the profile filling defects, as the rolling reduction cannot be uniform along the ring height.

Allwood et al. [24] thought about modifying radial ring rolling process for flexibility through different final profiles. They found that feasibility for the process is at hand but cycle time increases due to nature of the increment forming processes. It is also mentioned that stability of the process is dependent on proper tool path design. Incremental ring rolling could be applied to both hot and cold ring rolling. Shaping mandrel could be placed in each circumferential and side surfaces. Authors stated the success of different final ring profiles from any material with designated preforms. Besides, incremental process yield appropriate die designs for successive ring rolling operations.

Simulation tool could enable aerospace industry people to apply profiled ring rolling for any complex profile. Ranatunga et al. [45] simulated a profiled ring rolling process and found it effective to be used for ring rolling process design.

Stanistreet and Allwood [34] thought about required profile shapes to be formed by their proposed incremental ring rolling process. The necessity is defined as appropriate tool paths should be found for each final profile. Radial path combinations could produce target profile. Authors gave the information that the aforementioned radial paths should be short to avoid ring conicity.

CHAPTER III

PROBLEM DESCRIPTION

This chapter gives information about general metal forming processes and the specific cold ring roll forming process, process parameters, tools used in the process and ring rolling applied product types with examples. Deformation characteristics such as shape of the deformation zone and affecting parameters are defined. General information about the ring rolling equipments is also provided.

3.1. Ring Rolling Process Mechanism

Profiled ring rolling operation is beneficial in terms of material saving for ring shaped parts that have complicated cross-sections. Cold metal forming operation is good at obtaining high quality parts in terms of mechanical properties, precise dimensions and good surface quality. It will be a precious property when the aforementioned advantages of profiled ring rolling and cold metal forming are combined with simulations of operation before making trials at the shop floor. Making trial and errors while working on obtaining the required blank shape and dimensions at the rolling machine should bring in very high costs and loss of excess time due to nature of ring rolling process. Trial and errors require each blank to be manufactured separately at the turning shop floor before rolling tests.

Requirement of simplified model comes into place at this circumstance. Ring rolling process include three-dimensional deformation characteristics so two-dimensional finite element approaches will not be directly adapted to the process. Three-dimensional ring rolling simulations take too much time in case of making so many trials for blank shape calculation. Therefore, economical application of three-dimensional models could not be established for profiled ring rolling trials up-to-date. For efficient application of finite element method, simplified ring rolling simulations need subsidiary mathematical models to obtain in process ring dimensions.

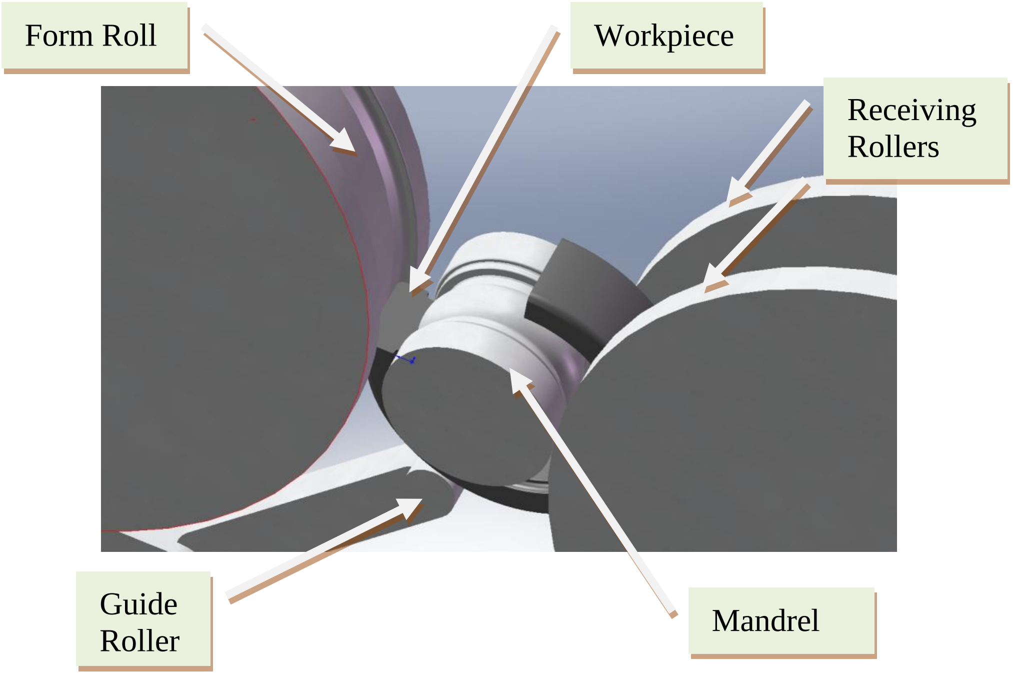


Figure 26 Schematic representation of ring rolling

Three-dimensional model as seen in Figure 26; represents the profiled ring rolling process with tools. The smaller diameter inside the ring workpiece is named mandrel and the bigger diameter is named form roll. Form roll is rotated 127 revolutions per minute and advances through the ring with 0.3 to 0.8 mm/sec. feed rate. Form roll has a perpendicular way to the axis of the mandrel with a rotation axis parallel to the mandrel or ring axis. Mandrel is rotated by the effect of ring rotating around.

Roll forming machines generally consist of roll stations, a drive system to power the rolls and drive the material, a brake that prevents coasting after shutdown, and a coolant/lubricant system, to reduce tool wear and energy requirements as well as galling and material buildup on rollers.

Computer-Aided Tooling Design is depicting the anticipated flow of material through the dies.

Tool material improvements have increased and improved roll life.

Uniformity of roll formed shapes allows them to be easily bent. When producing rings or segments of rings, shapes can be curved to uniform radii at the rolling machine without wrinkles and without disturbing a pre-finished surface.

Once a process design leads to satisfaction, there is little chance to occurence for fractures such as wrinkles and crancks in somewhere of the produced parts.

Tolerances for Roll formed Shapes defines that dimensional variations in roll formed parts are based on material, equipment and application. Tolerances vary due to material springback, variations in material width and thickness, material properties, tooling quality and wear, machine condition and setup, and operator skill. While the greatest economies are usually realized when specified tolerances are as generous as possible, tolerances tighter than those cited below are routinely achieved. Often dimensional problems can be avoided by ordering the material to be formed with somewhat tighter than commercial quality tolerances.

Ring is squeezed between the mandrel and form rolls. Cross-sectional area reduces by the time causing the ring diameter to increase.

In flat ring rolling operation, mandrel and form roll tools have no detailed edges around the outer diametrical surface. The tools have only a flat surface that able to roll only cylindrical rings to have larger diametrical values at the end of operation. Flat rolling process can also be thought as rough rolling since machining operation is followed after ring rolling. Complex profiled rings require, for example, turning operation to be created. To have the profiles machined from flat rolled rings, without unprocessed areas, flat rolled ring dimensions need to be set by excess portion of material.

It becomes a target for the process planners to machine minimum amount of material from the ring surface. As outcomes from the profiled ring rolling project success high amount of material savings, product quality, productivity increase due to shorter cycle times of rolling with respect to machining operations. During the rolling operations the fiber structure is formed parallel to the edges and accomplishing more stabile and longer fatigue life. Fiber structure will not be cut during the machining operation. Therefore, the material will resist more to the hertzian contact stresses.

3.2. Process Parameters

Characteristic parameters in ring rolling process are listed below;

1. Profile of the form roll and mandrel
2. Rolling ratio
3. Rotation speed of the ring
4. Feed rate of the form roll
5. Material flow(shape of deformation zone)
6. Rolling force and torque
7. Pressure distribution between workpiece and tools.
8. Lubrication and friction between contacting surfaces.

Technological subsidiaries in the research study for thesis can be given as different topics. Expertise needed for accomplishing tasks during thesis study can be listed as following;

1. Production of bearings;
2. Metal forming
3. Finite element analysis
4. Metallurgical knowledge
5. Residual stresses
6. Tool and die design

Broadest subject in thesis is metal forming. Cold ring rolling as a metal forming process needs to be modeled via finite element method. Accordingly preform design should be implemented to obtain desired profile across the rolled ring cross-section in axial crossing radial direction. Success in preform design is achieved when the required profile of the ring is completely filled with material.

3.3. Tools Used in the Process

Tools defined here are related with the ring rolling equipment and method of ring rolling process used throughout the thesis. Tool names are figured out in ring rolling machine illustration that is Figure 26. Tool definitions are given as following;

Mandrel: Used to shape the inner diametrical face of the ring during forming. Cases requiring the inner diameter of the formed ring, to have contour leads to profiled mandrel. Whereas, the contrary case also leads to flat mandrel without contour along the axis. Tool outer diameter needs to be smaller than the inner diameter of the blank workpiece. In the machine used throughout thesis study that are experimental and modeling stages; mandrel is not rotated. Mandrel is rotated by the effect of rolling workpiece. Role of the mandrel tool, is to support the workpiece from an axis parallel to rolling direction. Accordingly, having a smaller diameter; this tool becomes the weakest link in the process in case of getting damage. Damage could be in form of crack leading to splitting along a plane perpendicular to axial direction. Thus, mandrel has probably shortest tool life in ring rolling process.

Form Roll: Form roll is the main powered tool for shaping the ring workpiece during process. Roll motor rotates this tool in opposite to the rolling direction providing rotational forming and servo loading motor advances this tool against the ring thickness providing section forming. Form roll is used to shape outer diametrical surface of the ring workpiece during forming. Contour along the outer surface of the formed ring requires to be designed via form roll. Both the forming torque and forming force are endured by this forming roll (main roll).

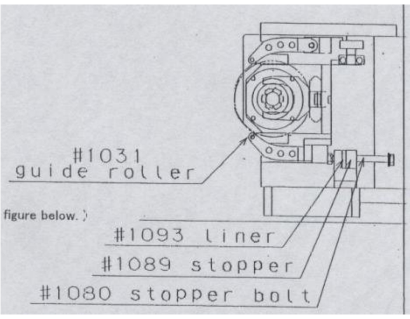


Figure 27 Mechanism of guide rollers

Guide Rollers: Used to keep circularity of the ring workpiece while rolling at good levels. By a mechanism shown in Figure 27, guide rollers are fed by hydraulic cylinders. During rolling process; oscillation of the ring is hindered with the forces applied by guide rollers. By the help of low circularity values; the workpiece is able to enter calibration case without damages to both die and ring itself. The calibration pressures are kept at lower values by the help of this additional guide roller tools.

Receiving Roll: Used to support mandrel at the opposite side to the forming force action. Having a large mass it provides inertia to smooth out big torque changes during forming of the ring. Therefore, ring is kept rotating smoothly with oscillation and circularity at low values. Receiving roll supports mandrel during rotating namely during forming; to annihilate bending of the rolling mechanism and possible harm to the mandrel movement guides.

3.3.1. Design and Design Development

Process improvement study is only at hand so there is no product design refinement. Design stage is determination of the preform shape and dimensions that is to be used for rolling a prespecified ring. Tool shapes and dimensions and process details such as cycle time, feed rate and rotation speed will also be resolved.

3.3.2. Design Verification

All resolved parameters for ring rolling process, shall be verified by making physical experiments. Afterwards, revisions come into prominence in case of any irregularities.

3.4. Process Design

In this study, profile of the rolled ring is kept constant. Therefore, change in design of ring profile is not at hand. Process design stages for profiled ring rolling are defined as following;

1. Blank size calculation according to volume constancy principle.
2. Sizes of the forming tools are determined.
3. Feed rates determination.
4. Roll revolution speed determination.
5. Tryout of the process at simulation.
6. Change of the blank-tools-feed rates-revolution speed parameters.
7. Again tryout with the simulation.
8. Tryout of the process at shop-floor.
9. Rechange of the above parameters if required.

CHAPTER IV

NUMERICAL MODELING OF RING ROLLING PROCESS

4.1. Basic Modeling Knowledge

Finite element method is a computational technique used to obtain approximate solutions of boundary value problems in engineering. Boundary value problem is a mathematical problem in which one or more dependent variables must satisfy a differential equation everywhere within a known domain of independent variables and satisfy specific conditions on the boundary of the domain. Boundary value problems are also sometimes called field problems. The field is the domain of interest and most often represents a physical structure [50].

The FE method was developed more by engineers using physical insight than by mathematician using abstract methods [51]. In engineering, it was initially developed on a physical basis for the analysis of problems in structural mechanics. However, it was soon recognized that the technique could be applied equally well to the solution of many other classes of problems [52]. The method was first used to solve less complex problems (design problems). In case of mechanical engineering, it was used to determine stress intensity factors in component designs. These designs are structural mechanical components (not mechanical working systems). Based on to the stress intensity factor, failure criteria is defined later on. This failure or yield phenomenon can be determined according to several different methods. Examples of these different methods can be listed as following; von mises stress, shear stress, e.g... After a time period, design problems led solution of process problems by finite element method.

The development of finite element methods for the solution of practical engineering problems began with the advent of the digital computer. That is, the essence of a finite element solution of an engineering problem is that a set of governing algebraic equations is established and solved, and it was only through the use of the digital computer that this process could be rendered effective and given general applicability.

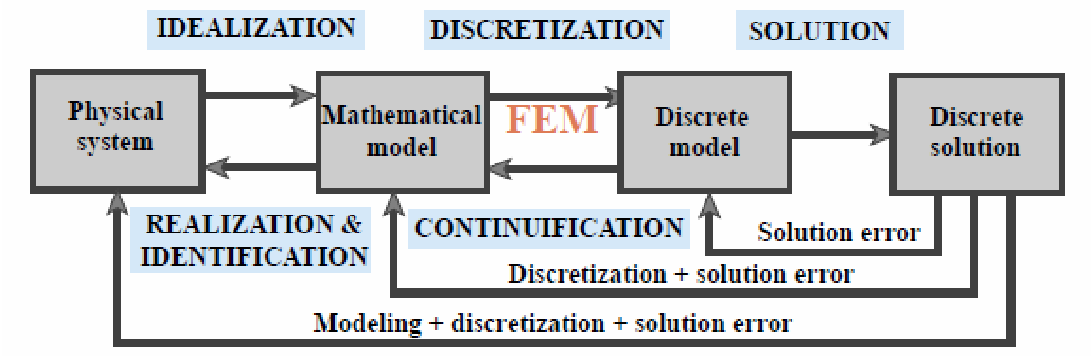


Figure 28 A simplified view of the physical simulation process, primarily useful to illustrate modelling terminology [51]

Idealization of the physical problem at hand comes first for the sake of simplicity to deal with. Mathematical model is said to be an idealization of the physical system. This stage requires purely engineering sense that is combining physics and mathematics knowledge for a problem at hand.

Finite Element technology requires discretization of the problem domain into smaller sub-domains. These sub-domains are in terms of length/area/volume with respect to dimensional type of the problem at hand. The sub-domains are called as finite elements. Typical finite element geometries are given on Figure 29. Element technology can be classified as linear elements and nonlinear quadratic elements. Linear elements are defined by linear functions along the edge, while nonlinear elements are defined by quadratic functions along the edges.

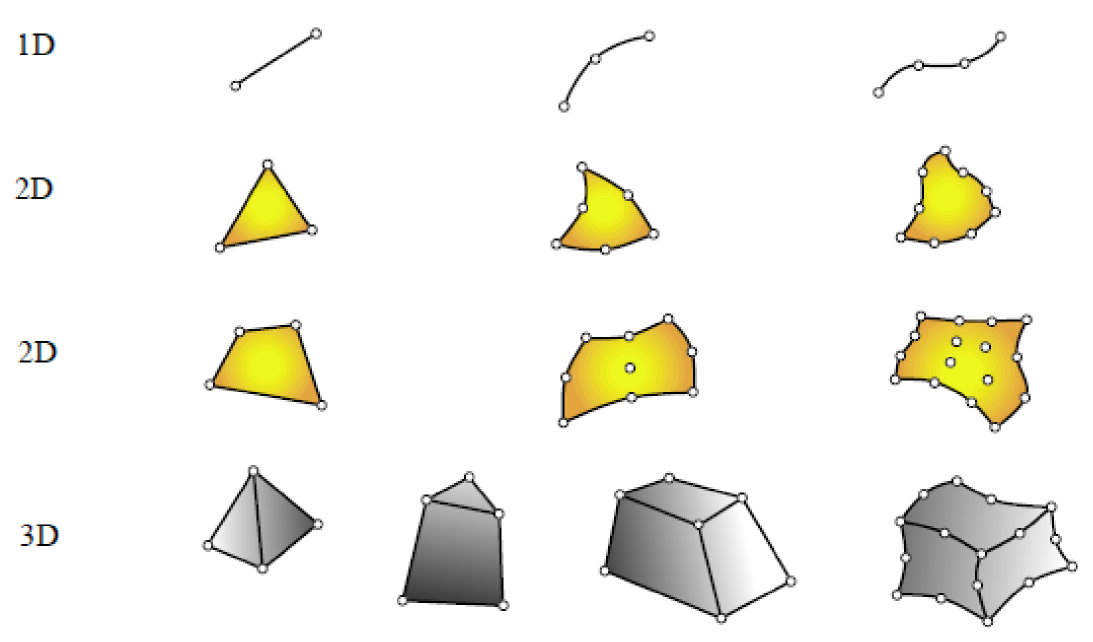


Figure 29 Typical finite element geometries in one through three dimensions[51]

Local properties of finite elements can be developed by considering them in isolation, as individual entities. In the Direct Stiffness Method, elements are isolated by disconnection and localization steps. This procedure involves the separation of elements from their neighbors by disconnecting the nodes, followed by referral of the element to a convenient local coordinate system.

Following is a summary of the data associated with an individual finite element. This data is used in finite element programs to carry out element level calculations.

Intrinsic dimensionality: Elements can have one, two or three space dimensions. There are also special elements with zero dimensionality, such as lumped springs or point masses.

Nodal points: Each element possesses a set of distinguishing points called *nodal points* or *nodes* for short. Nodes serve two purposes: definition of element geometry, and home for degrees of freedom. They are usually located at the corners or end points of elements, as illustrated in Figure 29; in the so-called refined or higher-order elements nodes are also placed on sides or faces, as well as the interior of the element.

Geometry: The geometry of the element is defined by the placement of the nodal points. Most elements used in practice have fairly simple geometries. In one-dimension, elements are usually straight lines or curved segments. In two dimensions they are of triangular or quadrilateral shape.

In three dimensions the three common shapes are tetrahedra, pentahedra (also called wedges or prisms), and hexahedra (also called cuboids or "bricks") as seen in Figure 29.

Degrees of freedom: The degrees of freedom (DOF) specify the *state* of the element. They also function as "handles" through which adjacent elements are connected. DOFs are defined as the values (and possibly derivatives) of a primary field variable at nodal points. The actual selection depends on criteria studied at length in Part II. Here we simply note that the key factor is the way in which the primary variable appears in the mathematical model. For mechanical elements, the primary variable is the displacement field and the DOF for many (but not all) elements are the displacement components at the nodes.

Nodal forces: There is always a set of nodal forces in a one-to-one correspondence with degrees of freedom. In mechanical elements the correspondence is established through energy arguments.

Constitutive properties: For a mechanical element these are relations that specify the material behavior. For example, in a linear elastic bar element it is sufficient to specify the elastic modulus E and the thermal coefficient of expansion α.

Fabrication properties: For mechanical elements these are fabrication properties which have been integrated out from the element dimensionality. Examples are cross sectional properties of MoM elements such as bars, beams and shafts, as well as the thickness of a plate or shell element [51].

As one of the methods of structural analysis, the direct stiffness method (DSM), also known as the displacement method or matrix stiffness method, is particularly suited for computer-automated analysis of complex structures including the statically indeterminate type. It is a matrix method that makes use of the members' stiffness relations for computing member forces and displacements in structures and based on following two assumptions;

1. Compatibility of displacements: The joint displacements of all members meeting at a joint are the same.

2. Force equilibrium: The sum of forces exerted by all members that meet at a joint balance the external force applied to that joint.

In applying the method, the system must be modeled as a set of simpler, idealized elements interconnected at the nodes. The material stiffness properties of these elements are then, through matrix mathematics, compiled into a single matrix equation which governs the behavior of the entire idealized structure. During solution of finite element models, stiffness matrix of the system is defined by summing individual stiffness effects of simple elements in the correct direction at the system coordinates. Unknown displacement and force parameters defined at nodal points by are calculated by using system stiffness matrix. Every other parameter such as stresses and strains are calculated from the displacement values at hand or differences in values between calculation steps of analysis.

Stiffness matrix compiled with two degree of freedom at three nodes is given in Equation 3 with force and displacement vectors. The same equation also shows the application of direct stiffness method using compatibility of displacements and force equilibrium. Equation 4 shows the reduced form that resembles simple stiffness theory of spring.

$$\begin{bmatrix} f_{x1} \\ f_{y1} \\ f_{x2} \\ f_{y2} \\ f_{x3} \\ f_{y3} \end{bmatrix} = \begin{bmatrix} K_{x1x1} & K_{x1y1} & K_{x1x2} & K_{x1y2} & K_{x1x3} & K_{x1y3} \\ K_{y1x1} & K_{y1y1} & K_{y1x2} & K_{y1y2} & K_{y1x3} & K_{y1y3} \\ K_{x2x1} & K_{x2y1} & K_{x2x2} & K_{x2y2} & K_{x2x3} & K_{x2y3} \\ K_{y2x1} & K_{y2y1} & K_{y2x2} & K_{y2y2} & K_{y2x3} & K_{y2y3} \\ K_{x3x1} & K_{x3y1} & K_{x3x2} & K_{x3y2} & K_{x3x3} & K_{x3y3} \\ K_{y3x1} & K_{y3y1} & K_{y3x2} & K_{y3y2} & K_{y3x3} & K_{y3y3} \end{bmatrix} \begin{bmatrix} u_{x1} \\ u_{y1} \\ u_{x2} \\ u_{y2} \\ u_{x3} \\ u_{y3} \end{bmatrix} \quad (3)$$

$$F = K \; x \; U \quad (4)$$

K is defined as stiffness of the system, U is defined as displacement at nodal points that occurs due to applied force and F is defined as applied force on the system.

During the solution phase; stiffness matrix of a flexible body is modified with the contribution of boundary conditions. When applied boundary conditions change during the time course of a system or either, boundary conditions have to change in the system that requires a solution; you have to update the stiffness matrix to obtain a reasonable solution. Updating stiffness matrix requires the problem to be divided into segments. These segments can be defined in terms of time, displacement and strain values. Segmenting the problem means, you obtain the final solution by solving different phases affected by the previous phase result. This outcome from the previous phase should have different types of data to be transferred according to type of nonlinearity the system has.

Static finite element analysis includes boundary conditions that are not changed during the analysis. Namely, static means there is not a process change during analysis. It is only a time instant and can also be defined as steady state analysis. There is no alteration in the model in course of time.

Boundary condition change should occur when one or all of the following are observed;

1. Part of body or whole body comes into contact or loose contact
2. Part of body or whole body is affected by a changing amount or newly defined vectored force.
3. Part of body or whole body is affected through the use of power that can be defined by pressure, heat, vectored motion.

There are three kinds of nonlinearity that may occur in finite element analyses. First one is material nonlinearity, second one geometric nonlinearity and third one contact nonlinearity.

The application of the finite-element method to metal-forming problems began as an extension of structural analysis technique to the plastic deformation regime. thus, early applications of the finite-element method to metal forming problems were based on the plastic stress-strain matrix developed from the Prandtl-Reuss equations.

Material nonlinearity is defined by the nonlinearity of the function defining stress-strain relationship of the material in the finite element model of engineering problem. In case of material linear models; when the strain occurring in the part during the analysis exceed the elastic strain limit defined for the material in case, it should be noted that solution for the model continues as nothing happens but the experiment shows abnormal behaviors in contrast to the model predicts. In reality; up to a limit strain hardening occurs. Whereas; strain hardening means that when the material is kept free after deformed with a strain higher than elastic limit, hardness of the material is observed to have higher values. This can be confirmed in Figure 30 of the bearing steel that will be used during the thesis work. It can be figured out that there are higher values of yield stresses for increasing strain values above elastic limit.

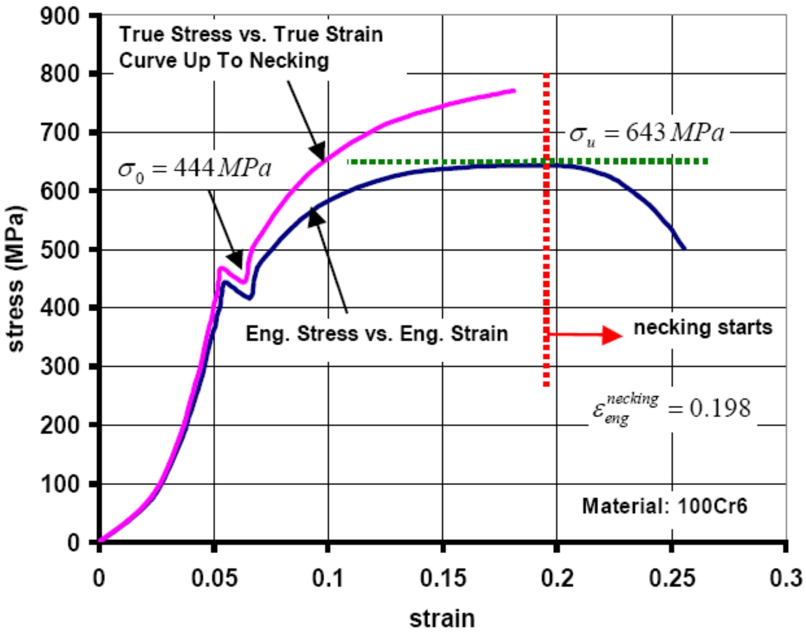


Figure 30 Stress-Strain Curve of the Bearing Steel 100Cr6 [53]

While solving contact only nonlinear problems, data types that should be kept in mind are displacements calculated on nodes and boundary applied on nodes. From these data, one should accordingly calculate new conditions of contact state and new values of forces and/or heat transfer. There are different contact algorithms defined in theory and practically applied programs. Contact algorithms can be defined into following groups:

- Defining newly formed contact conditions

- Motion of nodes in contact
- Contact separation criteria

Example algorithms and definitions for each group are given below;

4.1.1. Contact Nonlinearity

4.1.1.1. Defining Newly Formed Contact Conditions

Solving a segment of the finite element model introduces new positions of nodes. When these new coordinates for the nodes come in a predefined boundary layer of the surface that the system deals with, those nodes are meant to be in contact state. Thus meaning a shift of the node coordinates to the exact function defining the surface. Nodes are shifted to new coordinates resulting a strain in the flexible body. Then the choice of repeating the previous segment with updated node coordinates comes into place. This choice can be defined by two different contact algorithms.

There are other possibilities one can deal with such contact occurring conditions. One does not shift the nodal coordinates to the exact function values of the surface. One can fix the coordinate whenever a node is located in an arbitrary position of boundary layer. Then the node is characterized to be in contact state. Such an algorithm maybe recommended as alternative and faster converging.

4.1.1.2. Motion of Nodes in Contact

When a node goes into contact state it is not kept fixed. The motion of the nodes in contact state is defined as the frictional motion that the nodes possess. There are also different models for frictional motion in contacting bodies. Models can be grouped as flexible body-rigid body contact and flexible body-flexible body contact.

Treatment of frictional motion includes calculation of friction forces in contact area. General trends include Tresca and Coulomb friction models. These two models both work with a constant friction coefficient during the simulation. Tresca friction model works on nodal stresses whereas Coulomb model works on nodal forces. Nodal Force method directly calculates the friction force by multiplication with Coulomb friction coefficient affecting at the node. Whereas, nodal stress method extrapolates the stress values from the Gaussian integration points to the surface nodes and multiplied by the contacting area and shear friction coefficient to achieve frictional force. Treatment of material models include sophisticated laws such as plasticity or viscoplasticity, but conventional and inadequate friction laws such as Coulomb's or Tresca's laws make the results generally not very reliable [14].

Both friction models Coulomb and Tresca have different numerical implementations in case of motion calculation at contacting nodes. These implementations can be velocity based, displacement based and stick-slip based for Coulomb theory [54]. These methods can be applied in different types of analysis. At this stage user intuitive comes into place; the user of the finite element theory (namely simulation program) or the coder of the simulation program should try different algorithms and select the most appropriate algorithm. Some of them may require higher solution time in terms of too many recycles for calculating the motion or movement case and neutral point position. There is another parameter comes to place that is the minimum velocity value that the node has to have in order to move. This has to be applied to achieve convergence and stability in case of numerical errors.

4.1.1.3. Contact Separation Criteria

There are also different methods for calculation of which nodes leave contact state. Calculation of separation criteria depends on the same method as calculation for frictional force. Separation can be based on stress or force applied on the nodes in contact state. One can define separation threshold value that the contacting node can deal with due to numerical errors or stability requirement. This separation threshold can be tensile force or tensile stress value applied on the node. Tensile force is calculated readily on nodes during solution of system. Therefore, you define a minimum value of tensile force perpendicular to the surface to enable separation. The other criterion is the value of tensile stresses on the contacting nodes. These stress values can be calculated from the force values divided by the equivalent area that encloses the node in contact. Minimum tensile stress value is defined again to enable separation.

These different criterions can be applied in different types of analysis. It is again the choice for the application of the finite element analysis. The user of the finite element theory (namely simulation program) or the coder of the simulation program should try different algorithms and select the most appropriate algorithm. Some of them may require higher solution time in terms of too many recycles for calculating the previous segment of solution for contact state.

In case of contact separation algorithms, one can select whether the node comes into contact state at the middle of the segment or at the end of segment that is being solved. When the first algorithm is applied, one should continue iterations and modify the stiffness matrix during each change of contact conditions. The second choice is a faster method that you do not deal with modifying stiffness matrix until the current increment or segment is finished. One may change the boundary condition only before starting the new segment solution. The first method is more reliable but takes much longer time in case of solution. It is recommended in analysis of metal forming with rolling processes. The second one is more applicable and useful in solution of forging and extrusion type metal forming analysis.

There is another algorithm choice that you check or do not check a new contact state for the same node that comes into contact during the same segment [54]. Checking makes the solution more reliable but the solution time is again longer.

4.1.2. Material Nonlinearity

Material nonlinearity can be described with plasticity procedures and nonlinear elasticity like rubber materials.

Plasticity is defined as "the ability to retain a shape attained by pressure deformation" [55]. When the forces are applied to a material it may undergo elastic deformation or elastic and plastic deformation. Elastic deformation is recovered but plastic is not recovered. Therefore, one needs to include plasticity effects to the material model in finite element code whenever dealing with large deformations. Solutions from finite element codes give results in terms of displacements and accordingly the strains and stresses in the material can be calculated. If the strain value passes over the specific elastic limiting value for the material at hand, the material starts yielding and plasticizes afterwards. When the material is released, elastic strain is recovered but plastic strain is not recovered. For each element you need to check whether the material plasticize there in terms of strain values. In order to see plasticization effects you need to have material model and finite element code accordingly. Material model includes flow stresses in terms of constant temperature and constant strain rates.

Material models have been listed as examples;

Elastic Material: There is no plasticity calculation.

Rigid Plastic Material: Plasticity is regarded as the only acting deformation characteristic. There is no elastic part while distributing strain values in material model. There is no elastic-spring-back effect. This material model is faster and more easily coded but the results are not reliable when deformations are small where plasticity still exists in reality also.

Elastic-Plastic Material: Material both has elastic and plastic deformation. This model does not include strain-rate effects. Strain rate is regarded as constant and is not included in any applied code up to now. A recommendation to coders would be application of strain rate update to the elastic-plastic material model. Element's strain value is calculated and strain rate is calculated according to previous strain value and time increment between two segments. At hand, one has the strain-rate and strain value. From the flow curve, one selects the correct flow stress value/tangent stiffness value. It is now your choice to repeat the iterations for the current segment or use the strain-rate values for the next segment.

Visco-elastic Material: Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscous materials, like honey, resist shear flow and strain linearly with time when a stress is applied. Viscoelastic materials have elements of both of these properties and, as such, exhibit time dependent strain. viscoelasticity is the result of the diffusion of atoms or molecules inside of an amorphous material [56].

Visco-plastic material: Viscoplasticity is a model for rate-dependent plasticity. Rate dependent plasticity is important for (high-speed) transient plasticity calculations. It should be used, however, in combination with a plasticity law. In that aspect, viscoplastic solids exhibit permanent deformations after the application of loads (like plastic solids) but continue to undergo a creep flow as a function of time under the influence of the applied load (equilibrium is impossible) [1].

4.1.3. Geometric Nonlinearity

Finite elements are defined by angles that are defined between edges of the element. Element quality is defined by the values of these angles and length ratio between perpendicular edges. If there are large rotations in an element, angles used to formulate the element properties at the starting of the analysis should be modified. At this stage, one can also choose not to modify these formulations to make the code simpler or maybe faster solution time. The choice and choosing the optimum method of solution is dependent on the user of the finite element theory. The modification to the stiffness matrix can be applied at each segment of solution or at each iteration during a segment.

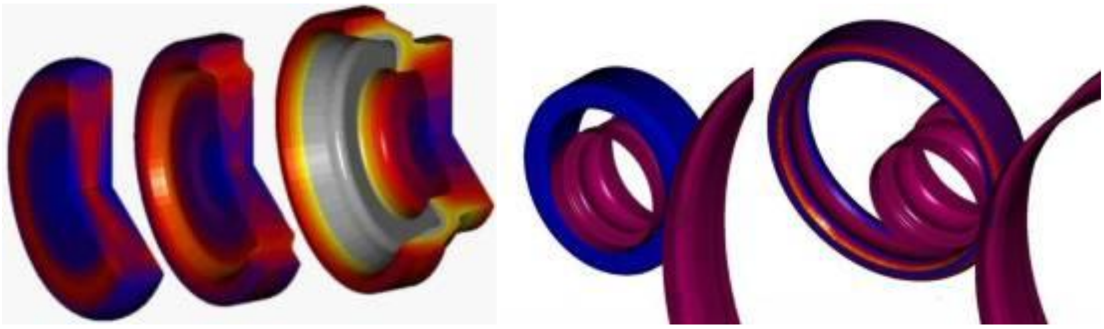
The second geometric nonlinearity is large deformations that occur during solution of the problem. This brings the problem of lower element quality due to deformations resulting in angle and length ratio irregularities. In this case, one should remap the mesh region and transform the previous nodal values to the new mesh structure.

4.2. Metal Forming and Finite Element Analysis

Designs of metallic parts in products require production by different techniques. These techniques can be given as changing the already part shape in hand or combination with different materials. Change in shape can be achieved by forming with or without material removal, cutting material by different type of cutting mechanisms and grinding. Combination of different or same type of materials can be achieved by joining, coating, casting and powder metallurgy with or without different elements.

Definition of metal forming, according to DIN 8580, is given as it is the manufacturing by plastic (permanent) change of the form of a solid body by preserving both the mass and the cohesion.

Metal forming processes require a blank shape that has predetermined dimensions. So that, one needs to have a specific preform for each final shape. Examples for blank and final shapes are given as following;



a) Hot Forging b) Cold Roll Forming of Bearings

Figure 31 Examples of Blank and Final Shapes in Simulations

Preform of the metal forming process has to have exactly the same weight as the final formed part, when there is no material removal. Exception to this case is the situation where material is removed from the sides. The chip forming at sides is due to excess material and cavity filling requirements in complex surface shapes.

Classification of metal forming processes according to deformation characteristics can be figured as following;

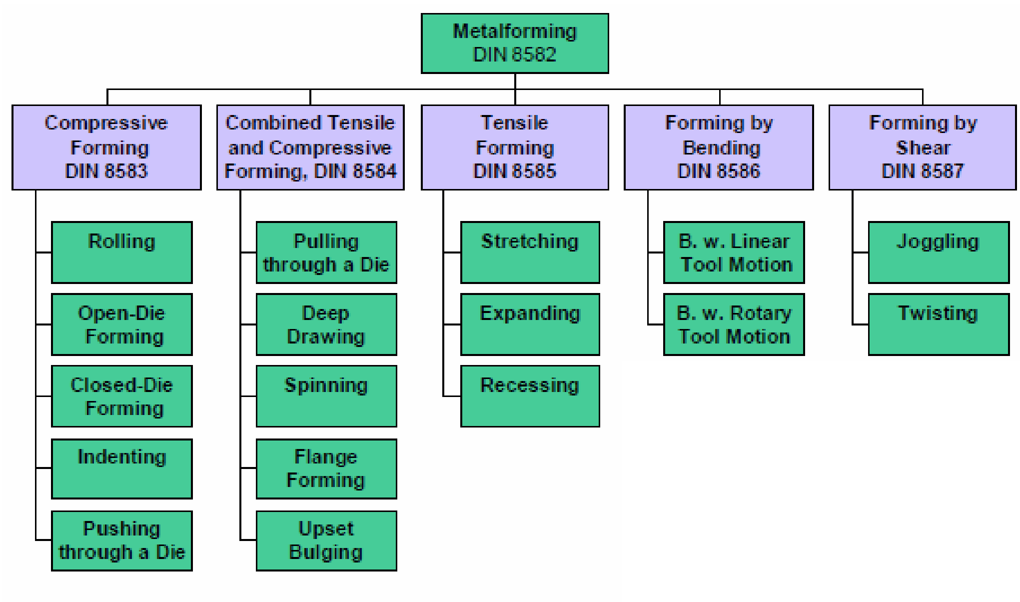


Figure 32 Classification of Metal Forming Processes [57]

Differences between metal forming and metalworking processes are energy requirement, initial setup of the process, material use efficiency, redemption of the process, productivity rate and product quality of the formed part. Metal forming processes require more energy input than metalworking due to large forces during the process. Initial setup costs of the metal forming processes are higher due to large and expensive costs when compared with metal forming. Also initial setup of the metal forming is more time consuming since every part requires specific and heavy tools and dies. Metal forming processes require no metal removal on selected parts while attaining the final shape whereas metal working process mainly works on material removing by different cutting mechanisms. Minimum workpiece quantities are necessary for metal forming parts due to high initial setup times and tool costs whereas in metal working universal tools can be used for different parts on selected types. Production cycle times are generally smaller for metal forming in comparison with metal working since there are too many steps in working for example for each turning feed in turning operation. Metal forming generally requires one to specified number of steps like ~30 whereas metal working steps may be hundreds or thousands. Metal formed parts have great mechanical properties in case of high strength values and long fatigue life by the help of arrangement of fibers formed by grain boundaries in comparison with metal worked parts.

Advantages of the metal forming processes can be given as material saving, high material strength, high productivity rate for selected processes and dimensional persistence of the formed parts.

Yield stress is the stress limit in the solid body at which the material starts to flow namely advances through nonreturnable shape change. Shape changing in metals can be named as deformation. The strain value observed at yield point is named as yield strain. Below the yield stress state, elastic deformation is observed whereas above yield stress and accordingly yield strain, the material has both elastic deformation and plastic deformation. Elastic deformation resulting in elastic stresses can be defined as the deformation that is recovered when the applied force is removed. Plastic deformation of metals can be defined as permanent deformation due to movement of dislocations on slip systems by applied boundaries. The total of elastic and plastic strain is total equivalent strain in the part. When the part is unloaded, the elastic strain is recovered and plastic strain remains. Recovery of elastic strain creates a new stress state in the part resulting in residual stresses. Residual stress term originates from the intention of the part to deform yet the deforming forces are removed.

Complicated relationships exist between the parameters in ring rolling process. It is highly time consuming and costly to examine these relationships physically. Both economical and less time advantages of computer simulations shall be applied to ring rolling. Computer simulations could be prepared with finite element and finite volume technique applied programs like MSC.Marc, simufact, Deform, Q-Form, Forge-3D et cetera.

Main study topic in the thesis leads to making finite element models for the profiled ring rolling process. Finite element model will be prepared by Simufact program using MSC.Marc as the implicit solver code. Tool drawings will be imported and used in the simulations. Success of the study in thesis mainly depends on making efficient and reliable enough models having faster solution times. Results that can be obtained from simulations can be listed below;

1. Material flow during embodiment of the part.
2. Stress and strain values in the deforming material.
3. Forming force variations of the tools with respect to movements and process time.
4. Frictional forces over the tool surfaces.
5. Normal stresses (pressures) affecting on the tools giving clues about tool life.

Concept of the study can be at the physical side when the numerical models are validated with experiments. Validation could only be processed by following the above results during experiments. In addition to the above general terms, specific residual stress can be processed both in finite element simulation results and in experimental results.

Residual stresses will be measured by X-Ray Diffraction technique. This technique depends on dimensional change between crystallographic planes. Dimensional change is used in calculating engineering strain and residual stresses in the workpiece. Elastic part of the strain is used during calculation, since residual stress means elastic leftover part of the elastic-plastic strain during deformation. In metal forming processes tools are released from the worked part and accordingly strain recovery is observed. During forming total equivalent strain is not uniform around the whole part so is elastic recovery. Therefore, nonuniform elastic recovery creates elastic stresses in various parts of the workpiece.

4.3. Axisymmetric Finite Element Model of Ring Rolling

In ring rolling process as defined before; there is metal flow in both circumferential and radial direction. Creating a simplified model might be established as an axisymetric finite element model. However, there is cross-sectional area reduction, so that one should define cross-sectional area change and accordingly change the inner / outer diameters for the ring. Changing inner / outer diameter for the ring should comprise shift of the symmetry axis in the axisymmetric finite element model.

Simplified simulation model for profiled ring rolling operation could be established by following the defined steps below;

1) Investigation of the form roll movement mechanism in ring rolling equipment

Acquired information: Feed rate is continuously changing at the hydraulic type form roll movement mechanism. Feed rate is defined as the decrease rate of the cross-section namely gap between mandrel and form roll. However, this changing feed rate values cannot be modeled in simplified simulation model of ring rolling. So that a new model or constant feed rate values should be used in the simulations. Up-to-date simulations for ring rolling also include only constant feed rate values throughout the process. Elastic-plastic material model will be used in the finite element simulations throughout this study. Elastic-plastic model is rate insensitive. So that, changing feed rate values will not affect in terms of strain rate. Difference from the real condition would be the deformation zone in single pass of the ring through the roll gap between mandrel and form roll. In other words, cross-sectional area will decrease differently for single ring pass.

2) It is recommended to make outer diameter growth rate constant to increase the stability of the ring rolling process [18]. Following the given information in the research by Yan et.al, it is anticipated to input a table of the inner / outer diameter values in terms of time to the simplified axisymmetric finite element model of ring rolling.

3) Creating a mathematical model for inner / outer diameter growth rate values.

- Calculation of inner / outer diameter values in flat ring rolling with respect to time according to volume constancy principle.
- Creation of best-fit function for the obtained diameter values from volume constancy principle to input into the simulation of ring rolling.
- Application of second order functions for calculating inner / outer diameter values.

Mathematical Modeling:

For efficient application of finite element method, simplified ring rolling simulations need subsidiary mathematical models.

Axial symmetric finite element model requires boundary condition definitions for mandrel and form roll positions. Positional boundary conditions in terms of time are applied to curves defining rigid tools. Radius values for the preform and final ring shapes are used in order to input the values into the axial symmetric analysis. Instantaneous radius values will be the distance from the symmetry axis. Process parameters are given in Table 1.

Table 1 6208 type bearing ring profiled ring rolling process parameters

Phyical Property	**Value**
Blank Ring Inner Radius (r)	21.8 mm
Blank Ring Outer Radius (R)	29.68 mm
Blank Ring Thickness	7.88 mm
Formed Ring Thickness	4.36 mm
Mandrel Outer Radius	15.75 mm
Mandrel Center Coordinate	6.05 mm
Form Outer Radius	87.50 mm
Form Center Coordinate	122.18 mm
Form Roll Rotation Speed	13.3 rad/sec
Process Rolling Time	~6 seconds

Volume Constancy Model:

$$\pi(R^2 - r^2) = Constant \tag{5}$$

$$(R + r)(R - r) = {R_0}^2 - {r_0}^2 \tag{6}$$

$$R - r = h \tag{7}$$

$$R + r = \frac{{R_0}^2 - {r_0}^2}{h} \tag{8}$$

$$r = R - h \;\rightarrow\; R + R = \frac{{R_0}^2 - {r_0}^2}{h} + h = D \tag{9}$$

$$R = r + h \;\rightarrow\; r + r = \frac{{R_0}^2 - {r_0}^2}{h} - h = d \tag{10}$$

Note:

D: Ring outer diameter [mm]
d: Ring inner diameter [mm]
R: Half of the outer diameter of the ring [mm]
r: Half of the inner diameter of the ring [mm]
h: Ring thickness along the cross-section [mm]

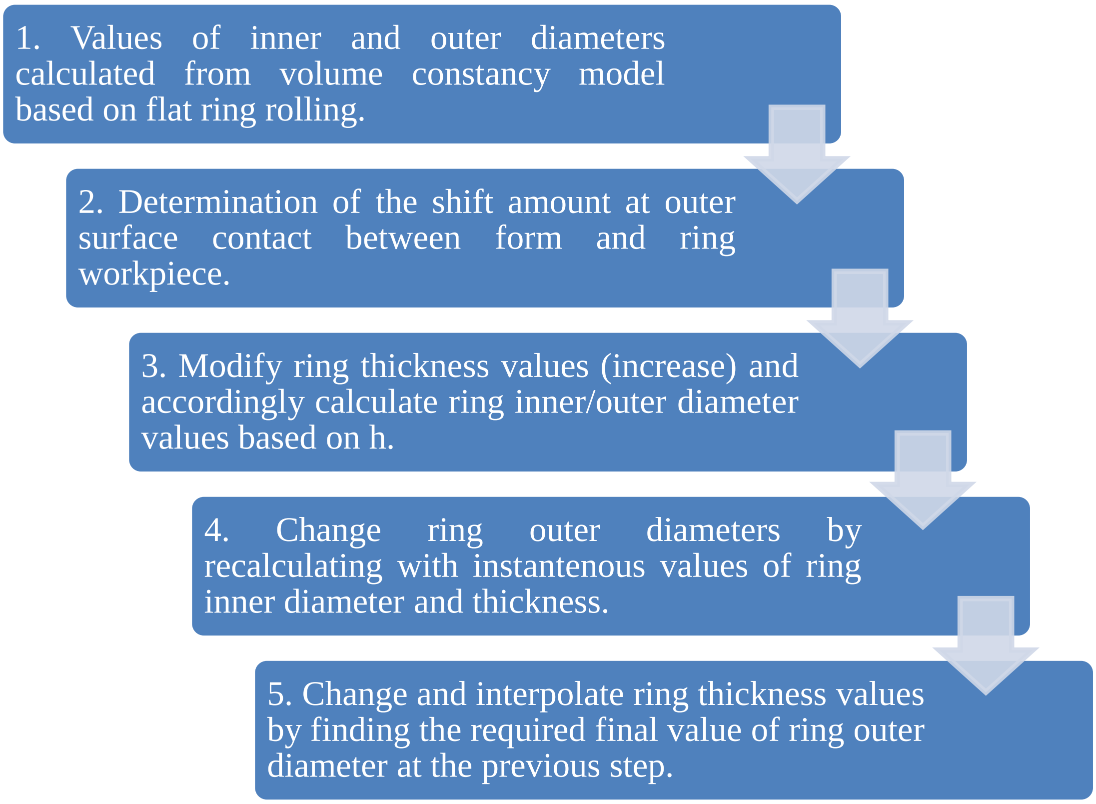


Figure 33 Mathematical Modelling Steps for Axisymmetric Analysis

In accordance with the aforementioned volume constancy model, inner / outer diameter values are calculated in terms of ring thickness and given as a graph in Figure 34. However, values are only valid for flat ring rolling and they are not applicable to profiled ring rolling. Due that, when the inner diameter reaches required value, the outer diameter ends up with a different value rather than required exact value. Ring rolling process has the advantage of calculating inner / outer diameter in terms of one of the parameters at hand. Equation 11 enables to calculate outer diameter from the inner diameter input. R is the ring outer radius, r is inner radius and h is the ring thickness.

$$R = h + r \tag{11}$$

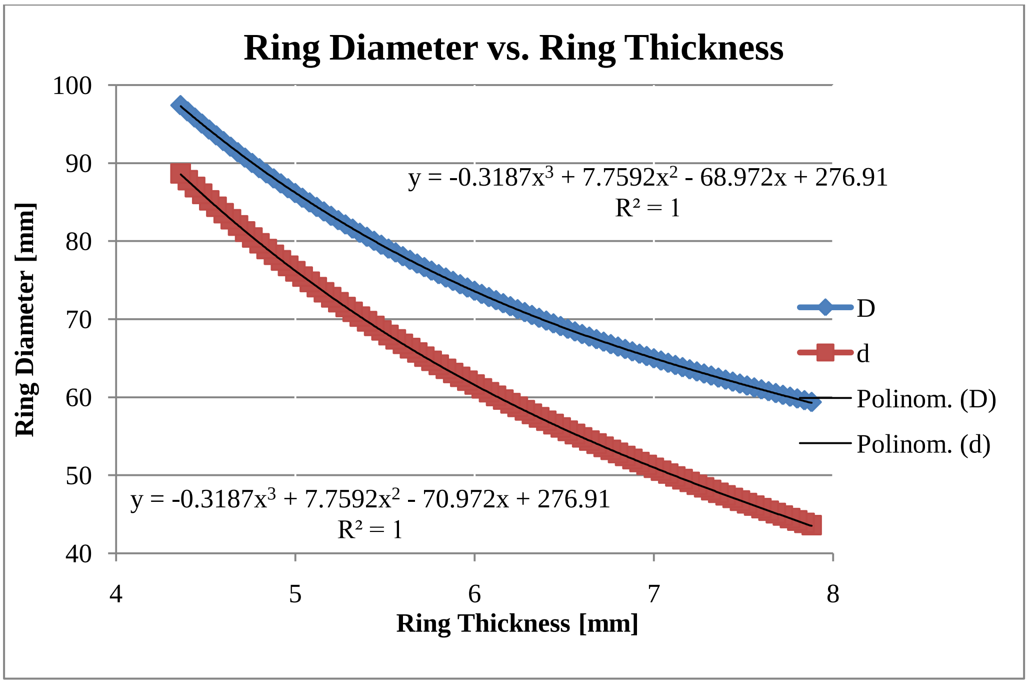


Figure 34 Best-fitted polynomial functions adapted to model result values

However, as seen in Figure 35 when the form roll and blank outer diameter comes into contact, there becomes a shift for the form roll initial position. The value for such a shift also changes due to combination of blank outer corner radius, outer diameter and width values and profile of the form roll. Shift at the initial position of the form roll can be calculated by Equation 12.

$$30.30903 - 29.68 = 0.629\ mm \tag{12}$$

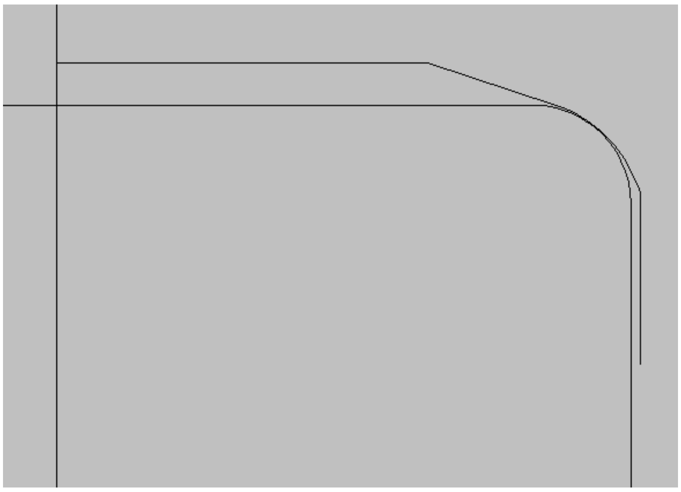


Figure 35 Shift at the initial position of form roll during the first contact with blank ring

Boundary conditions were defined as positions of contacting bodies. Contact bodies were axisymmetric elements for ring and rigid curves of mandrel and form roll. It comes out that the finite element code used in the simulations move the bodies as relative differences between the set of positions with respect to time. Namely, the finite element software does not use the position inputs exactly for mandrel and form roll but only the changes among time intervals. Outer radius of the ring is supposed to change from 29.68 mm to 40.06 mm, yet the end position of form roll is 40.68903 mm. When the modified initial position of form roll is remembered, the value was 30.30903 mm. That is the same difference above the exact value for outer radius of the blank with the form roll end position difference from the requirement. The reason for this is the initial shift on form roll position due to blank ring and profiled form roll contact. This issue obliterates the advantage of volume constancy in an axial symmetric model. Right solution for the ring rolling process cannot be acquired consequently.

Obtaining the required final value of inner radius and outer radius combination requires interpolation of ring thickness (h) through the previous modified coordinates. Accordingly, the final versions of the coordinates are obtained.

As can be seen from the final version of simplified model for ring rolling, inner and outer diameters attain the exact values required from the rolling process and no abnormal burr formation or cavity is observed between form roll and mandrel.

Obtained geometry and equivalent plastic strain by using mathematical model defined are represented in Figure 36.

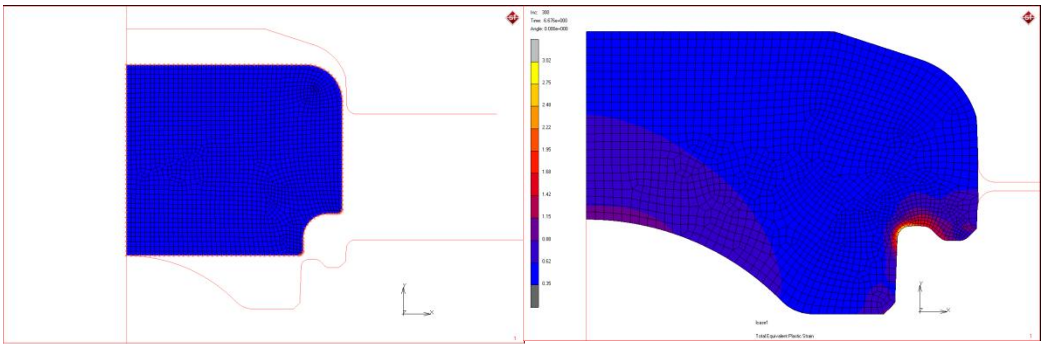


Figure 36 Resulting geometry and plastic strain by application of mathematical model

Created mathematical model requires tables of positions from known inner and outer diameters of ring and interpolations for each different preform shapes. In order to prevent manual table operations with hand calculations and accordingly make the analysis process shorter, a C++ code is prepared. From the compiled code, we can obtain positions of mandrel and form roll in terms of analysis time. Set of values can be input to the simulation program as boundary conditions. The inputs for C++ code are defined;

- Inner radius of preform
- Outer radius of preform
- Position of the form roll at the instant of initial contact between blank ring and form roll

With the help of above inputs, C++ code, which brings in the inner radius (mandrel position) and outer radius (form roll position) values, is given in Appendix A.

Finite Element Modeling:

Axial symmetry assumption is used. Symmetry axis is the centerline of the rolled ring. The benefit from the axial symmetry assumption is the area reduction during inner / outer diameter increase because of volume constancy. The model exactly provides constant volume during the analysis only creating inconvenience when the cross-section is remeshed due to excess deformation.

Mechanical and static loading case is used. Finite element model includes all nonlinear effects in terms of material, contact and geometry. Coupled thermal effects are neglected due to small temperature increase, as the ring rolling process at hand is cold metal forming operation. Loadcase time is the output from the prepared C++ code. Temperature is kept constant during analysis, so that temperature change due to plastic deformation and heat transfer between workpiece and tools are neglected.

Friction model uses Coulomb theory, which is effective in rolling operations. Friction model is working with forces and velocities at surface nodes. Nodal velocities below 0.1 mm/sec. at contact interfaces are neglected, namely treated as not moving. Friction coefficient is obtained from the previous study by Music [58] ad has the value of 0.08 to be used with Coulomb type friction.

Material model is elastic-plastic model that does not include rate effects. Flow stress curves are prepared at constant discrete temperatures and strain-rates. Flow curves for different temperatures are interpolated to get the requested flow stress at the desired temperature value. Convenient flow stress values and elastic modulus are obtained from 100Cr6 bearing steel material model [58] using constant temperature that is 50 degrees Celsius.

Discretization:

Edges of the half ring cross-section are divided into segments that form the edges of the finite elements. In Figure 37, the element discretization is accomplished by the aforementioned technique. Four noded, axisymmetric, consisting linear interpolation functions and having four integration points (full integration) elements are used.

Contact Bodies:

Figure 37 gives the illustrations of the following named contact bodies.

Ring defines the deformable ring workpiece.

Mandrel is the rigid cylindrical rolling tool that is placed inside the ring in actual three-dimensional process.

Form defines the rigid cylindrical rolling tool that is lying on a axis outside the workpiece.

Symmetry named curve defines the symmetry axis, which is perpendicular to the ring centerline and passes through center of the ring cross-section.

Symmetryx is the curve defining centerline of the ring namely axis of the axisymmetric model.

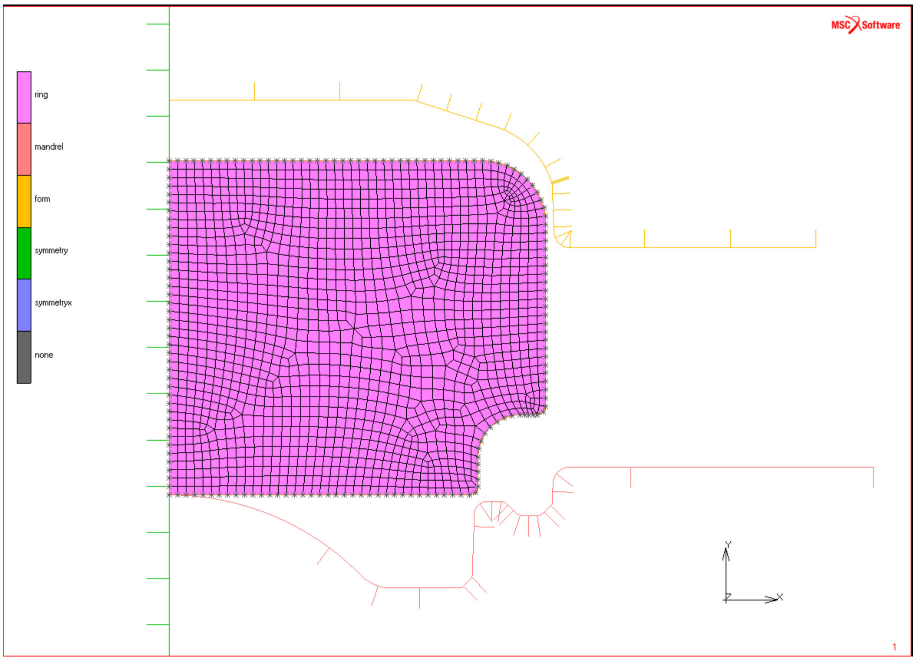
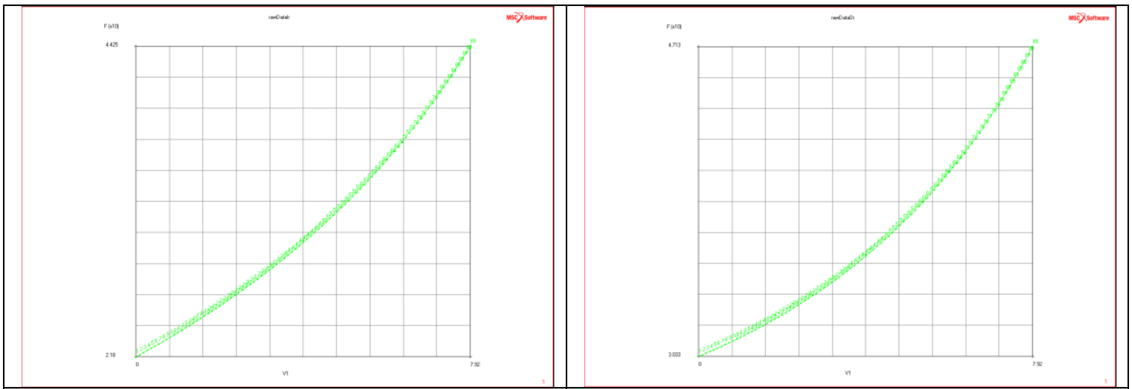


Figure 37 Contact Bodies in axial symmetric model of profiled ring rolling

Boundary Conditions:

As seen in below Figure 37, rawDataIr named coordinate table is applied as a position boundary condition to curves defining rigid mandrel contact body. rawDataOr named coordinate table is applied as position boundary condition to curves defining rigid form roll contact body.



(a)	(b)

Figure 38 a) rawDataIr b) rawDataOr coordinate table

Initial Conditions:

50 degrees Celsius temperature state variable (initial condition) is applied to every nodal point at the ring workpiece.

4.4. Three Dimensional Finite Element Model of Ring Rolling

In the model, three-dimensional eight noded solid elements are used. Thermal effects are neglected, only mechanical solution is performed at constant temperature. Explicitly, finite element model created does not include temperature changes due to heat transfers and plastic deformation. Friction model depends on Coulomb law that is effective in rolling operations. Frictional effects depend on nodal forces and nodal velocities at contact area. Nodal velocities smaller than 0.1 mm/sec. at the contacting surface are treated as not moving. Friction coefficient obtained from previous works done with 100Cr6 bearing steel is used. The value is 0.08 to be used with Coulomb friction theory.

Profiled ring operation is applied on a symmetric ring in this study. The ring is symmetric along the plane perpendicular to the ring centerline axis. Therefore, plane passing through the center of the ring cross-section that is also perpendicular to the axis, is treated as symmetry plane.

Finite element model includes all nonlinear effects in terms of material, geometry and contact. While ring is rotated, all the elements coming into contact state should have at least 3 to 4 increments before leaving contact state.

Convenient flow stress values and elastic modulus are obtained from material model using constant temperature that is 50 degrees Celsius.

Material model is elastic-plastic model that does not include rate effects. Flow stress curves are prepared at constant discrete temperatures and strain-rates. Flow curves for different temperatures are interpolated to get the requested flow stress at the desired temperature value.

Discretization:

Half of the ring section along x-y plane is meshed with quad elements as seen in Figure 39. These quadratic plane elements are expanded around ring axis with 2 degrees segments resulting in 180 repetitions for the complete ring. By this way, three-dimensional elements could be formed as seen in Figure 40 below.

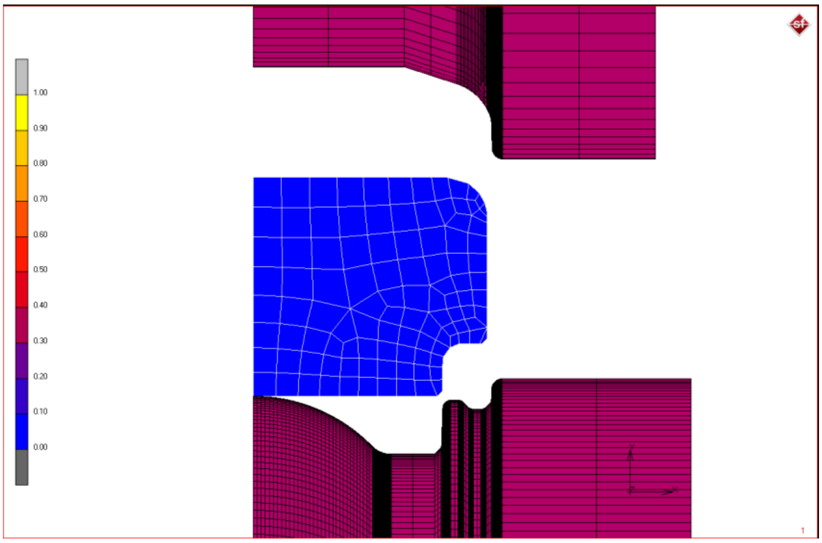


Figure 39 Half-cross-section mesh structure for ring workpiece

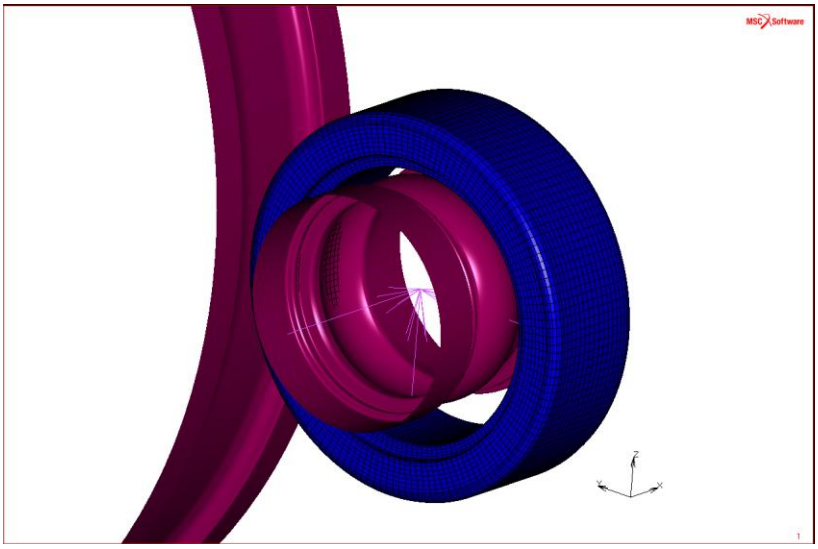


Figure 40 Solid mesh structure for ring workpiece in three-dimensional finite element model

Contact Bodies:

As seen in Figure 41, contact body “ring” defines the deformable ring workpiece.

Mandrel is the tool inside the ring workpiece that is formed by rigid surfaces.

Form is the cylindric tool that has bigger diameter and named as form roll tool. Form roll is also composed of ridig surfaces.

Symmetry is the plane that passes through the middle part of the ring perpendicular to the centerline of the ring.

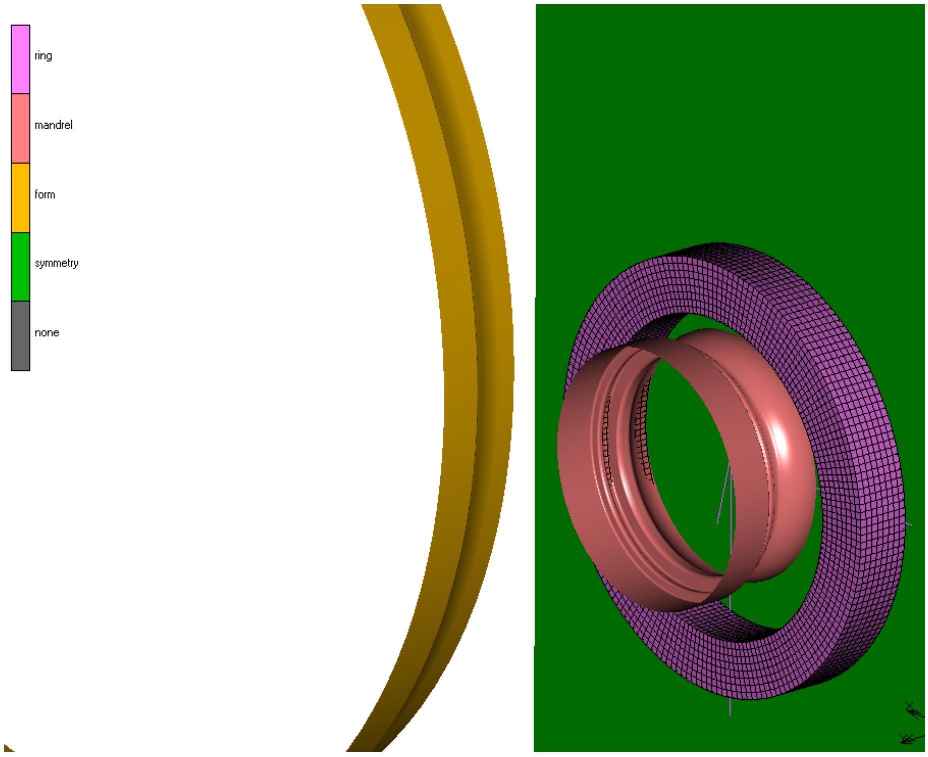


Figure 41 Contact Bodies in three-dimensional finite element model of profiled ring rolling

Boundary Conditions:

As seen in Figure 42, pivot, rotation and initial named boundaries are applied to the model. Mandrel defines a massles contact body that has movement only due to forces effecting on it. Boundary condition pivot fixes the center point of mandrel. Rotation named boundary enables the mandrel to only rotate around y-axis while restricting rotation around other axes. The other boundary initialHold restricts the movement of the whole ring along z-axis due to instability only during first contact occurrence between ring and tools.

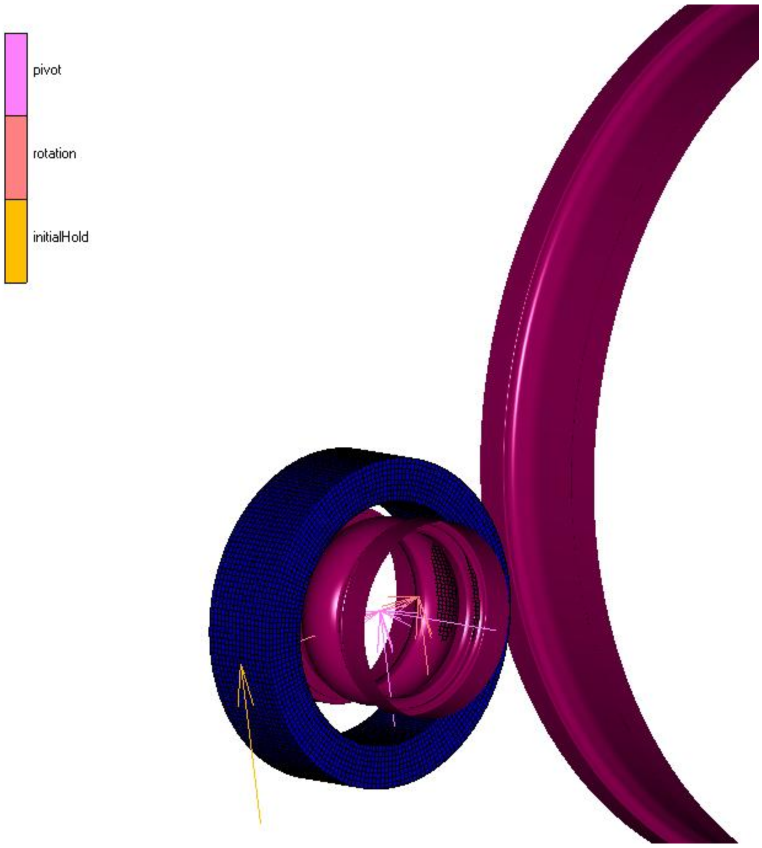


Figure 42 Boundary conditions of three-dimensional finite element model

Initial Conditions:

Every nodal point of the ring is assigned 50 degrees Celsius temperature state variable.

4.5. Resulting Ring Workpiece from Three-Dimensional Profiled Ring Rolling Simulation

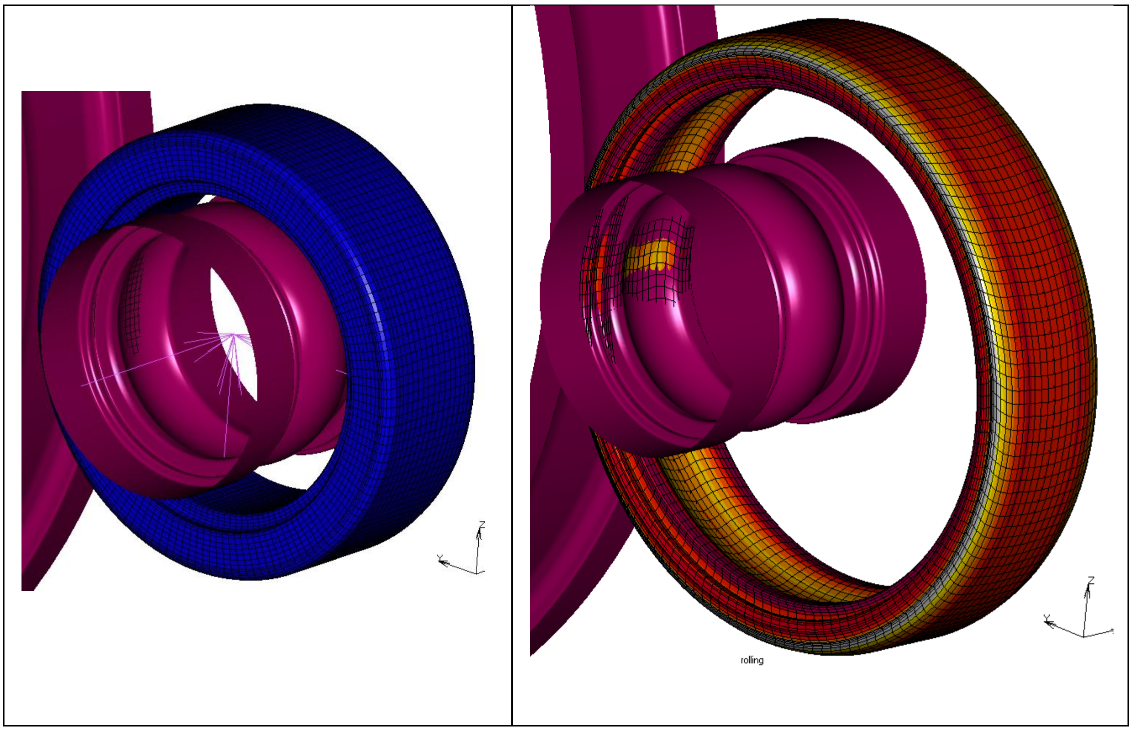


Figure 43 Final ring workpiece (right) rolled from the blank ring (left)

As seen in the above Figure 43, three-dimensional profiled ring rolling has gathered the resulting workpiece with 15408 elements and 15015 increments. The solution time on an HP-xw6400 workstation (8 Intel Xeon 5335 CPUs & 4GB Ram) is 71 hours of CPU time.

4.6. Comparison between 2-D Axisymmetric and 3-D Full Finite Element Model

Parameters of finite element models are investigated in detail and compared one by one. At first, numeric solver parameters are compared such as element type, element number, node number, friction model, contact types… Solution process is compared in terms of solution time, domain decomposition method. Finally, results of the simulations are compared in terms of contour results along the cross-section of the ring and three-dimensional view. Contour results are prepared for von mises stress and total equivalent plastic strain.

4.6.1. Numeric Solver Parameters Comparison

Table 2 Numeric Simulation Program Parameters

	Axisymmetric Model	Three-Dimensional Model
Element Type	Mechanical Axisynnetric Solid Quadratic	Mechanical 3-D Solid Hexagonal
Integration Type	Full Integration	Ful Integration
Element Number	2006	15408
Node Number	2094	19010
Friction Model	Coulomb Arctangent Velocity	Coulomb Arctangent Velocity
Contact Type	Rigid Body Single Sided	Rigid Body Single Sided
Contact Seperation Criteria	Stress	Stress
Contact Seperation Threshold	0 MPa (Default Value)	10 MPa

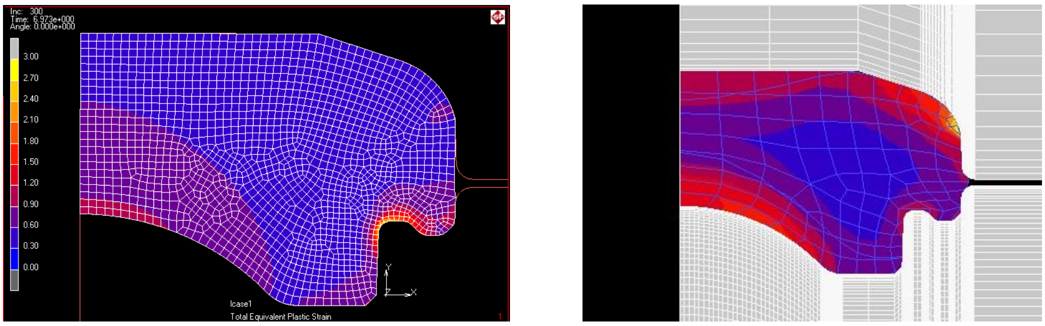
4.6.2. Solution Process Parameters Comparison

Table 3 Finite Element Solver Parameters

	Axisymmetric Model	Three-Dimensional Model
Increments	300	15015
Convergence Criteria	Relative Residual and Displacements	Relative Residual and Displacements
Convergence Ratio	0.05	0.1
Solution Time (CPU Time)	234 seconds	71 hours
Remeshing	19 times	Not Applicable
Number of Domains (DDM)	Single Domain	8

4.6.3. Simulation Results Comparison

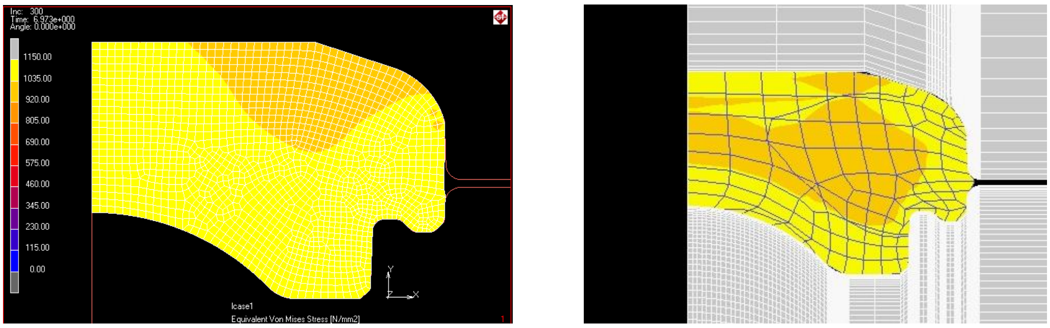
In Figure contour results of total equivalent plastic strain is compared after rolling at the cross-section between axisymmetric and three-dimensional model.



a. Axisymmetric Model Result   b. Three-Dimensional Model Result

Figure 44 Total Equivalent Plastic Strain Comparison

In Figure contour results of von mises equivalent stress is compared after rolling at the cross-section between axisymmetric and three-dimensional model.



a. Axisymmetric Model Result   b. Three-Dimensional Model Result

Figure 45 Von Mises Equivalent Stress Comparison

CHAPTER V

CASE STUDY

This chapter gives information about general metal forming processes and the specific cold ring roll forming process, process parameters, tools used in the process and ring rolling applied product types with examples. Deformation characteristics such as shape of the deformation zone and effecting parameters are defined. General information about the ring rolling equipments is also provided.

Advancements in the ring rolling machine are planned for more effective experimentation in the research study. Some modifications will be applied to achieve our needs. Force values and torque of the tools need to be acquired to compare with finite element simulations.

Throughout the case study, investigated variables and effects are listed at below figures.

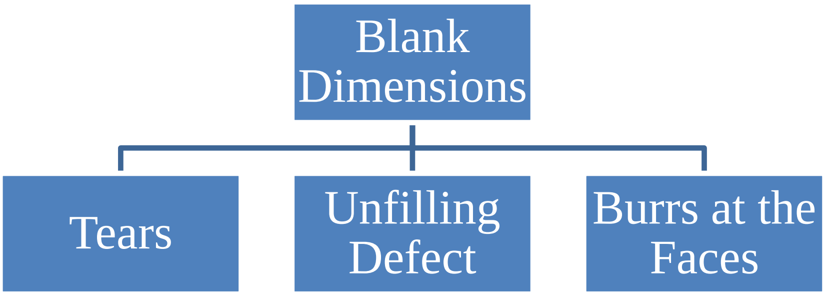


Figure 46 Effects Study due to Blank Dimensions

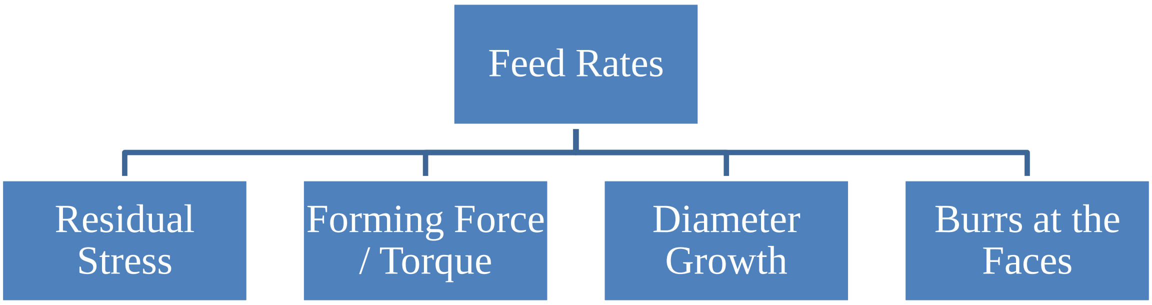


Figure 47 Effects Study due to Feed Rates

5.1. Experimental Setup

Figure 48 KYOEI NCRF-120 OR Ring Rolling Machine

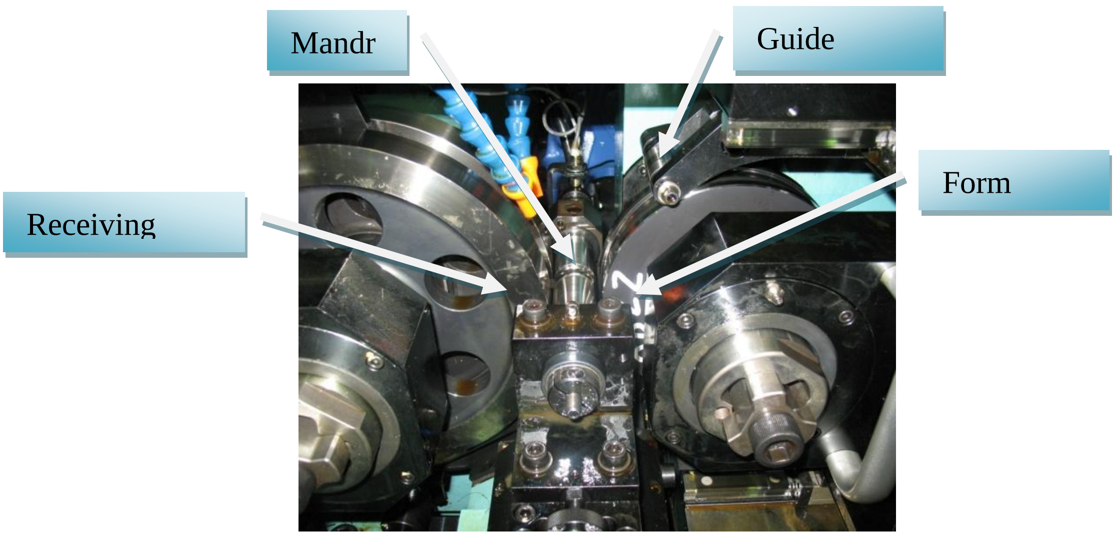


Figure 49 KYOEI NCRF-120 OR Ring Rolling Machine Forming Tools

Servo Controlled Form Roll Advance enables a stabile cold metal forming process.

Up to 130 mm diameter rings' production is at hand. Minimum blank inside diameter is 30mm whereas maximum thickness is limited to 40mm.

Maximum rolling force in the advancement direction of the form roll is 18 tonnes. Rotation speed of the form roll can be input between 10 to 200 revolutions per minute. Both of these two parameters can be monitored with current consumption of the main form roll motor that consequently gives torque value of the form roll. There is no limit for the feed value adjustment between 0 to 500 mm/min in case of experimental rolling equipment. However, there are lower and higher limits for feed values due to higher forming loads in aforementioned cold roll forming operation.

Adjustable feed and rotation speeds of the form roll enables to input process parameters with high accuracy.

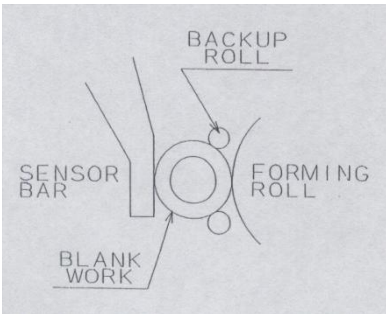


Figure 50 Sensor Bar (In Process Diameter Measurement Apparatus)

In process measurement and control of the parameters are obtained by sensor bar as seen on the figure. Sensor bar also controls the size at the beginning of the process to eliminate erroneous loading or erroneous dimensional blank part.

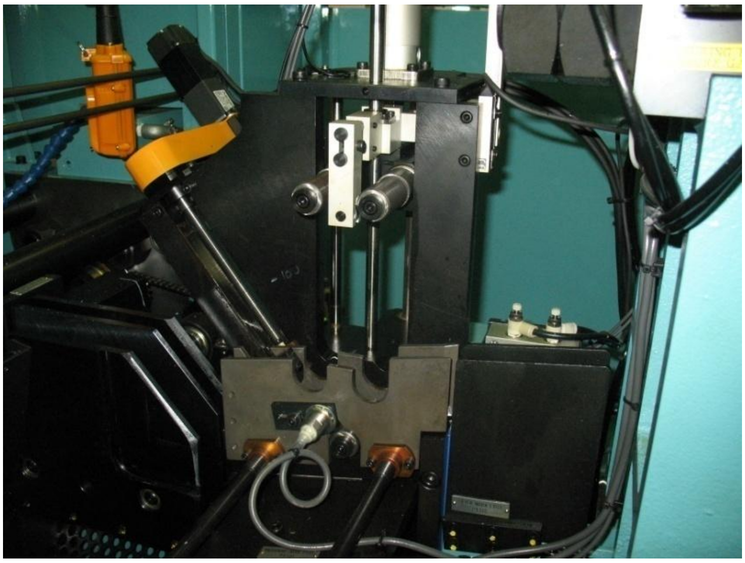


Figure 51 Outer Diameter Measuring Unit

Diameter and roundness measurement device measures rolled rings in a separate process after forming.

Data acquisition of force and torque parameters of the form roll keeps track of the previous forming sequences.

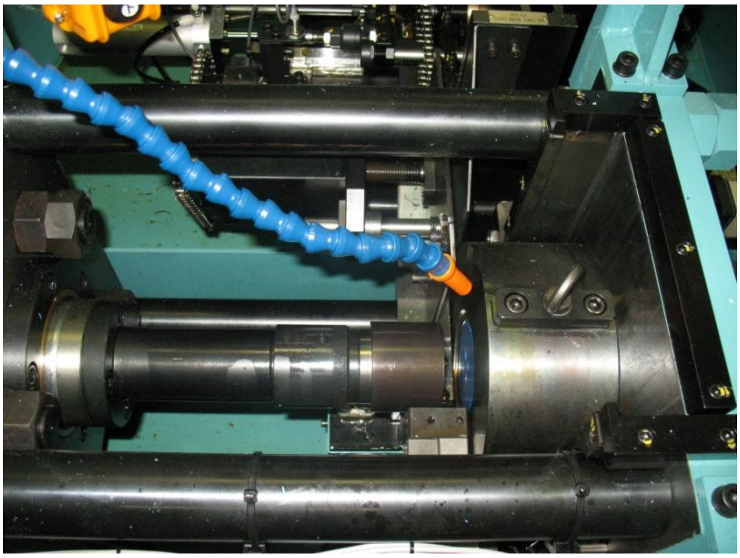


Figure 52 Sizing Unit

Separate sizing unit handles bigger diametrical parts after forming operations. This unit helps to achieve dimensional accuracy between produced parts and keeps roundness values lower.

5.2. Effects Study due to Blank Dimensions

Blank dimensions directly affect the formed product after ring rolling. It is desired to obtain the following cross-section of the ring after profiled ring rolling.

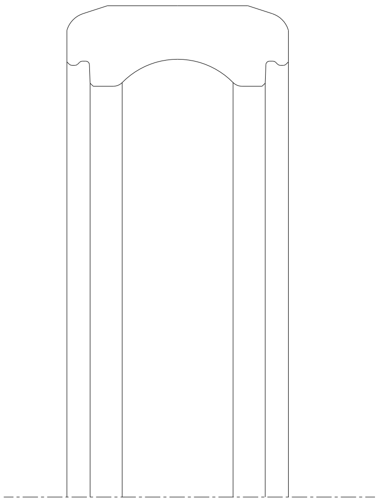


Figure 53 Cross-section of the profile to be formed

The tolerances for the roundness and diameter values are 60µm and ±50µm respectively.

Detailed dimensions obtained through the rolled ring profile measurement are matching to the nominal dimensions. All dimensions between the rolled ring and nominal ones are measured and comparisons performed. The tolerance zone is only ±50 microns and the rolled rings well conforming to the requirements. Meaning cold metal forming operation can be precise as high as having only 50 microns tolerance. Surface quality is much higher than machined rings.

5.2.1. Unfilling Defect

Uniflling defect is defined as the gaps between the workpiece and forming tools during rolling operation. Main cause for such an occurence comes from inappropriate blank dimensions.

In Figure xx, unfilling defect is represented with a mark at most happening position for such profile in this case study.

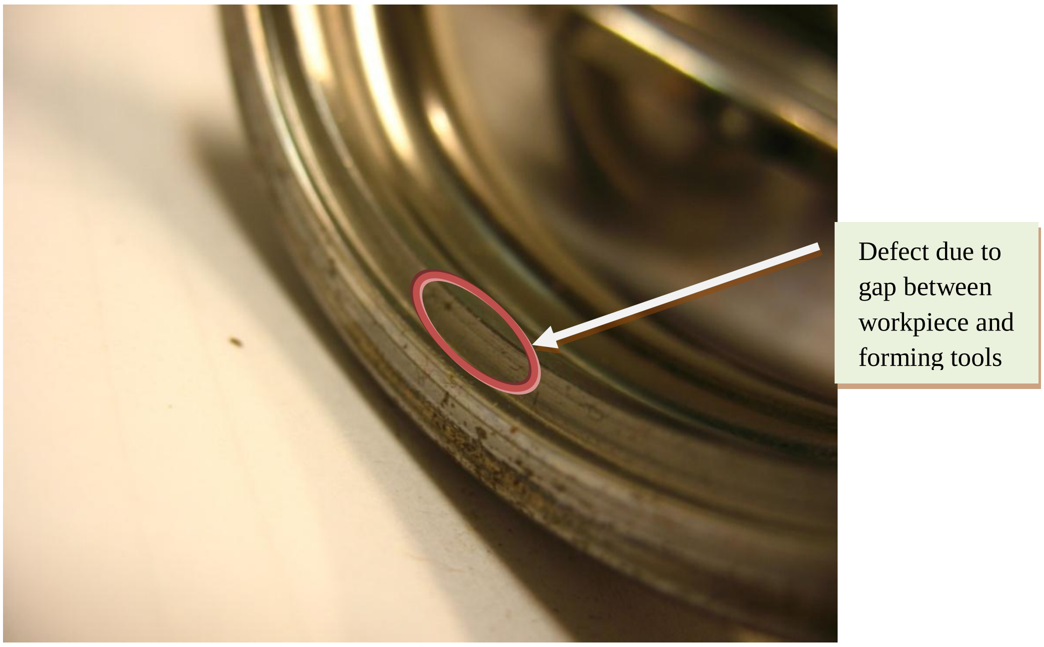
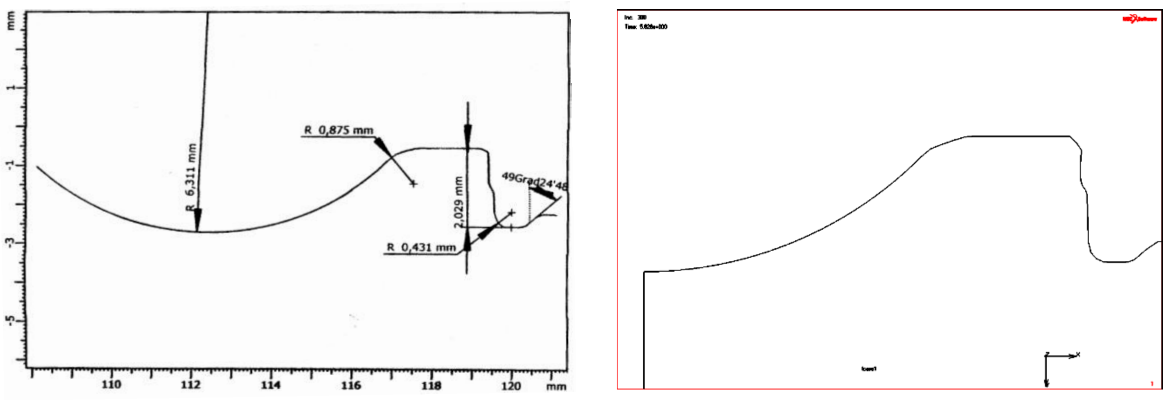


Figure 54 Unfilling Defect Observation at Bearing Ring

To represent unfilling defect by both axisymmetric simulation and experiment at cross-section, following figures are results both from experiment and simulation. Inspection at the rolled ring is made by measuring contour of the ring profile. Profile from the simulation is exported to dxf file format.



a.Contour Result from Profile Measurement

b. Contour Result from Simulation

Figure 55 Unfilling Defect Represented by Both Experiment and Simulation

In the below Figure results are overlapped. As seen on the figure maximum error between profiles is measured as 197µm. Therefore, profiles of the cross-section agree very well.

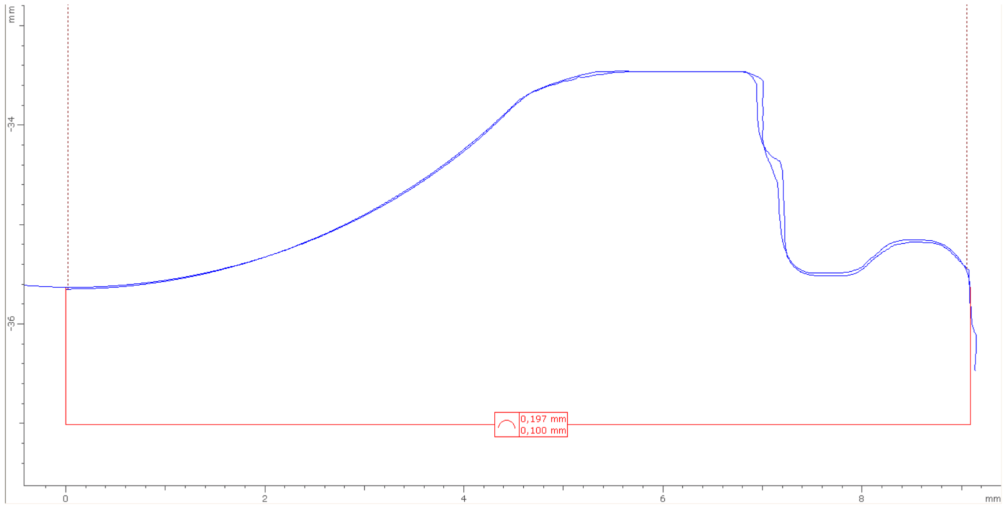


Figure 56 Comparison of Simulated Profile with Experiment

Blank shape and dimensions are modified according to the result obtained from finite element simulations. Rolled ring cross-section geometry will be checked by assigning a tolerance band around exact contour and by measuring all dimensional details by the contour measurement device.

At the below Table 4. Parameters for the blank dimensions are given. These parameters are used at the axisymmetric finite element simulations. From these preforms it is aimed to obtain the complete filling of the final profile at profiled ring rolling without any defects. Below Figure xx. shows parameter abbreviations and blank shape.

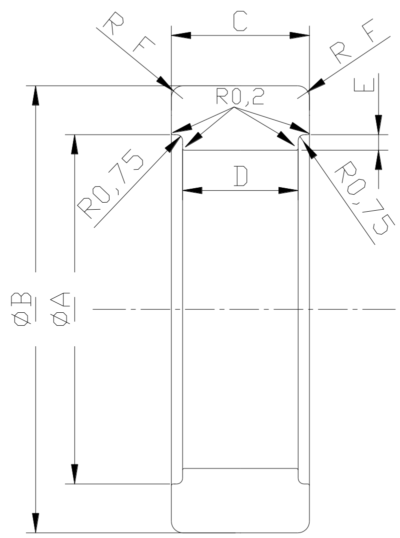


Figure 57 Blank Shape and Dimensions to be Modified

Table 4 Dimensional Parameters for the Blank Workpiece

Blank No.	Inner Radius-A	Outer Radius-B	Width -C	T Profile Width-D	T Profile Depth-E	Corner Radius-F
1	21.8	29.68	17.8	14.59	1.73	1.5
2	21.8	29.7	17.8	14.59	1.9	1.5
3	21.8	29.7	17.8	14.89	1.9	1.5
4	21.8	29.7	17.8	14.89	2	1.5
5	21	29.1	17.8	14.89	1.9	1.5
6	20	28.4	17.8	14.89	1.9	1.5
7	20.5	28.8	17.8	14.89	2	1.5
8	20.5	28.8	17.8	14.89	2	0.75
9	20.5	28.8	17.8	14.89	1.95	0.75
10	20.5	28.8	17.8	14.79	2	0.75
11	20.5	28.75	17.9	14.89	2	0.75

Simulation results with the above inputs are listed by maximum profile error. Listing of results are given in Table 5.

Table 5 Results of Simulation for the Blank Workpiece

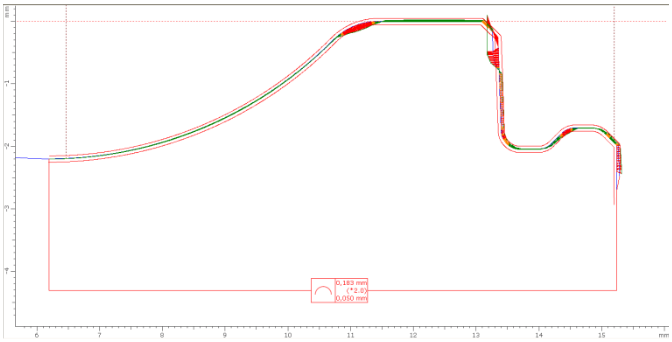
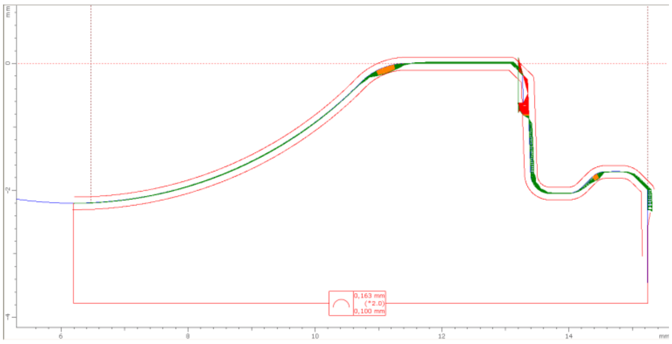
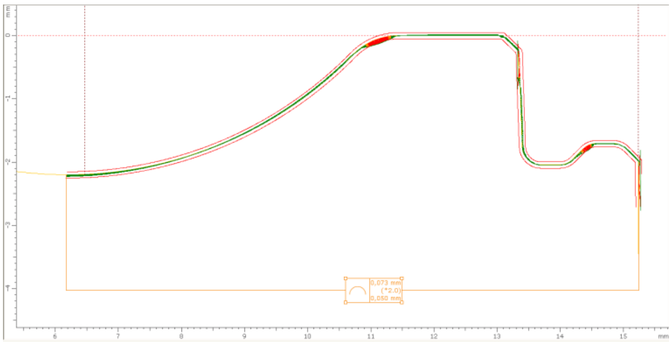
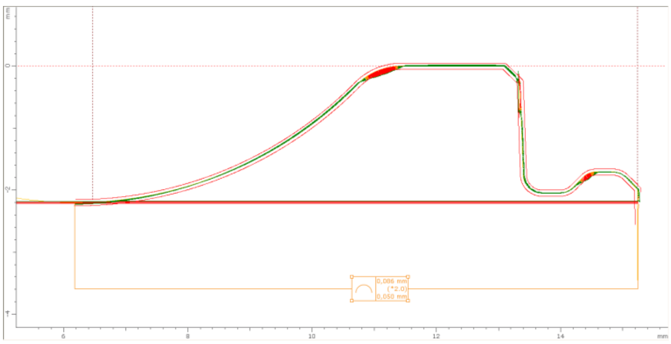
Analysis No.	Comparison of Output with Nominal Profile	Maximum Profile Error
1		0.183mm
2		0.163mm
3		0.0733mm
4		0.086mm

Table 5 (continued)

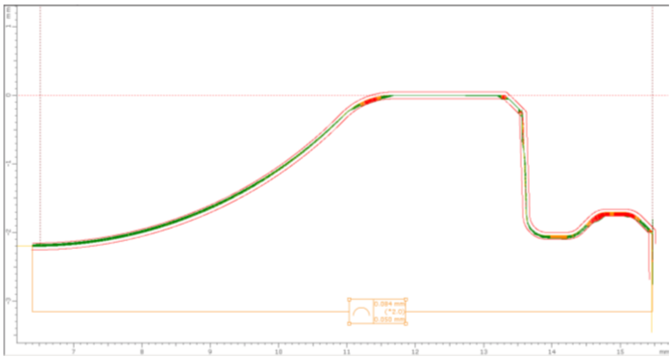
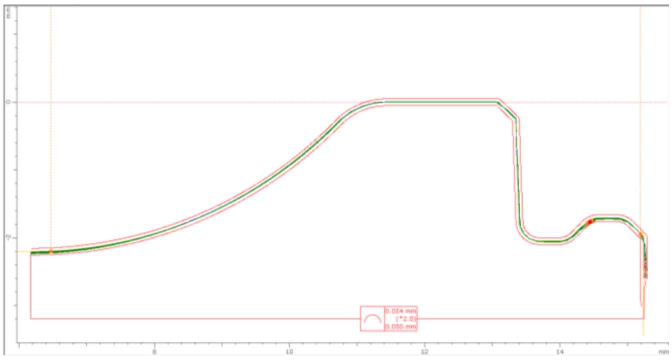
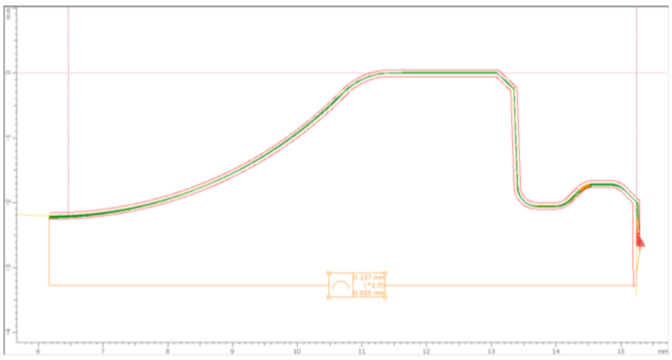
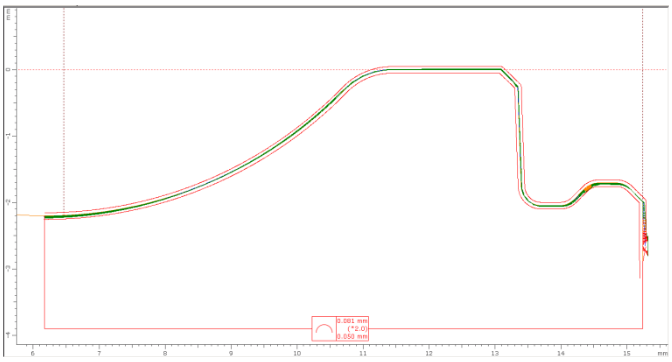
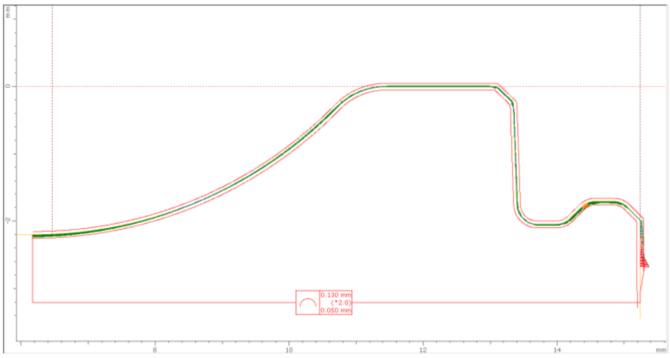
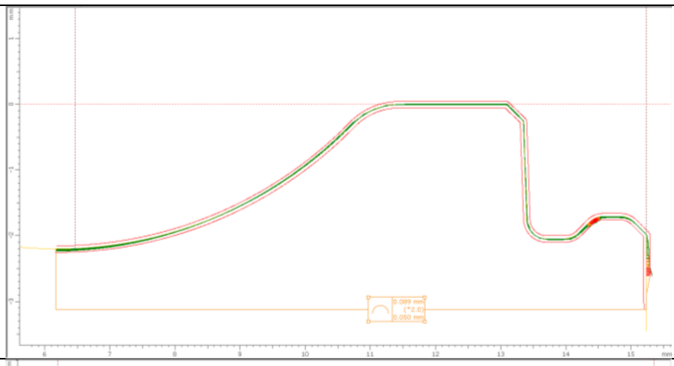
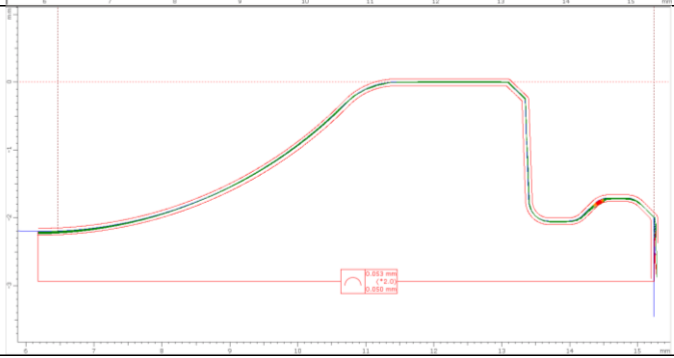
5		0.084mm
6		0.054mm
7		0.137mm
8		0.081mm

Table 5 (continued)

9		0.130mm
10		0.089mm
11		0.053mm

In the figures, profile errors are marked with bars along the profile. For all comparisons there is nominal profile defined with ±50μm error tolerance namely 100μm tolerance band. From the above simulation outputs best results are obtained from 6th and 11th analysis. 6th analysis result is better because in simulation 11 the width is not good and there is burr at the side section.

5.2.2. Tears

Another effect occuring due to blank dimensions is tearing along the walls where seals are settled at the bearing outer ring. This was seen at the blank output of the axisymmetric analysis result. Tearing defect is shown at the below figure.

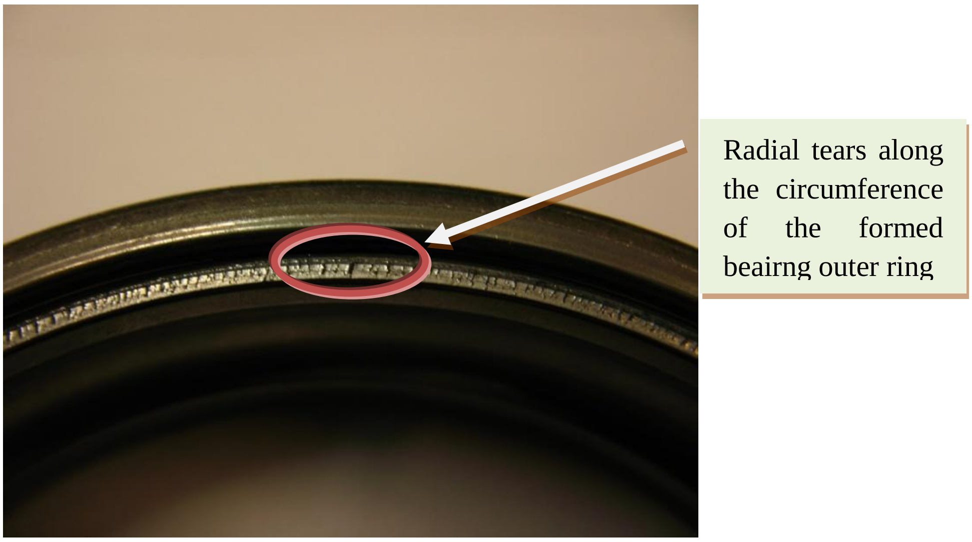


Figure 58 Radial Tearing Defect

Reason for this is came out at the three dimensional ring rolling analysis. During forming, width of T-profile was rubbed by the profile at the mandrel. So that, very high amount of friction or material removal caused radial crack in the produced ring part. Event leading to tearimg defect formation can be seen at the below figure.

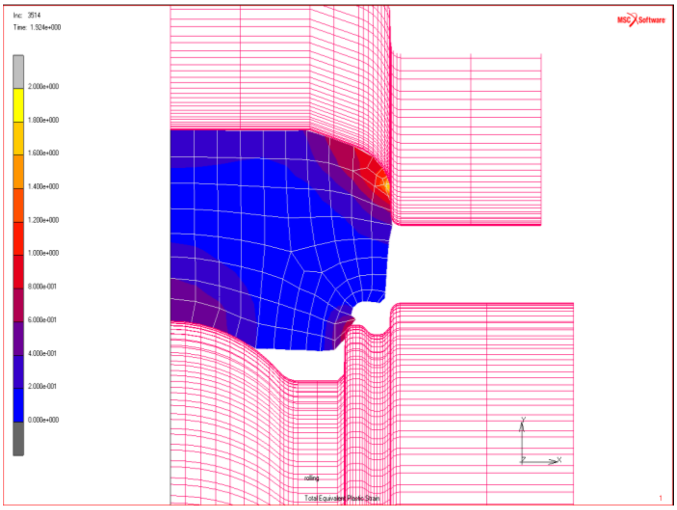


Figure 59 Tearing Defect Formation

5.2.3. Burrs at the Faces

Excessive blank material or inappropriate dimensions eventuate in burrs at the sides of the formed ring product. Burrs occur usually at places where no contact of forming tools happen. At the below figure, example burr occurring places are shown.

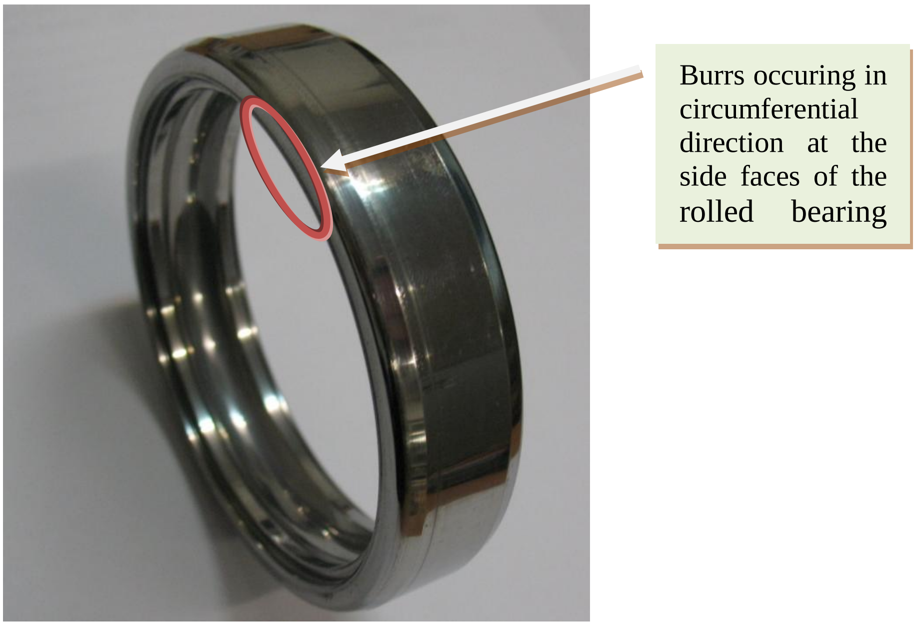
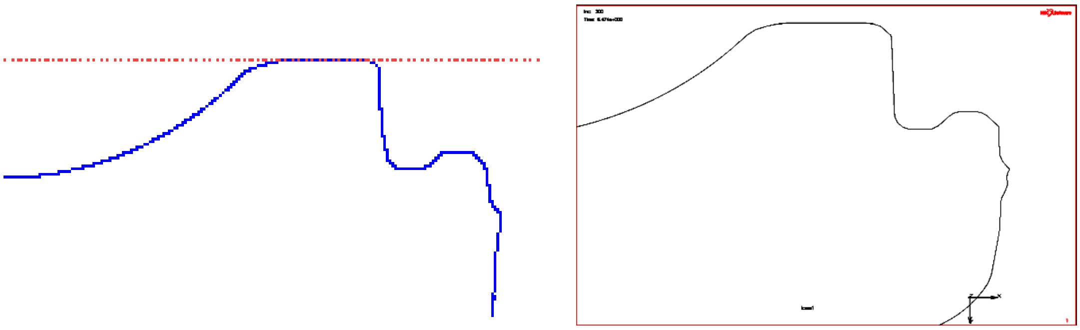


Figure 60 Burrs occuring at the rolled bearing outer ring

Below figures show the simulation output and contour measurement device of the burrs at an bearing outer ring.



a. Contour Result from Profile Measurement   b. Contour Result from Simulation

Figure 61 Burr Defect Represented by Both Experiment and Simulation

5.3. Effects Study due to Feed Rates

Feed rate in the profiled ring rolling operation is defined as moving speed of the form roll. Form roll advances through ring thickness with rotating at the same time.

5.3.1. Residual Stress

Determination of residual stress from simulation is at hand. Therefore, comparison of simulation with experiments is performed.

At the Table 6, effect of feed rates at the raceway axial stress is listed. Stress measurement is made by X-Ray Diffraction technique. Measurement is performed at the deepest point in bearing raceway in axial direction as seen in Figure 62.

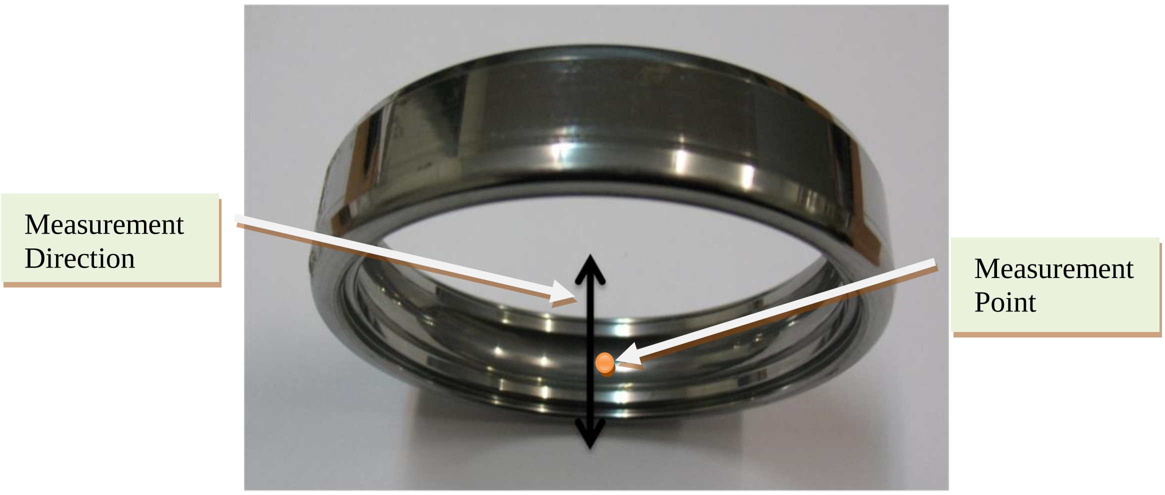


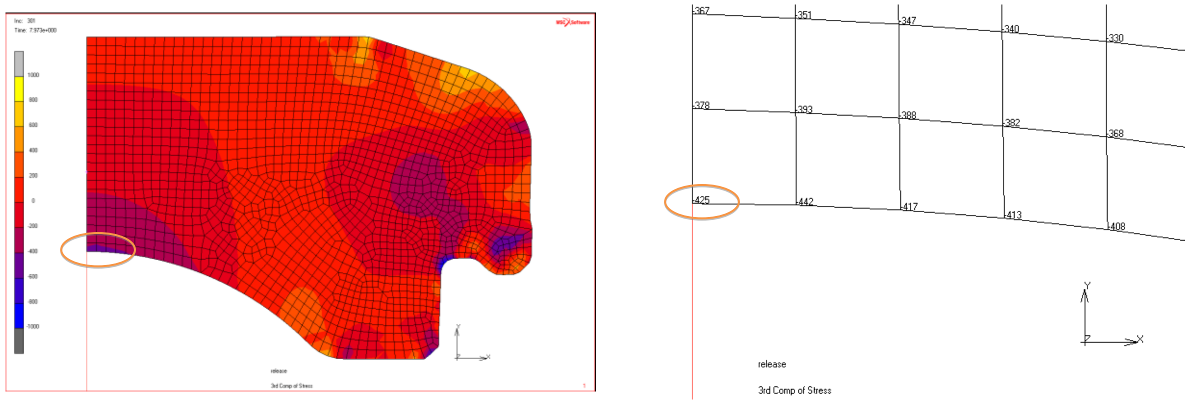
Figure 62 Residual Stress Measurement of the Rolled Bearing Ring

Table 6 Residual Stress Values vs. Feed Rates

Residual Stress [MPa]	Feed Rate [mm/s]
-500 MPa	0.7 mm/s
-500 MPa	1.0 mm/s
-500 MPa	1.2 mm/s

As seen from the stress values, feed rate has no effect on the residual stresses during ring rolling of bearing ring.

Simulated values of the residual stresses are given in Figure 63. In Table 6, measured values were -500 MPa at the aforementioned spot. At the same measurement point, simulations resulted in -425 MPa. These values lead to a 15% error, which is acceptable when you think of axisymmetric simplified model and Residual Stress Measurement by X-Ray Diffraction technique. Circular marks in the separate figures show the measurement point.



a. Contour Band Representation of Axial Stress b. Numeric Representation of Axial Stress

Figure 63 Residual Stress Values from Simulation

5.3.2. Forming Force / Torque

During cold roll forming, main deformation energy comes into place as forming force and forming torque at the main (form) roll. Forming force shows up in negative direction to the feed direction. Forming torque also occurs in negative direction to the form roll turning direction. Below Figure 64 shows the effect of different feed rates at the forming force. As it can be seen there is no significant effect of different feed rates in case of simulation. The reason for this case is the rate independent material model that is used in the simulations.

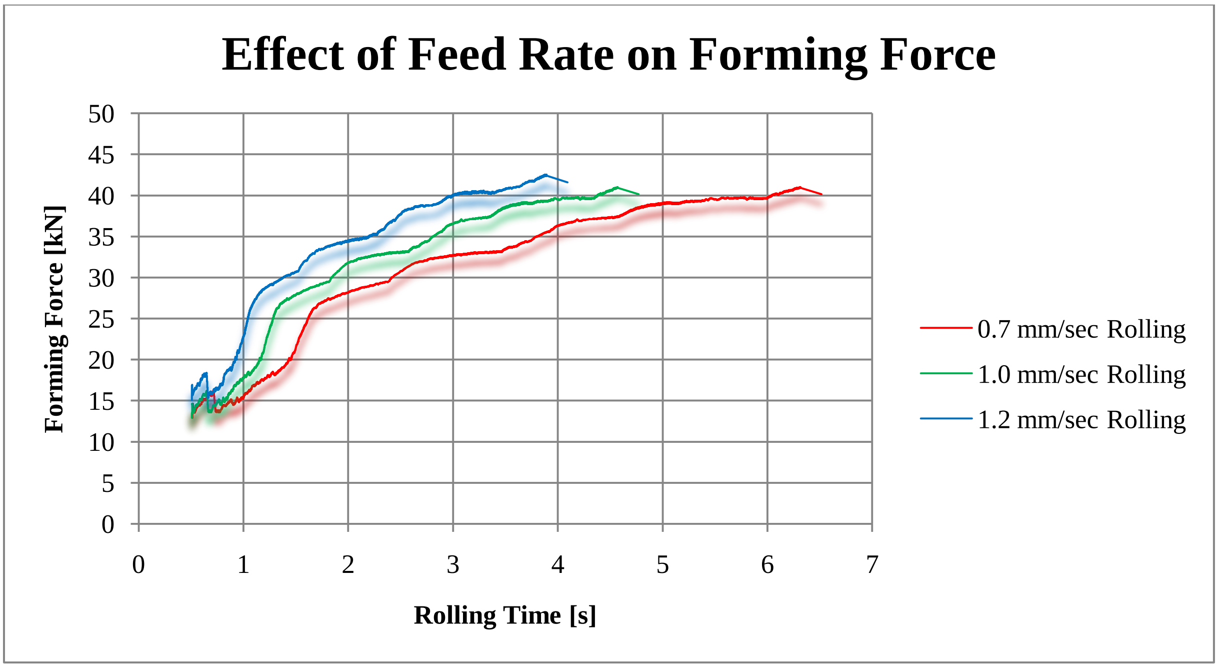


Figure 64 Graph of Force Values vs. Time

Figure 65 shows the experimental values of forming force at the same situation. Force values again do not change significantly.

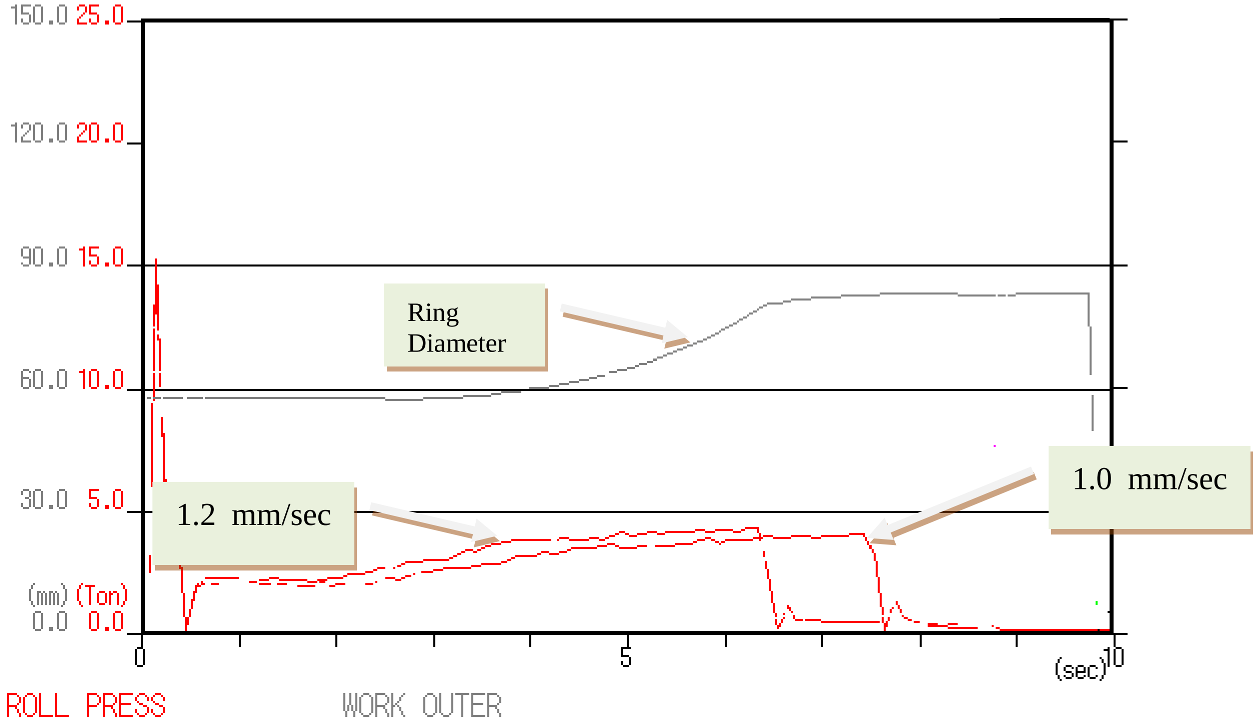


Figure 65 Experimental Forming Force Values

Below Figure 66 shows the effect of different feed rates at the forming torque via simulation.

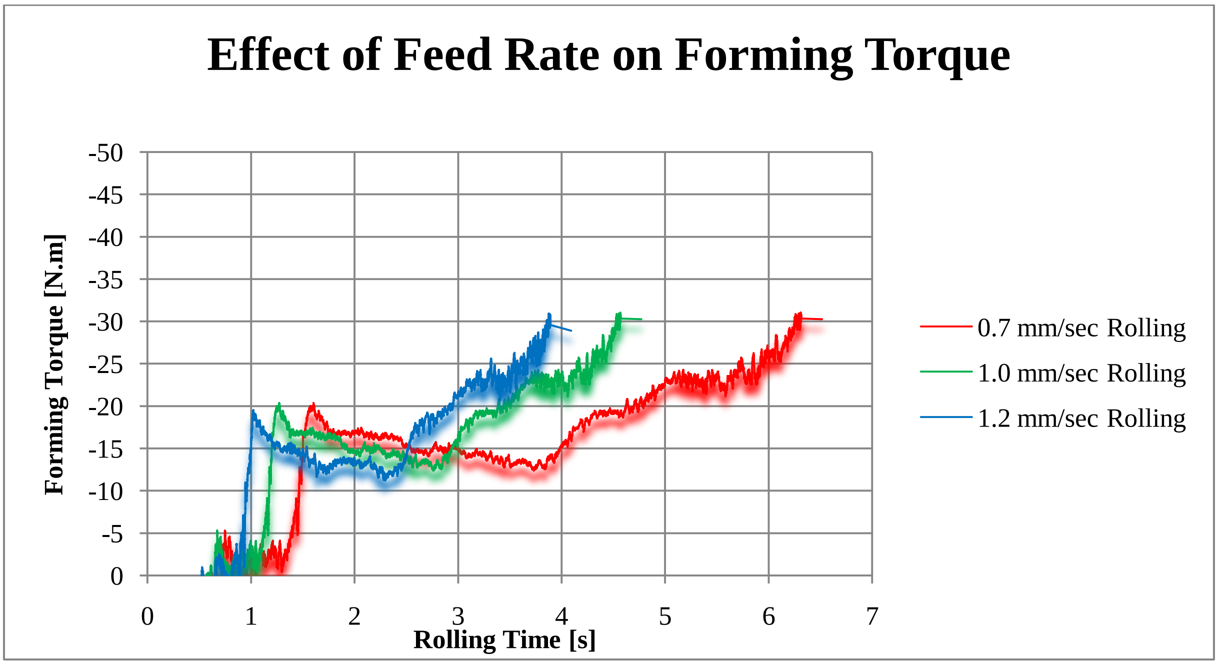


Figure 66 Graph of Rolling Torque vs. Time

Figure 67 shows the experimental torque values during rolling operation.

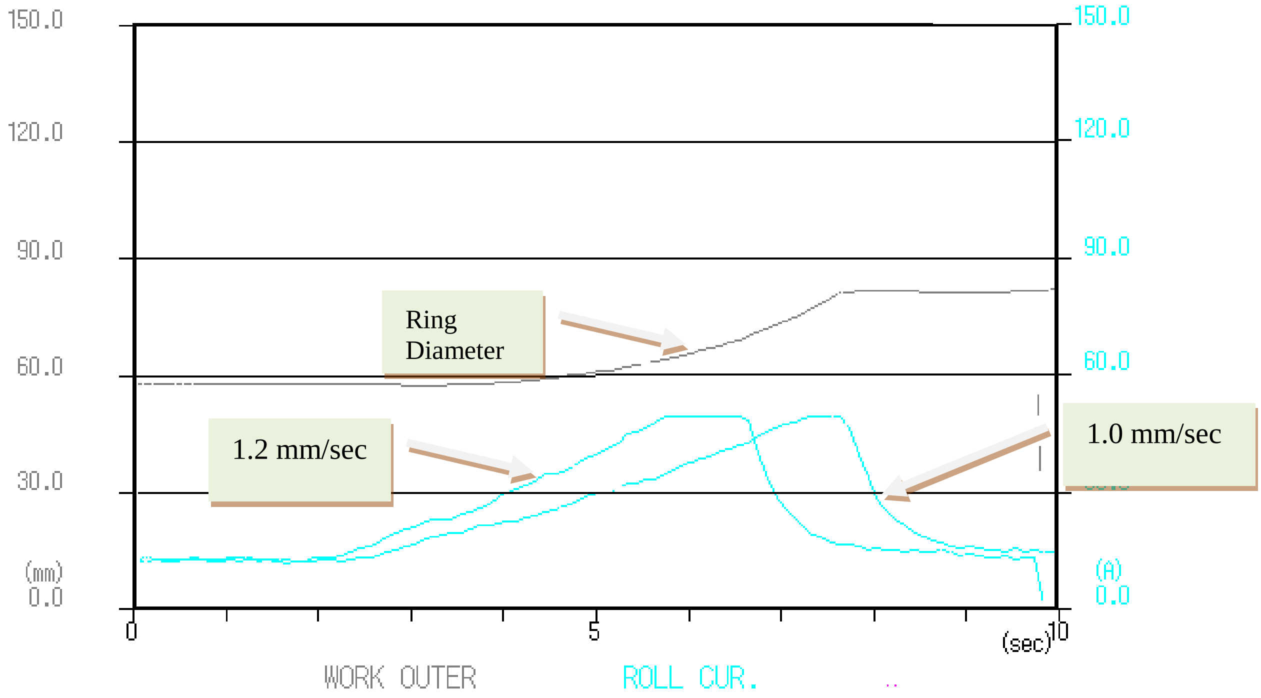


Figure 67 Experimental Forming Torque Values

5.3.3. Diameter Growth

Different diameters at the rolled profile have different values after forming. This phenomenon is not related with profile filling, but related with conicity, spring-back after releasing from tools, axial spread in the ring material and residual stresses. Axial spread is a significant effect of feed rate, however it is beyond the topic of this thesis study.

5.3.4. Burrs at the Faces

Burrs occurring at the faces is again a result of axial spread study. It is beyond the study of this research. Rate dependent material models should be used to work on axial spread and diameter growth.

5.4. Comparison of Simulation Results with Experiments

In order to determine correctness of the simulation a filling defect rolled ring is cross-checked by both simulation and nominal profile of the product. In Figure 66, contour of the rolled ring is measured by profile measurement device. Red lines show the experimental profile. Black lines show the nominal profile. Blue lines show the simulation profile. It is confirmed that simulation estimates well the experimental profile even side spread.

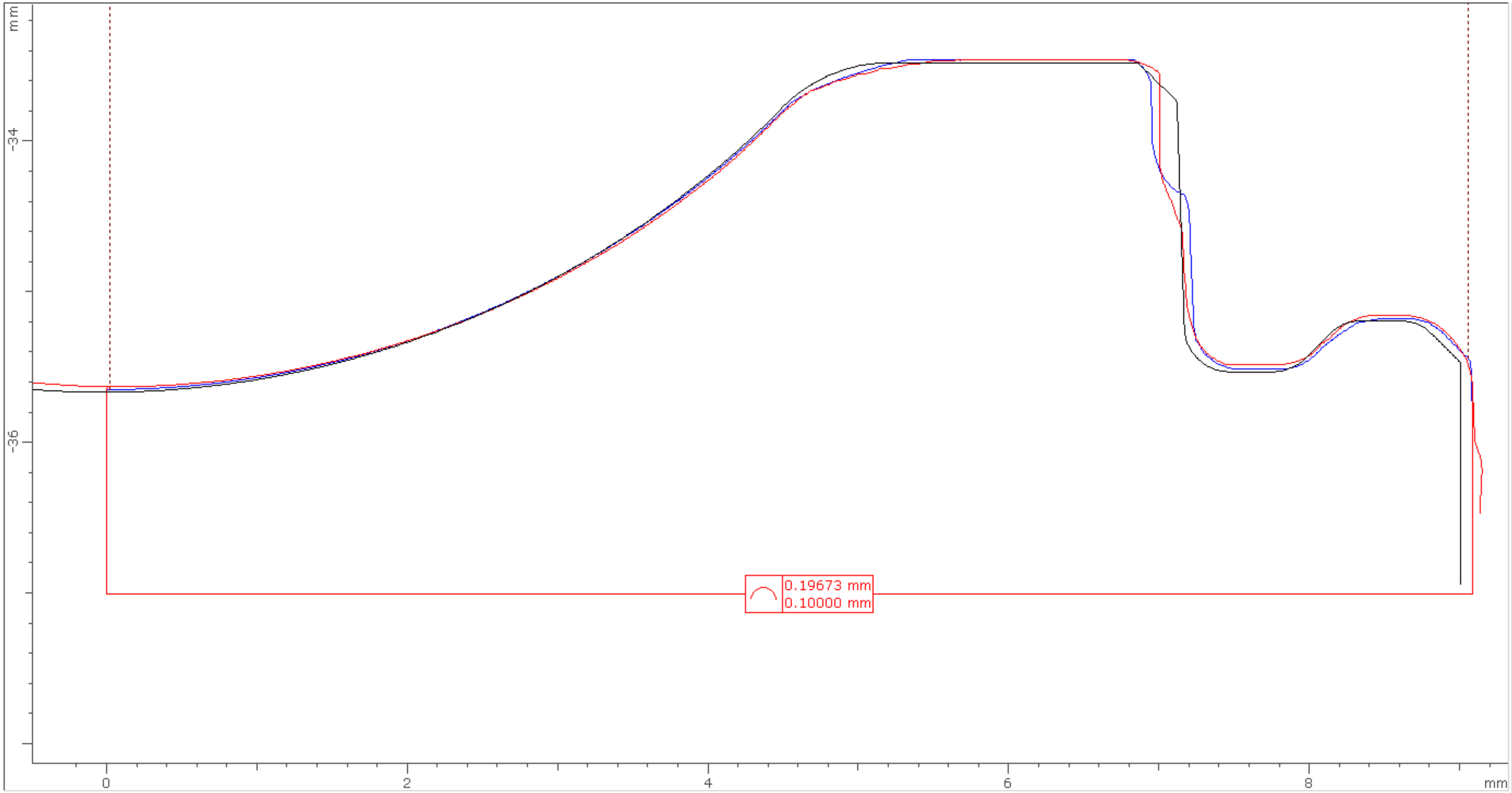


Figure 68 Comparison of Simulation with Experiment and Nominal Profile

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Metal forming process is nonlinear due to its nature. It has large displacements. It has nonlinear stress-strain relationship due to plasticity with elastic effects. It has changing contact conditions due to tool-workpiece interfaces. Cold metal forming gives us a benefit in terms of static and dynamic strength increase. Therefore, crack forming is impeded.

Coordinate tables to be used for mandrel and form roll curves positions can be received from the prepared mathematical model and C++ compiled code. Positions of the mandrel rigid curves and form roll rigid curves are defined in terms of time variable of the simulation.

Simplified axisymmetric finite element model is created for profiled ring rolling with the aid of mathematical model defined for tools movement.

Results obtained from simplified simulation model of profiled ring rolling shall be checked with three-dimensional models and ring rolling equipments. If the solution time is considered, simplified simulation model with prepared C++ code becomes an applicable tool in trial and error part of profiled ring rolling process.

As observed from the results, success of profiled ring rolling depends very much on the preform shape and dimensions. The filling phenomenon is sensitive to small dimensional changes. Profiled ring rolling is a stabile process in terms of continuity of the rolled product dinesions.

Works upon three-dimensional simulations have been completed. Preform shape is corrected using the three-dimensional model. In advanced works, these simulation tools can be used to optimize blank dimensions for other types of profiled rings without physical trial and errors at the shop floor.

Preform shape and dimensions are obtained for rolling 6208 type bearing ring with full profile that is raceway and seal groove details.

Work will be progressing on the analysis of profiled ring rolling with new type of bearing rings. Preform shape optimization could be performed successively at the initial sight, by simplified axisymmetric simulations and verified by three-dimensional simulations.

Results of this research study can be listed as following;

1. Costly and time consuming trial and error process could be accomplished by simulation studies in computer with a faster succesion.
2. All dimensions and tolerances will be obtained by cold ring roll forming instead of manufacturing by ongoing machining (turning) process.
3. Material saving and increased turnout will be obtained.
4. New technology about simulation of cold metal forming will be produced.
5. Working life of the produced bearing shall improve by the effect of ring rolling process.

REFERENCES

1. Marinov, V.: Manufacturing Technology (ME 364) Lecture Notes, Eastern Mediterranean University, Gazimagusa, 2000.
2. Todd, R.H.; Allen, D.K.; Alting, L.: Manufacturing Processes Reference Guide, Industrial Press Inc., 1994.
3. Davey, K.; Ward, M.J.: A practical method for finite element ring rolling simulation using the ALE flow formulation, International Journal of Mechanical Sciences 44 (2002) 165–190.
4. Wang, Z.W.; Zeng, S.Q.; Yang, X.H.; Cheng, C.: The key technology and realization of virtual ring rolling, Journal of Materials Processing Technology 182 (2007) 374–381.
5. Lim, T.; Pillinger, I.; Hartley, P.: A finite-element simulation of profile ring rolling using a hybrid mesh model, Journal of Materials Processing Technology 80–81 (1998) 199–205.
6. Runguang, L.; Yan, L.; Qiaohe, D.; Qirang, S.: A new forming technology for bearing rings by means of precision rolling, Journal of Materials Processing Technology 52 (1995) 515-523.
7. Wen, J.; Petty, D.M.: A novel method for prediction of rolled cross section shape, Journal of Materials Processing Technology 80–81 (1998) 356–360.
8. Joun, M.S.; Chung, J.H.; Shivpuri, R.: An axisymmetric forging approach to preform design in ring rolling using a rigid-viscoplastic finite element method, Intrenational Journal of Machine Tools & Manufacture 38 (1998) 1183-1191.
9. Song, J.L.; Dowson, A.L.; Jacobs, M.H.; Brooks, J.; Beden, I.: Coupled thermo-mechanical finite-element modelling of hot ring rolling process, Journal of Materials Processing Technology 121 (2002) 332–340.

10. Sun, Z.; Yang, H.; Li, L.: Determining and Optimizing of Guide Rolls Motion Track in Cold Ring Rolling Process, Materials Science Forum Vols. 532-533 (2006) pp. 141-144.
11. Alfozan, A.K.; Gunasekera, J.S.: Development of an Experimental Ring Rolling Mill and Associated Instrumentation, Journal of Materials Processing Technology (2007), doi:10.1016/j.jmatprotec.2007.03.090.
12. Wang, M.; Yang, H.; Sun, Z.; Guo, L.; Ou, X.: Dynamic explicit FE modeling of hot ring rolling process, Trans. Nonferrous Met. SOC. China 16(2006) 1274-1280.
13. Utsunomiya, H.; Saito, Y.; Shinoda, T.; Takasu, I.: Elastic–plastic finite element analysis of cold ring rolling process, Journal of Materials Processing Technology 125–126 (2002) 613–618.
14. Boman, R.; Ponthot, J.-P.: Finite element simulation of lubricated contact in rolling using the arbitrary Lagrangian–Eulerian formulation, Comput. Methods Appl. Mech. Engrg. 193 (2004) 4323–4353.
15. Szabo, Z.J.; Dittrich, E.: Manufacturing systems for the production of seamless-rolled rings, Journal of Materials Processing Technology 60 (1996) 67-72.
16. Tiedemann, I.; Hirt, G.; Kopp, R.; Michl, D.; Khanjari, N.: Material flow determination for radial flexible profile ring rolling, Prod. Eng. Res. Devel. DOI 10.1007/s11740-007-0030-z.
17. Han,X.; Hua, L.; Lan, J.: Numerical Simulation and Experimental Research on Rolling Process of Conical Ring with Inner Steps, Advanced Materials Research Vols. 26-28 (2007) pp. 993-997.
18. Yan, F.-L.; Hua, L.; Wu, Y.-Q.: Planning feed speed in cold ring rolling, International Journal of Machine Tools & Manufacture 47 (2007) 1695–1701.
19. Yea, Y.; Ko, Y.; Kim, N.; Lee, J.: Prediction of spread, pressure distribution and roll force in ring rolling process using rigid–plastic finite element method, Journal of Materials Processing Technology 140 (2003) 478–486.
20. Yeom, J.T.; Jung, E.J.; Kim, J.H.; Lee, D.-G.; Park, N.-K.; Choi, S.S.; Lee, C.S.: Process Design of Profile Ring Rolling for Turbine Diaphragm using FEM Simulation, Key Engineering Materials Vols. 345-346 (2007) pp. 1557-1560.

21. Souza, U.D.S.; Vaze, S.; Pursell, Z.; Phillips, K.: Profile Ring Rolling, Advanced Materials & Processes (2003).
22. Bruschi, S.; Casotto, S.; Negro, T.D.; Barianil, P.F.: Real-Time Prediction of Geometrical Distortions of Hot-Rolled Steel Rings during Cooling, CIRP Annals - Manufacturing Technology Volume 54, Issue 1, 2005, Pages 229-232.
23. Tani, K.; Ishigai, S.; Sato, T.; Tsumori, Y.: The Evolution of Near-net-shape Ring-rolling processes for Large Rings Made of Ti-6Al-4V, Kobelco technology review no. 26 (2005) pp. 43-48.
24. Allwood, J.M.; Kopp, R.; Michels, D.; Music, O.; Oztop, M.; Stanistreet, T.F.; Tekkaya, A.E.; Tiedemman, I.: The Technical and Commercial Potential of an Incremental Ring Rolling Process, CIRP Annals - Manufacturing Technology Volume 54, Issue 1, 2005, Pages 233-236.
25. Casotto, S.; Pascon, F.; Habraken, A.M.; Bruschi, S.: Thermo-mechanical-metallurgical model to predict geometrical distortions of rings during cooling phase after ring rolling operations, International Journal of Machine Tools & Manufacture 45 (2005) 657–664.
26. Pan, L.; Hua, L.; Lan, J.: 3-D FE Simulation and Analysis on Radial-axial Large Ring Rolling, Materials Science Forum Vols. 561-565 (2007) pp. 1903-1906.
27. Davey, K.; Ward, M.J.: An ALE approach for finite element ring-rolling simulation of profiled rings, Journal of Materials Processing Technology 139 (2003) 559–566.
28. Sheikh, M.A.; Palavilayil, R.R.: An assessment of finite element software for application to the roll-forming process, Journal of Materials Processing Technology 180 (2006) 221–232.
29. Guo, L.; Yang, H.: Effect of sizes of forming rolls on cold ring rolling by 3D-FE numerical simulation, Trans. Nonferrous Met. SOC. China 16(2006) s645-s6il.
30. Moon, H.K.; Lee, M.C.; Joun, M.S.: Predicting polygonal-shaped defects during hot ring rolling using a rigid-viscoplastic finite element method, International Journal of Mechanical Sciences 50 (2008) 306–314.

31. Takizawa, H.; Matsui, T.; Kikuchi, H.: Rigid-plastic finite element analysis of partially modeled ring rolling, Journal of Materials Processing Technology Volumes 125-126, 9 September 2002, Pages 613-618.
32. Yeom, J.T.; Kim, J.H.; Park, N.K.; Choi, S.S.; Lee, C.S.: Ring-rolling design for a large-scale ring product of Ti–6Al–4V alloy, Journal of Materials Processing Technology 187–188 (2007) 747–751.
33. Forouzan, M.R.; Salimi, M.; Gadala, M.S.: Three-dimensional FE analysis of ring rolling by employing thermal spokes method, International Journal of Mechanical Sciences 45 (2003) 1975–1998.
34. Stanistreet, T.F.; Allwood, J.M.: Two simple models for exploring a novel flexible ring rolling process, Esaform 2005, Romania.
35. Alfozan, A.; Gunasekera, J.S.: Design of profile ring rolling by backward simulation using upper bound element technique (UBET), Journal of Manufacturing Processes; 2002; 4, 2; ABI/INFORM Global pg. 97.
36. Kim, K.H.; Suk, H.G.; Huh, M.Y.: Development of the profile ring rolling process for large slewing rings of alloy steels, Journal of Materials Processing Technology 187–188 (2007) 730–733.
37. Xiong, S.; Rodrigues, J.M.C.; Martins, P.A.F.: Numerical simulation of three-dimensional steady-state rolling by the reproducing kernel particle method, http://www.emeraldinsight.com/0264-4401.htm, 2002.
38. Guo, L.; Yang, H.; Zhan, M.: Research on plastic deformation behaviour in cold ring rolling by FEM numerical simulation, Modelling Simul. Mater. Sci. Eng. 13 (2005) 1029–1046.
39. Yang, H.; Guo, L.; Zhan, M.; Sun, Z.: Research on the influence of material properties on cold ring rolling processes by 3D-FE numerical simulation, Journal of Materials Processing Technology 177 (2006) 634–638.
40. Xie, C.; Dong, X.; Li, S.; Huang, S.: Rigid–viscoplastic dynamic explicit FEA of the ring rolling process, International Journal of Machine Tools & Manufacture 40 (2000) 81–93.
41. Sawamiphakdi, K.; Pauskar, P.M.; Jin, D.Q.; Lahoti, G.D.: Ring Rolling Process Modeling Using Explicit Finite Element Analysis, Advanced Technology of Plasticity Vol. 1 (2002).

42. Li, H.W.; Yang, H.; Sun, Z.C.; Wang, M.; Li, L.Y.: Simulation of Cold Ring Rolling based on Rate Dependent Crystal Plasticity, Materials Science Forum Vols. 561-565 (2007) pp. 1813-1817.
43. Pauskar, P.M.; Sawamiphakdi, K.; Jin, D.Q.: Static Implicit vs. Dynamic Explicit Finite Element Analysis for Ring Rolling Process Modeling, AIP Conf. Proc. -- June 10, 2004 -- Volume 712, pp. 412-417.
44. Davey, K.; Ward, M.J.: The practicalities of ring rolling simulation for profiled rings, Journal of Materials Processing Technology 125–126 (2002) 619–625.
45. Ranatunga, V.; Gunasekera, J.S.; Vaze, S.P.; Souza, U.D.: Three-Dimensional UBET Simulation Tool for Seamless Ring Rolling of Complex Profiles, Journal of Manufacturing Processes 2004, vol. 6, no. 2, pp. 179-186.
46. Forouzan, M.R.; Salimi, M.; Gadala, M.S.; Aljawi, A.A.: Guide roll simulation in FE analysis of ring rolling, Journal of Materials Processing Technology 142 (2003) 213–223.
47. Guo, L.G.; Yang, H.: Numerical Analysis of Force and Power Parameters in Cold Ring Rolling, Materials Science Forum Vols. 561-565 (2007) pp. 805-808.
48. Kim, K.J.; Choi, S.S.; Hwang, C.Y.; Kim, J.S.; Yeom, J.T.; Lee, C.S.: Ring-Rolling Process for Manufacturing Ti-6Al-4V Plane and Profiled Ring-Products, Advanced Materials Research Vols. 26-28 (2007) pp. 429-432.
49. Stanistreet, T.F.; Allwood, J.M.; Willoughby, A.M.: The design of a flexible model ring rolling machine, Journal of Materials Processing Technology 177 (2006) 630–633.
50. Hutton, David V.: Fundamentals of finite element analysis, McGraw-Hill, 2004.
51. Felippa, C.A.: Introduction to Finite Element Methods (ASEN 5007) Lecture Notes, University of Colorado at Boulder, 2008.
52. Bathe, K.-J.: Finite element procedures, Prentice Hall, 1996.
53. Koçak, Ö.: Analysis of the formability of metals, Master of Science Thesis, Middle East Technical University, 2003.
54. simufact sfFormingSFM User's Guide version 8.1.
55. Merriam-Webster Collegiate® Dictionary.

56. Lin, H.; Zhi, Z.Z.: The extremum parameters in ring rolling, Journal of Materials Processing Technology 69 (1997) 273-276.
57. Tekkaya, A.E.: Metal Forming Technology (ME 453) Lecture Notes, Middle East Technical University, Ankara, 2001.
58. Music, O.: Analysis of cold ring rolling process, Master of Science Thesis, Middle East Technical University, 2005.

APPENDIX A

ROLLING ANALYSIS COORDINATE EXTRACTION CODE

```
#include <stdio.h>
#include<conio.h>
int main(void)
{
    FILE *outputir,*outputor;
    outputir=fopen("rawDataIR.dat","w");
    outputor=fopen("rawDataOR.dat","w");

    int i,upperbound;
    float step,h[100],r[100],rr[100],t[100],tfinal,rrmodified,hmodified,hupper;

    printf("***6208 Profiled Ring Rolling***\n");
    printf("Input the blank inner diameter.=>\n");
    scanf("%f" ,&r[0]);
    printf("Input the blank outer diameter.=>\n");
    scanf("%f" ,&rr[0]);
    h[0]=rr[0]-r[0];
    t[0]=0;
```

```
printf("Input the difference value for outer diameter fillet.=>\n");
scanf("%f" ,&rrmodified);
step=0.02;

for(i=0;i<=88;i++)
  {
  h[i+1]=h[i]-step;
  r[i]=((rr[0]*rr[0]-r[0]*r[0])/h[i]-h[i])/2;
  t[i+1]=t[i]+0.09;
  }
for(i=0;i<=88;i++)
  {
  if(r[i]>23.29)
    {
    upperbound=i;
    i=89;
    }
  }
tfinal=t[upperbound]-(r[upperbound]-23.29)*(t[upperbound]-t[upperbound-1])/(r[upperbound]-r[upperbound-1]);
hmodified=rrmodified-r[0];
hupper=(-t[upperbound]*hmodified+hmodified*tfinal+t[upperbound]*2.77)/tfinal;
h[0]=hmodified;

for(i=1;i<=88;i++)
  {
```

```
        h[i]=h[i-1]-(hmodified-hupper)/(upperbound);
        }
    for(i=0;i<=88;i++)
        {
        rr[i]=r[i]+h[i];
        }
    for(i=0;i<=88;i++)
        {
        fprintf(outputir,"%f\t%f\n",t[i],r[i]);
        fprintf(outputor,"%f\t%f\n",t[i],rr[i]);
        }
    printf("h[upperbound]= %f\n",h[upperbound]);
    printf("tfinal= %f",tfinal);
    getch();
}
```