

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**COLD FORGING TOOL DESIGN AND
ANALYSIS FOR WHEEL NUT
MANUFACTURING**

by

Alper KARAKAŞ

August, 2024

İZMİR

**COLD FORGING TOOL DESIGN AND
ANALYSIS FOR WHEEL NUT
MANUFACTURING**

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for Master of Science in
Department of Mechanical Engineering**

by

Alper KARAKAŞ

August, 2024

İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**COLD FORGING TOOL DESIGN AND ANALYSIS FOR WHEEL NUT MANUFACTURING**” completed by **ALPER KARAKAŞ** under supervision of **PROF.DR. BİNNUR GÖREN KIRAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

.....
Prof. Dr. Binnur Gören KIRAL

Supervisor

.....
Prof. Dr. Çınar Emine YENİ

Jury Member

.....
Dr. Öğr. Üyesi Melis YURDDAŞKAL

Jury Member

Prof. Dr. Okan FISTIKOĞLU

Director

Graduate School of Natural and Applied Sciences

ACKNOWLEDGMENT

First of all, I would like to thank Prof. Dr. Binnur Gren KIRAL with my sincere feelings for the courage and confidence she gave me for this study. I am grateful that he believed in me more than myself and never withhold her support.

I would also like to thank Hatice Sandallı YILDIZ, who guided and supported me with her knowledge and experience during my thesis study. I would like to express my sincere gratitude to all Norm Somun A.Ş. family, especially Burak Berk ARINCI and Fuat Can AĖARER, for their helps during the design and analysis process.

Finally, my biggest thanks to my family and friends for their constant support.

Alper KARAKAŞ

COLD FORGING TOOL DESIGN AND ANALYSIS FOR WHEEL NUT MANUFACTURING

ABSTRACT

Wheel nuts are fasteners used in industry, especially for connecting the wheels of motor vehicles and trailers to hub flanges. Although wheel nuts, like other fasteners, can be produced using various manufacturing methods, the cold forging method is preferred due to its advantages in cycle time and cost. The aim of this study is to examine the difficulties encountered in the production of wheel nuts, which are particularly difficult and costly to produce by the cold forging method due to their geometry, and to perform the analysis of optimum tooling design using the finite element method. The method to be used is to determine the appropriate design with the support of the finite element program (Simufact).

In this study, general information will be given about fasteners, and focus will be on wheel nuts. Information about the material to be investigated will be listed by discussing issues such as the functionality, geometry, expected mechanical properties, and areas of use of wheel nuts. Basic information about cold forging production method will be given, and machine operation principles and process information will be transferred. Tooling design will be made based on preliminary evaluations on the technical drawing of the prototype product, and forging forces will be determined by analyzing cold forming design with the finite element program. Solutions will be produced for dies exposed to high stress identified in the simulation study, and actions will be determined, and the design will be reviewed again.

In light of this study, it is planned to provide production approach information for various types of bolt nuts that cannot be produced by the cold forging method and female fasteners with a similar form.

Keywords: Fasteners, cold forging, tooling analysis, numerical simulation methods

BİJON SOMUNU ÜRETİMİ İÇİN SOĞUK DÖVME KALIBI TASARIMI VE ANALİZİ

ÖZ

Bijon somunları endüstride özellikle motorlu taşıtların ve römorkların jantlarını, göbek flanşlarına bağlamak için kullanılan bağlantı elemanlarıdır. Diğer bağlantı elemanlarında olduğu gibi bijon somunu üretimi birçok imalat yöntemiyle gerçekleştirilebilse de, hız ve maliyet açısından bakıldığında soğuk dövme yöntemi ile üretilmesi tercih sebebi olmuştur. Bu çalışmanın amacı, geometrisi sebebiyle soğuk dövme yöntemiyle üretilmesi oldukça zor ve maliyetli olan bijon somunlarının üretiminde yaşanan zorlukları irdelemek, sonlu elemanlar yöntemiyle optimum kalıp tasarımının yapılıp analizinin gerçekleştirilmesidir. Kullanılacak yöntem, sonlu elemanlar programı (Simufact) desteğiyle uygun şekillenme tasarımının ve kalıp analizlerinin gerçekleştirilmesidir.

Bu çalışmada bağlantı elemanlarından genel olarak bahsedilecek ve bijon somunu üzerinde odaklanılacaktır. Bijon somununun fonksiyonelliği, geometrisi, beklenen mekanik özellikleri ve kullanım alanları gibi konulardan bahsedilerek araştırılacak malzeme ile ilgili bilgiler sıralanacaktır. Soğuk dövme üretim yöntemi üzerine temel bilgilerden bahsedilerek, makine çalışma prensibi ve proses bilgileri aktarılacaktır. Prototip ürünün teknik resmi üzerinde yapılan ön değerlendirmeler ışığında kalıp tasarımı yapılacak ve sonlu elemanlar programı ile soğuk şekillendirme tasarımı analiz edilerek dövme kuvvetleri belirlenecektir. Yapılan simülasyon çalışmasında tespit edilen yüksek strese maruz kalan kalıplar için çözümler üretilecek ve aksiyonlar belirlenip tasarım tekrar gözden geçirilecektir.

Bu çalışma ışığında soğuk dövme yöntemi ile üretilemeyen çeşitli bijon somunu tipleri ve benzer forma sahip dişi bağlantı elemanlarının üretilmesi için üretim yaklaşım bilgisi sağlanması planlanmaktadır.

Anahtar kelimeler: Bağlantı elemanları, soğuk dövme, kalıp analizi, sayısal benzetim yöntemleri

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CHAPTER ONE

INTRODUCTION

1.1 Fasteners

Fasteners play a crucial role in connecting various components in different sectors, including automotive, machinery, aviation, and construction. The use of fasteners is widespread due to their easy design, quick assembly, and cost-effectiveness. These components create connections through grip surfaces known as threads, which are found on the outer surface of bolts and the inner surface of nuts. The engagement of these external and internal threads ensures a secure connection. While there are various types of nuts available, such as hexagon nuts, welding nuts, prevailing torque nuts, this study specifically focuses on wheel nuts used in wheel connections.

Fasteners are designed in different geometries to accommodate various assembly conditions and requirements. International standard organizations have standardized these components for specific geometries and product ranges, providing guidance for manufacturers and users. These standards cover aspects such as product geometry, material selection criteria, and expected mechanical performances of fasteners, which are widely utilized in the industry.

Designers often require specific mechanical performance values from fasteners based on assembly conditions, leading to the development of products with unique geometric designs. Non-standard fastener designs are sometimes necessary to meet specific assembly requirements and to limit alternative manufacturers, creating a demand for specialized wrench in the industry.

1.2 Wheel Nuts

Wheel nuts are critical safety components. Used to attach the wheels of motor vehicles and trailers to the hub flanges, the failure of wheel nuts due to any reason or their inability to function properly can lead to accidents with potentially fatal

consequences. Therefore, wheel nuts require meticulous attention and careful work in terms of material, geometry, and functionality.

Due to their geometry, the production of wheel nuts by forging is quite restricted. Various wheel nuts used in the industry are shared its images below Figure 1.1. Wheel nuts are generally not solely produced by forging but are also machined to achieve the desired final dimensions. High forging loads and the high stress occurring during the shaping of the flange in the center of the part increase production costs and prevent the achievement of the expected quality. Another challenging issue is the tight tolerance expectations for wheel nuts. To overcome such challenges, alternative designs should be created using numerical simulation methods, and a study should be conducted before production investment to address potential problems in production (Erbil & İnce, 2010).



Figure 1.1 Wheel nut types (speedwaymotors.com)

Use of simulation programs; It is very important to respond to the increase in product diversity with the developing sector, to carry out production trials at minimum cost in order to provide competitive prices, to increase production capabilities and to gain know-hows. In line with these purposes, in this study, wheel nuts with very challenging geometry were discussed and the production approach was determined by performing forming analysis with the help of the Simufact FEM program. In addition,

die loads were examined and the aim was to carry out the production trial with the minimum possible cost and time loss.



CHAPTER TWO

PREVIOUS STUDIES

In 2022, Nurhidayah Abd Hamid and colleagues from Gyeongsang National University published an article titled “Ejector pin-related high-cycle fatigue fracture of the critical die corner during automatic multistage cold forging of an automotive wheel nut” in which they investigated fractures due to high stress on the ejector pin in a wheel nut made of S25C material using cold forging. Both experimental and FEM analysis were conducted to examine the correlation between the end geometry of the ejector pin and the part’s strength.

In 2016, N. Emrah Kılınçdemir and his colleagues from the Norm Cıvata R&D Center published an article in Metal Dünyası Magazine titled “Yenilikçi kalıp sistemleri tasarımı ile eksen kaçıklığına sahip soğuk dövme parçalarının üretimi” which outlined an approach for manufacturing parts with axis misalignment using the cold forming process. This study, which was carried out to enable the production of parts with axis misalignment—a novel product geometry resulting from evolving industry needs—through cold forming, in addition to hot forming, warm forming, or machining, led to a utility model application being filed with the Turkish Patent Institute. The design approach conducted in the study included material flow analyses, the determination of forging forces, and numerical damage detection using the finite element method. It demonstrated that the desired geometry of the target part could be achieved within the existing machine limits, production was feasible, and forming was possible below the maximum damage threshold. Alongside the experimental study, a pre-production of up to 5,000 units was carried out.

In a 2017 publication in the Journal of Science and Technology at Sakarya University titled “Cıvata soğuk dövme işleminde kalıp ömrünün arttırılması: Dövme kademe tasarımının etkisi”, Cenk Kılıçaslan and Umut İnce investigated the die damages that occur during the cold forming production of M10x32 dog-point bolts. Utilizing the Simufact.forming simulation program, they analyzed these damages and shared the findings from the analysis alongside the results from production trials. To achieve the targeted dog-point form, a preparatory phase was added to the design of the previous station, which effectively reduced the maximum principal stresses on the

dies. Moreover, the forging die design was configured in two parts, resulting in a 70% reduction in stresses. This study was conducted experimentally, and it was reported that the die life increased by 3.80 times.

At the 2020 seminar “Designing Engineering Structures Using Stochastic Optimization Methods”, Sezgin Yurtdaş and colleagues presented a paper titled “Geometrical Optimization for a Cold Extrusion Process”. The paper focused on simulation studies conducted on the geometry of an extrusion die designed for bolt production. The study examined input parameters such as extrusion angle, temperature, and friction coefficient, aiming to achieve the minimum extrusion force with optimum values. Regression models were performed using Mathematica software in conjunction with data obtained from FEM analysis, leading to the determination of optimal extrusion input parameters.

Burak Gökberk Özçiçek completed his master's thesis titled “Burç üretimi için soğuk dövme kalıbı tasarımı ve analizi” at İzmir Katip Çelebi University, Faculty of Science, Department of Mechanical Engineering, in 2020. The thesis covers the design of a die for bushing production, its analysis using the finite element method, and trial production. Additionally, it discusses production processes and design procedures, providing insights into problems encountered during production and their solutions.

The article titled 'Wear Improvement of Tools in the Cold Forging Process for Long Hex Flange Nuts,' written by Shao-Yi Hsia and Po-Yueh Shih in 2015, examines wear issues at the extension station of a flanged bushing. The authors compared the results obtained from FEM analysis, where they altered the tip geometry of the die component most prone to wear, with the results from experimental studies. They conducted comparisons of various geometry options using the Taguchi method and analyzed the types of wear through SEM analysis, indicating that the wear was adhesive wear due to extrusion.

CHAPTER THREE

PRODUCTION PROCESSES

In the production of wheel nuts, there are various production processes within the process flow from raw material to packaging. For producing nuts through cold forming, the process begins with raw material preparation, where the material is readied for cold forging. Subsequently, the cold forming process shapes the product to -nearly- final dimensions. Following cold forming, the tapping process is carried out to create internal threads. A chip removal operation is then performed to eliminate any material left after threading. Depending on the expected mechanical properties of the product, a heat treatment operation may be applied. If corrosion resistance is needed, a coating process is applied. There are many different coating methods available based on the desired corrosion resistance and coefficient of friction of the part. After coating application, the products are finally sorted in automatic sorting machines according to the customer's PPM (parts per million) expectation, packaged, and prepared for shipment.

3.1 Raw Material Preparation

The production of wheel nuts commences with the raw material preparation process. Parts such as bolts, nuts, and screws are manufactured using raw materials known as wire rods. These wire rods undergo surface treatment processes to eliminate any dirt and rust accumulated during transportation and storage. Various surface treatment methods exist with the objective of removing undesired formations such as oil, dirt, and rust from the raw material.

Following the surface treatment process, annealing is applied to facilitate the forming of the material with reduced forging load. Annealing operations aim to soften the materials by reducing their hardness and altering their microstructure, making them more suitable for the forging process.

Finally, wire drawing is utilized to tackle both variations in diameter arising from the raw material production method and surface defects that may occur during material transport. Through the wire drawing process, the wire rod's diameter is standardized from beginning to end. Consequently, during the cold forming process, the material is consistently shear in equal volume, minimizing variations in the dimensions of the parts.

3.1.1 Surface Cleaning

The initial stage of raw material preparation involves surface treatment operations. It's crucial not to perceive surface treatment operations solely as cleaning operations. Following the initial stage of surface treatment, which is cleaning, the material surface is treated with various chemicals or with sandblasting method.

There are two different methods for cleaning, mechanical and chemical. While each method has its own set of advantages and disadvantages, the ultimate goal of both is to remove unwanted formations such as oil, dirt, and rust from the materials. Mechanical cleaning, achieved through processes like sandblasting, has gained prominence in recent times due to its environmentally friendly nature, aligning well with the increasing emphasis on sustainability goals, compared to chemical processes. There are two different types of surface cleaning; sandblasting and chemical treatment.

In the sandblasting method, high-speed propelled sand particles reduce the oxide layer on the sample surface, eliminate surface contaminants, and induce localized plastic deformation in the surface layer. Additionally, a compressed residual stress layer forms beneath the surface (Kocatürk et al., 2020). Observations from studies have noted microstructure changes induced by sandblasting in austenitic steels (Ngaile et al., 2007).

There are various applications of sandblasting for surface cleaning. Apart from the method where the entire wire rod is sandblasted by wrapping the wire rod on a shaft and separating its coils, there are methods where the end of the wire is passed through straightening machines and then sandblasted at a certain wire speed. Ultimately, the

purpose of the process is to remove rust and dirt from the material. This is achieved by spraying sands, typically 0.20-0.50 mm in diameter, onto the material, which are harder than the material to be cleaned.

Due to the heating of the material during the sandblasting process, it is necessary to wait for the material to cool down. Additionally, if the material does not enter the coating process shortly thereafter, corrosion may occur due to its susceptibility to rust formation. The image of the sandblasting machine is given below Figure 3.1.



Figure 3.1 Sandblasting

The other surface cleaning method is called as chemical treatment as seen below Figure 3.2. The raw material preparation process through chemical treatment involves immersing the material in baths prepared with various chemicals for a specific duration. These baths are sequentially arranged to facilitate the removal of oil and dirt from the material's surface. They typically include a degreasing bath for oil removal, followed by a rinsing bath with hot water, an activation bath for phosphate coating preparation, a phosphate bath, and finally, a passivation bath. Parameters such as bath

temperature and duration are determined by the criteria set by chemical manufacturers and may vary based on the results obtained from the process.



Figure 3.2 Chemical treatment

3.1.2 Surface Coating

Prior to the cold forming process, coating the surface of the material aims to reduce friction between the material and the dies. This reduction in friction not only extends die life but also facilitates the shaping of the material. Without this, achieving the desired geometric dimensions of the workpiece becomes challenging, surface defects may occur, and there is a noticeable decrease in die life. Among surface coating methods, the most common is zinc phosphate coating followed by soap application.

Zinc phosphate coating is typically applied as a surface treatment method following the acid cleaning process. In this coating, which occurs as a result of the chemical reaction between the material and the chemical solution, process parameters such as chemical concentration, bath temperature, pH, processing time, free and total acidity are critical factors that affect coating quality. Excessive thickness of zinc phosphate coating increases the coefficient of friction. A thin coating can lead to complete loss of coating in multiple wire drawing operations and other issues. The purpose of zinc phosphate coating is to prevent damage to the wire passing through the die and to enhance the corrosion resistance of the drawn wire. Zinc phosphate coating also increases the wire drawing speed thanks to its lubricant feature. It is the preferred

method for materials used in cold forging because it adheres well to the metal surface and maintains its integrity even after multiple drawing processes. The crystal structure of zinc phosphate coating prevents film breakage and deterioration, providing an excellent surface for oils and soaps used in subsequent stages. The use of zinc phosphate-coated wire rods reduces wear on wire drawing dies and rolling mills, thereby extending their service life (Kocatürk et al., 2020).

Additionally, it should be noted that the major drawback of both the acid cleaning and zinc phosphate coating processes is the generation of hazardous waste. These processes consume a significant amount of water during coating, which is challenging to recycle. Due to heavy metals and chemicals involved, these processes are not environmentally friendly. Consequently, both regulatory restrictions and cost considerations are causing a decline in their share in the industry. For these reasons, the polymer coating alternative is used in the industry.

Polymer coating, conducted through the immersion method, reduces the coefficient of friction on the material's surface and enhances tribological conditions. The benefits of polymer coating can be outlined as follows:

- Environmental friendliness: Polymer coating offers a highly safe tribological system for both the workforce and the global environment by eliminating heavy metals, sludges, and hazardous waste.
- Cost-effectiveness: It reduces the overall cost of the coating process; there is no need for expensive waste treatment due to lower energy and water consumption.
- Reduction of ongoing tasks: Polymer coating is a moisture-sensitive dry process. Therefore, coated materials should be forged within a specified period, which helps reduce pending tasks.
- Facilitation of processing: Polymer-coated materials are easier to process in subsequent operations.

The cold forging industry has directed itself towards seeking better solutions and has been compelled to rapidly address the hazardous waste issue associated with the

zinc-phosphate coating system. Consequently, polymer coating can be regarded as an environmentally friendly coating method that promotes leaner production, reduces operational costs and inventories, and enhances profitability (Kocatürk et al., 2020).



Figure 3.3 Polymer coating

3.1.3 Annealing

In the cold forming process, the importance of the annealing process is high due to the adverse effects of the material being too hard, which can both shorten the die life and require high forging loads. Additionally, residual stresses remaining within the material after casting and rolling processes hinder plastic deformation during the cold forming process and increase the risk of crack formation. The annealing process is conducted in atmosphere-controlled furnaces where oxygen is removed and replaced with nitrogen gas. Through this controlled heating and cooling process, the dislocation density within the material decreases, and residual stresses are relieved. The material is then prepared for forging by spheroidizing the needle-like cementite within the perlite phase. The initial hardness value of 17MnB3 material coming from the manufacturer is approximately 150 HV. This hardness is not the same in every cross-section of the wire and there are also residual stresses remaining from its production. After the annealing process, the hardness of the raw material decreases to

approximately 110 HV. The image of the annealing machine is given below Figure 3.4.



Figure 3.4 Annealing machine

3.1.4 Wire Drawing

One of the significant steps prior to the cold forming operation is the wire drawing process. Steel manufacturers generally produce wire rods in specific diameters (e.g., Ø12 mm, Ø14 mm, Ø16 mm, etc.). However, in cold forming designs, the entry wire diameter is determined not in these standard sizes, but in more precise dimensions. Wire drawing is applied to the raw materials to obtain these precise diameters. Additionally, wire drawing is applied to eliminate diameter variations arising from the production method of the raw material manufacturer and damages occurring during transport. Consequently, a consistent wire diameter is achieved from the beginning to the end of the raw material. This ensures equal volume shearing for each part in cold forming production and prevents dimensional variations between parts in mass production. Thus, all produced parts are manufactured to the same dimensions.

Furthermore, wire drawing enhances the circularity of the raw material, thereby facilitating homogeneous material flow during forging.

The wire drawing operation involves passing the raw material through a die to reduce wire diameter. Prior to die, a powdered soap chemical is used to prevent die heating, prolong working time, and facilitate easy movement of the material through the die. As the reduction ratio increases, the dislocation density on the surface increases, leading to noticeable increases in hardness. This is an undesirable condition for cold forming operations, necessitating the material to undergo annealing again. Therefore, performing reduction above a certain ratio increases forging loads, die lifespans, and the risk of crack formation.

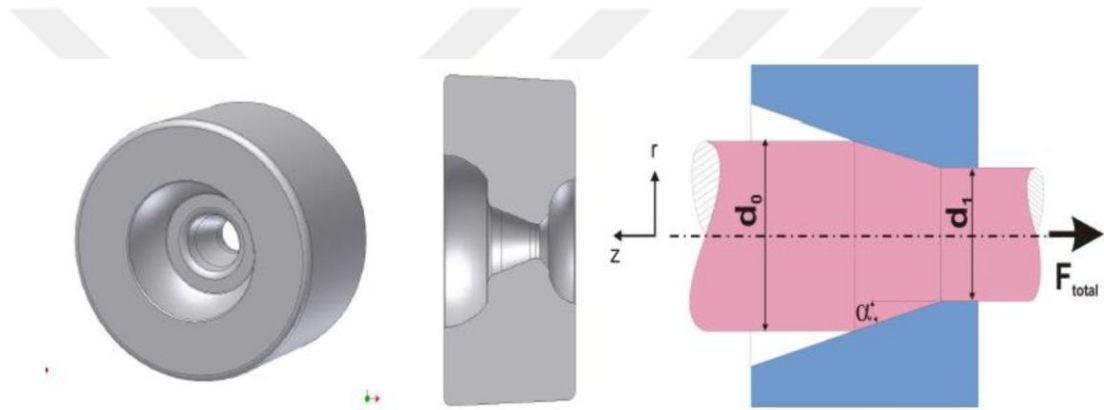


Figure 3.5 Wire drawing die

In the wire drawing operation, the reduction in cross-sectional area (Figure 3.5) and equivalent plastic strain are calculated using the following equations 3.1 and 3.2:

$$\Delta A = A_0 - A_1 \quad (3.1)$$

$$\epsilon = \ln \left(\frac{A_0}{A_1} \right) = \ln \left(\frac{d_0^2}{d_1^2} \right) \quad (3.2)$$

Here, A_0 and A_1 represent the initial and final cross-sectional areas, respectively, and d_0 and d_1 represent the initial and final diameters respectively.

3.2 Cold Forging

Cold forging, also known as cold forming, are classified into three different categories in the literature as below Table 3.1. These are referred to as cold, warm, and hot forging, and they are classified based on the ratio of the application temperature to the melting temperature of the workpiece material (Karamış, 2004).

Table 3.1 Forging method classifications

Process	T/T_m
Cold forging	$< 0,30$
Warm forging	$0,30 - 0,50$
Hot forging	$> 0,50$

T: forging temperature, **T_m**: melting temperature of the material

Cold forming, also known as cold forging, is considered a fundamental manufacturing method compared to other forging techniques because it does not involve energy input to the material, and it is widely used in many industries. Developed methods for producing products in the desired dimensions, this production method is based on forming the material under the influence of compressive forces within specified toolings while preserving the volume and mass of the material (Çapan, 1991).

The aim is to bring the material to the desired dimensions by subjecting it to permanent plastic deformation, altering its original geometry. Depending on the type of material to be shaped (wire, sheet), the working principle of the forging machine (hydraulic, mechanical), the direction of the forging force (horizontal, vertical), and the temperature of the workpiece as mentioned above, it can be classified. Like any other production method, it has advantages and disadvantages compared to other production methods.

The advantages of cold forming can be listed as follows:

- High production speed for mass production.
- Good surface roughness can be achieved.
- Production with tight tolerances is possible.
- Economical due to low material loss.

As for the disadvantages:

- Limited range of producible geometries.
- High machine and tooling costs.

The concept of deformation is examined in two classes: elastic and plastic deformations. Elastic deformation changes refer to non-permanent shape changes or those occurring in the elastic area on the stress-strain diagram. Plastic deformations refer to permanent shape changes or those occurring in the plastic area on the stress-strain diagram (Anık et al., 1994).

In the production of fasteners, the cold forming process is considered the main process. A good understanding of the process and material fundamentals is required to ensure the production of parts with complex geometries or relatively tight tolerance ranges without the need for additional processes. The principles related to material and process are listed below in headings.

3.2.1 Stress

In solid mechanics, stress is obtained by dividing the force acting on a unit area. There are two types of stress, normal stress and shear stress, according to the direction of the force applied surface axis. Tensile stress occurs when the force is applied perpendicular to the surface area and extends the material. Compressive stress, on the other hand, occurs when the material is compressed in a manner that shortens its length. Shear stress occurs when force is applied to the material's two opposite surfaces in parallel and opposite directions, allowing them to slide against each other. As shown in the image below, the following are depicted:

- a) Tensile stress
- b) Compressive stress

c) Shear stress

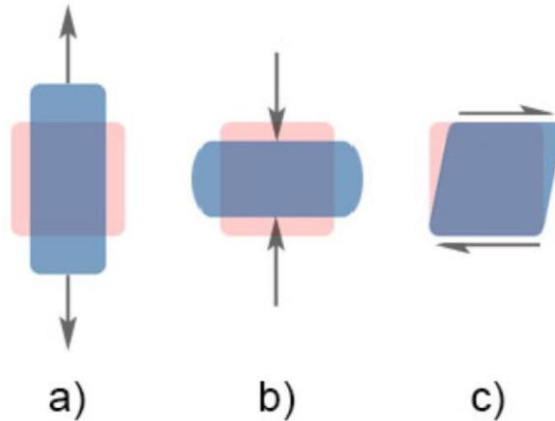


Figure 3.6 Types of stresses (muhendishane.org)

3.2.2 Strain

Strain is a concept that expresses how much a material shape changes under load. This change mathematically represents deformation and is related to the applied force. Strain is divided into two fundamental types: normal strain and shear strain. Normal strain occurs in the same direction as the applied force, while shear strain results from the shearing force acting on the material. Shear strain is determined by the displacement between the planes of the material and is expressed in terms of the shear angle. The concept of strain allows us to mathematically express the deformation of the material and understand its mechanical behavior.

If we denote the initial length of a ductile rod, which is subjected to force and consequently stress as σ_0 , and the length change of the rod as Δl , we can express strain mathematically with the following formula (3.3).

$$\epsilon = \frac{\Delta l}{l_0} \quad (3.3)$$

By considering the instantaneous changes in the applied force, we can reach an expression called true strain, by determining the instantaneous value of the cross-sectional area and the instantaneous length of the rod. If we denote the final length the

rod reaches as l_f , true strain can be represented by the following formula (3.4), and the next formula (3.5) can convert the true strain value into the engineering strain value.

$$\varepsilon = \ln \frac{l_f}{l_0} \quad (3.4)$$

$$\varepsilon = \ln(1 + e) \quad (3.5)$$

3.2.3 Stress – Strain Curve

The stress-strain curve, also known as the flow curve shown in the Figure 3.7., is a relationship widely used in solid mechanics, where we can observe the unit deformation of a material with the increase in applied stress.

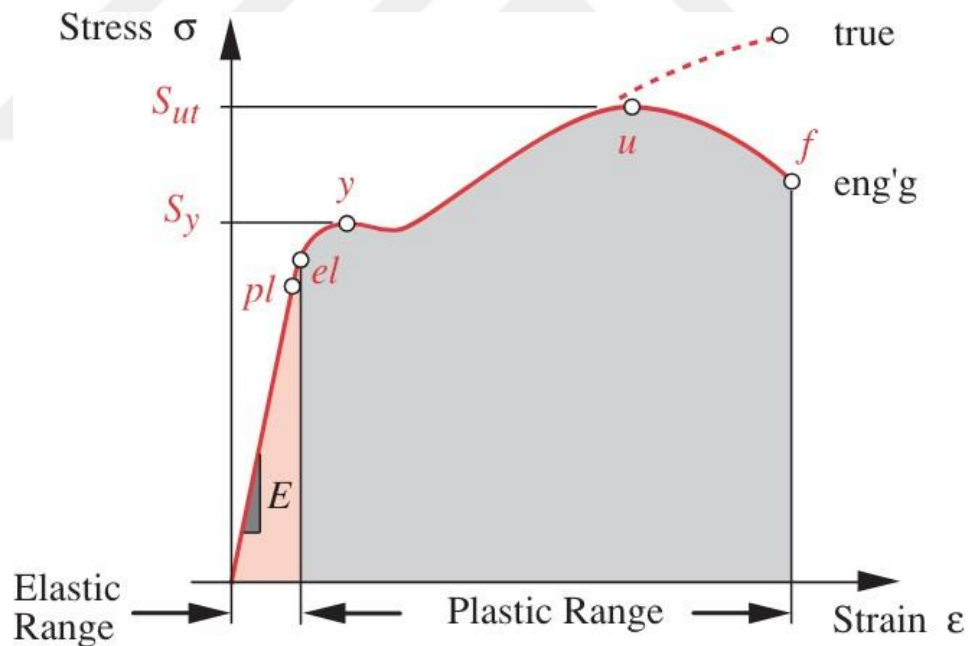


Figure 3.7 Stress – strain curve (Norton, 2010)

To understand the behavior of a material under stress, uniaxial tensile testing is commonly used. This test involves fixing one end of a specimen and applying force

only along its length at the other end. The data obtained during the test determines the relationship between the force acting on the specimen and the amount of elongation. However, to ensure the reliability of the test results, it must be ensured that the force applied to the specimen acts only in one axis.

Yield stress is the maximum stress a material can withstand before undergoing plastic deformation. Beyond this point, the material undergoes permanent deformation, known as the yield point. Yield stress can vary depending on factors such as material properties, process conditions, and material structure. As seen in the graph, there is a linear relationship between stress and strain up to the yield stress, after which the material undergoes permanent deformation. In the elastic region, the atomic bonds of the material behave like a spring, returning to their original state when the force is released. However, when the material is subjected to a force beyond the yield stress, crystal blocks slide over each other, causing permanent deformation. While it is possible to increase the amount of plastic deformation by increasing the force, at points where deformation increases, strain hardening will occur, leading to material embrittlement.

3.2.4 Strain Hardening

Strain hardening is the phenomenon where a material becomes harder as it undergoes plastic deformation. This is attributed to an increase in dislocation density within the material. Dislocations are defects in the material's crystal structure, and as dislocation density increases, it becomes more difficult for the material to deform further.

The true stress-true strain curve, often referred to as the plastic flow curve, depicts the stresses required for a material under specific deformation rates and clearly defines the plastic yielding conditions. This curve represents the plastic yield behavior of metals and is often expressed with an exponential relationship known as the Holloman Equation. The Holloman Equation describes the yield behavior from the yield point up to the homogeneous deformation zone. However, it should be avoided to determine the initial yield strength of metals using the Holloman Equation, as this relationship

describes the behavior of the material after plastic deformation has commenced and is applicable for further deformations. Mathematically, the equation is represented as follows, where

$$\sigma_g = \sigma \epsilon^n \quad (3.6)$$

σ determines the material's capability for strain hardening and increasing its deformation strength. Particularly, in conditions where no strain hardening is observed, such as in hot deformation conditions, the value of σ approaches zero. For engineering materials, this value typically ranges between 0.15 and 0.25. As the strain hardening exponent n increases, the amount of uniform strain also increases. The strength coefficient σ directly provides an indication of the material's strength; a high σ value implies a high strength of the material. Both σ and n are constants that characterize material properties (Pürçek, 2007).

3.2.5 Cold Forging Machine

Cold forming machines are divided into horizontal and vertical presses based on the direction of the applied force. They are further classified into machines with open and closed dies depending on the type of die. Various machines exist based on their operating principle, including hydraulic, mechanical, screw, and hammer types. In this study, one of the horizontal presses available at Norm Somun A.Ş. has been selected as the machine. The prototype production of a wheel nut will be carried out using a South Korea-made horizontal press machine, model HNP 637; this machine, with its six stations, a forging load of 300 tons, and a stroke length of 50 mm, is an appropriate choice for forming the product. (Figure 3.8)

In the cold forging machines, the motion transmission from the motor to all components is facilitated by a belt and pulley system. The synchronized operation of various components, such as the moving punch body, die and punch ejectors, and the finger systems that transport materials between stations, including the timing of these fingers' opening and closing, is adjusted with the help of camshafts. Machine operators

ensure that the parts are manufactured to the desired dimensions and quality by adjusting the alignments and the forward/backward distances of the dies and punches.



Figure 3.8 Cold forging machine

3.3 Threading Process

The threading operation is the process where the threads of fasteners are formed. The threads of externally threaded fasteners such as bolts and screws are typically created without shearing chips, using a method called rolling between two dies known as "thread rolls." This process can be performed adjacent to cold forming machines, following the cold forming process. However, for internally threaded fasteners such as nuts and bushings, a direct tapping operation cannot be performed right after cold forming. Cold-formed parts are transported to the tapping machines area.

There are two types of threading operations for female fasteners: rolling and tapping. The tapping method, which involves removing material to form threads, is a more commonly used approach. In this method, the parts to be threaded are first dumped into a basket and then correctly oriented towards the machine with the help of vibratory motions and various gating systems. The threading process is performed by a tool called a tap, typically made from hard metals. These taps, manufactured according to the required metric and thread tolerance, enter the nuts in succession,

removing material and forming the threads. On the other hand, the rolling method involves forming threads by displacing material. The advantage of this method is the increase in hardness and strength of the threads due to the rolling process. This method is predominantly used for parts with blind holes and parts that are difficult to feed into the machine.

3.4 Deburring Process

After the threading process, a deburring process is applied to remove chips from the parts. Initially, the parts are cleaned by washing with a cleaning chemical inside helical rotors spinning at a specific speed. Following the washing step, the parts are placed inside a high-speed spinning drum where centrifugal forces remove the chips and excess chemical liquid from the parts. Image of the deburring machine is given below Figure 3.9.

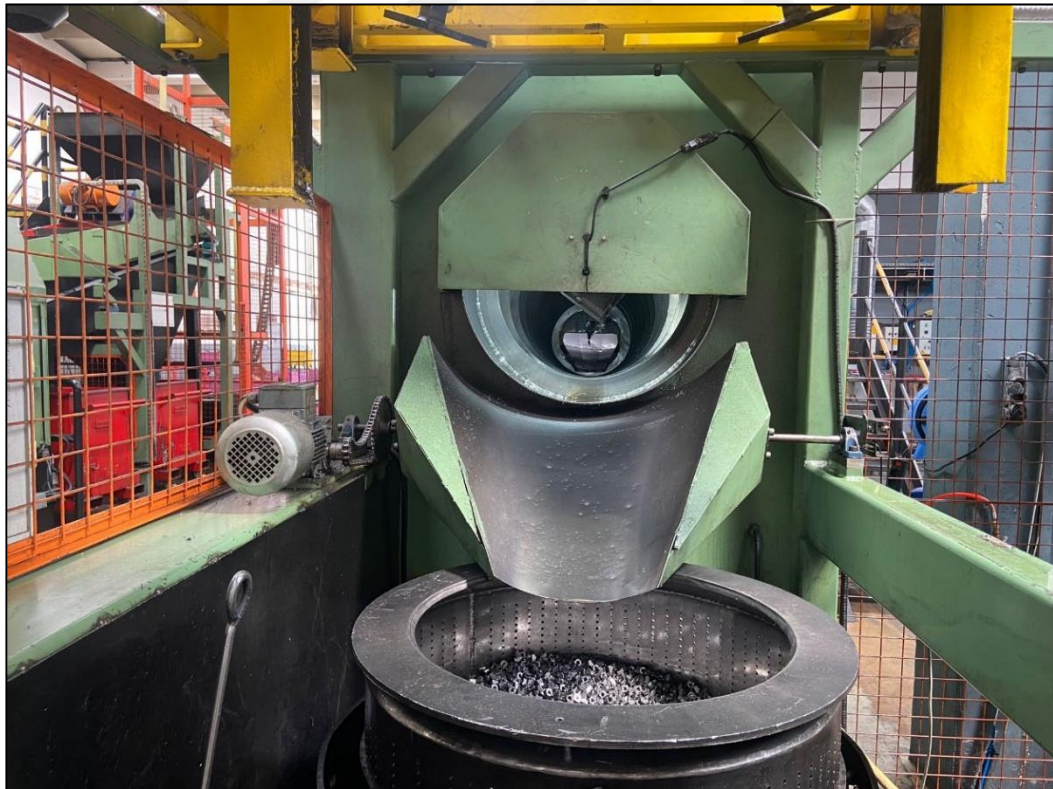


Figure 3.9 Deburring process

3.5 Heat Treatment

Heat treatment is generally defined as controlled heating and cooling processes applied in the solid state to metals or alloys, using high-tech equipment and control techniques, in order to give the desired properties (Köksal et al., 2004). The fundamental heat treatments of steel are performed to transform its microstructure. The type of transformation, along with the composition and metallographic structure, significantly affects the physical and mechanical properties of the steel. The mechanical properties of a steel depend on the type, amount, and metallographic structure of the transformation products contained within it.

Following the cold forming process, various heat treatments are applied to eliminate irregular internal stresses, achieve desired hardness levels, and enhance tensile and yield strengths. Although heat treatment increases strength, properties such as ductility, % reduction of area, and charpy impact are decrease.



Figure 3.10 Heat treatment line

3.6 Coating

The coating process, like other processes for iron and alloy parts, is applied to prevent corrosion of materials. Corrosion refers to the loss in material due to chemical and electrochemical reactions between the material and its environment (Çiçek & Numan, 2012). One way to prevent corrosion, a significant factor affecting the lifespan of a part, is by isolating the metal surface from air and water. For this purpose, metal surfaces are covered with a protective layer. While this layer can be a coat of paint, it is generally preferred to cover one metal and its alloys with another metal layer. In the industry, parts are commonly electrochemically coated with chromium, nickel, copper, silver, or tin. These metal layers are more resistant to thermal, physical, and chemical effects compared to painted surfaces (Demirgöz & Taralp, 2001).

Coatings, especially on fasteners that will have male or female threads, must be meticulously applied. A critical factor is the alteration of the thread geometry by the coating material, which can prevent achieving the desired thread tolerance in the product. Additionally, a significant portion of the torque applied to fasteners is converted into friction energy. The coating's ability to maintain a desired friction coefficient range on the surfaces of the fastener significantly affects its mechanical properties, altering the locking force's value (Bacchi et al., 2015).

Before the coating process, a cleaning operation is applied to the parts. This cleaning operation is divided into mechanical and chemical methods. There are two different methods of mechanical cleaning: brushing and sandblasting. In chemical cleaning processes, there are solvent-based and water-based chemicals, with water-based chemicals generally being more environmentally preferred in the industry. The aim of the cleaning process is to remove oil and dirt from the surfaces of the parts to be coated.

The coating methods used on fasteners are divided into two types: electrolytic coating and lamellar coating.

3.6.1 Electrolytic Coating

Although application techniques vary, electrolytic coatings fundamentally involve the electrolysis method, where the part to be coated is the cathode and the coating material is the anode in a specially prepared solution. After the main coating, chemicals called topcoats containing lubricants are used to determine the desired friction coefficient range on the part's surface. Commonly applied electrolytic coatings on fasteners include:

- Zinc Coating
- Zinc Phosphate Coating
- Zinc Nickel Coating

It can be said that zinc nickel coating provides the highest corrosion resistance among electrolytic coatings, while zinc phosphate coating offers the least.

Due to acidic washing in the pretreatment processes of electrolytic coatings and hydrogen evolution on the cathode, embrittlement occurs due to the atomic-level dissolution of hydrogen within the material's structure. This embrittlement can cause the part to fracture suddenly. This phenomenon, occurring during the coating of materials harder than 360 HV as determined by studies and standards, is addressed by a hydrogen embrittlement removal process, a tempering process at a specific temperature and duration, to eliminate this risk.



Figure 3.11 Electrolytic coating process (normcoating.com)

3.6.2 Zinc Lamellar Coating

Zinc lamellar coating is applied to parts with high life expectancy due to its high corrosion resistance compared to electrolytic coating types. Additionally, because of the risk of hydrogen embrittlement in hard materials with electrolytic coatings, zinc lamellar coating is generally preferred for this type of materials.

In the zinc lamellar coating process, as with other types of coatings, the cleaning process is the first step. A proper cleaning process is essential to achieve the desired performance from the coating. After cleaning, the parts to be coated are immersed or sprayed with the coating chemical. Unlike electrolytic coatings, which involve mechanical interlocking, lamellar coatings undergo a chemical reaction through a binder system. This chemical reaction requires a specific duration and temperature. The parts interacting with the coating chemical enter curing ovens. After the curing oven, cooling is performed, and if necessary or requested, a further coating process is carried out to add a topcoat (lubricant).

CHAPTER FOUR DESIGN PROCESS

The consecutive die system in cold forming is an iterative manufacturing method. In other words, the output from one die serves as the input for the next die. Consequently, any change in one die impacts the complete process. Reverse engineering is employed to design the product, tracing back from the final product to the initial wire part (the sheared raw material piece).

The design process begins with a review of the technical drawing of the desired final product. The specified geometry and required tolerances are examined in the drawing. Additionally, the raw material of the product is a significant factor influencing the forming process. A high initial hardness of the raw material entering the cold forming process negatively affects both the forming and the die life. In this study, technical drawing of the part is given below Figure 4.1 and 17MnB3 has been selected as the raw material for the product.

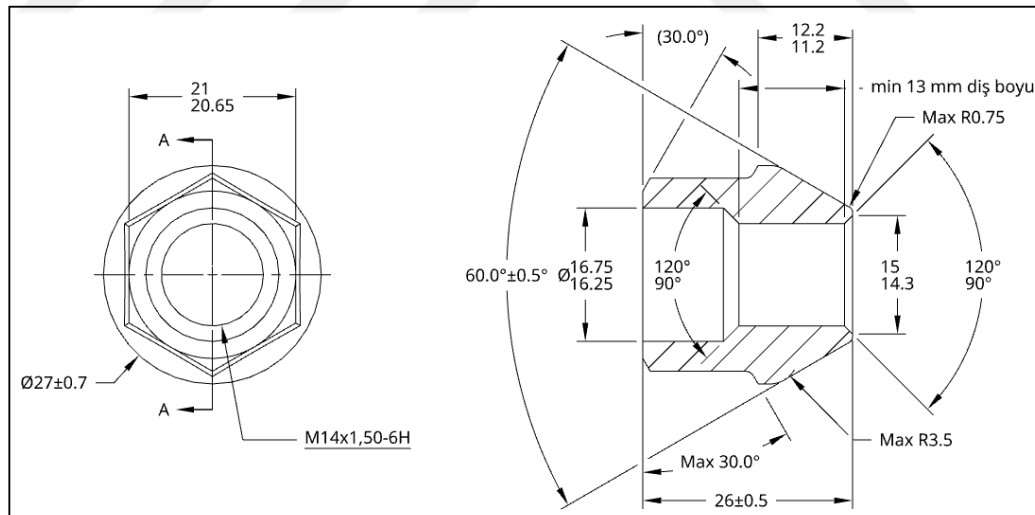


Figure 4.1 Wheel nut technical drawing

Chemical composition of the raw material 17MnB3 is given in the Table 4.1.

Table 4.1 Chemical composition of 17MnB3

C	S	P	Mn	Si	Cu	Cr	Ni	Mo	Al	B	Ti
0,23	0,015	0,015	1,00	0,15	0,15	0,20	0,15	0,05	0,02	0,005	0,05
0,18	max	max	0,80	max	max	max	max	max	min	0,002	max

The preliminary design process and the design of the forging steps begin with the product technical drawing. There are several forming methods in the cold forging as below;

- Preparation
- Reduction
- Backward extrusion
- Forward extrusion
- Upsetting
- Piercing
- Trimming

4.1 Simufact Program

The Simufact Forming software used in the study was developed by Simufact Engineering GmbH. Thanks to the program, simulations can be carried out for metal forming, mechanical joining, welding and additive manufacturing processes. Outputs such as forming force, material flow, folding, workpiece-mould contact status, flow lines, temperature distribution, hardness, stress and deformation distribution can also be obtained.

4.2 Station Designs

After the dimensions of the final product in the technical drawing are nominally transferred to the 3D model, the net volume of the product is calculated in mm³. The final dimensions of the product are the output of the 6th station, that is, the piercing

station. The output of the 5th station is the step where the final dimensions of the product are given but the scrap part is not removed. A certain percentage of scrap volume is determined according to the metric and volume of the product. In addition, the location of the scrap is also important for the 5th station design. It is taken into account that drilling will be done from the narrowest hole size in the product and the scrap thickness. In the light of this informations, a 3D model of the 5th station sample is drawn and the volume of this station is the gross volume of the product, is calculated in mm³. The designs of the stations are given below Figures 4.2 and 4.3.

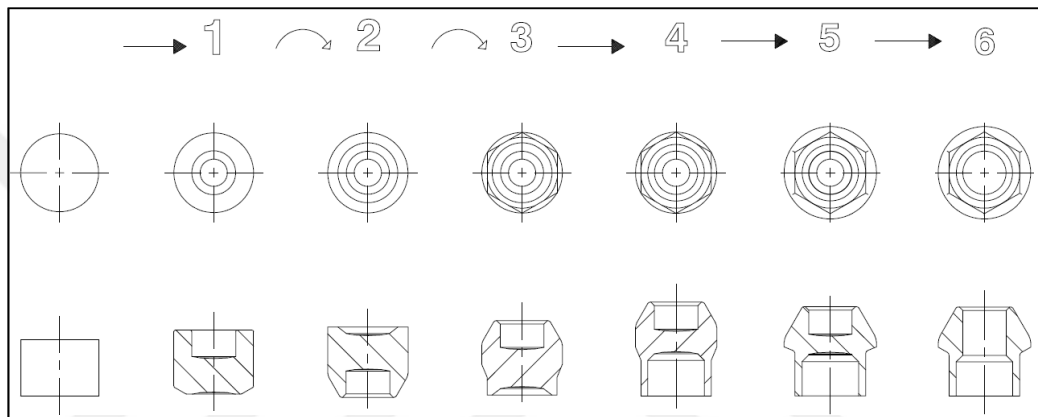


Figure 4.2 Cross-sectional view of station designs

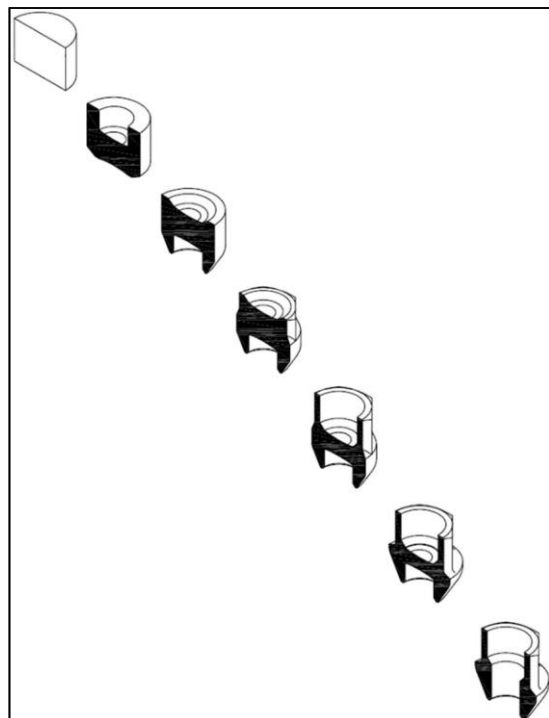


Figure 4.3 Isometric view of station designs

4.2.1 Shearing Station

Shearing station is the initial stage of the cold forging process. There are two types of shearing systems in the cold forging machines such as open shearing blade system and closed shearing blade system. Also cold forging machine producers have designed two types of wire feeding system which are roller system and horizontal pad-drive system. The most important features expected from the shearing station is feeding the desired volume of material and shearing the material in the best possible way without any material accumulation. The sheared cylindrical material must be axisymmetric. If not, the forming performance at the next station will be affected.

4.2.2 Station 1: Preparation & Backward Extrusion

The first station is generally referred to as the preparation station. At this station, the axial symmetry of the part transferred from the shearing station is improved, and the edges are rounded. Due to the complex geometry of the wheel nut, which is the focus of this study, a backward extrusion process is also performed at the first station. The image of the desired geometry to be achieved after the 1st station is given below Figure 4.4.

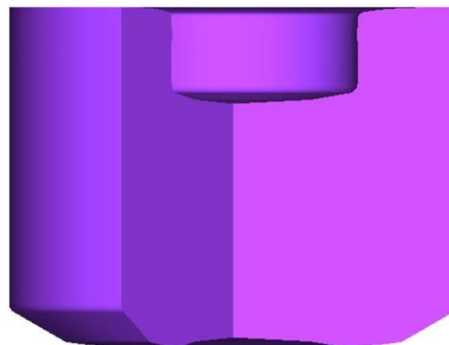


Figure 4.4 Station 1 geometry

4.2.3 Station 2: Preparation of Conical Area

The sample coming from the first station is rotated 180 degrees in the transfer system and transferred to the second station. At this station, the aim is to create a

conical shape in the area where the hole is extended before, and prepare for the hole to be created on the other surface as given Figure 4.5.

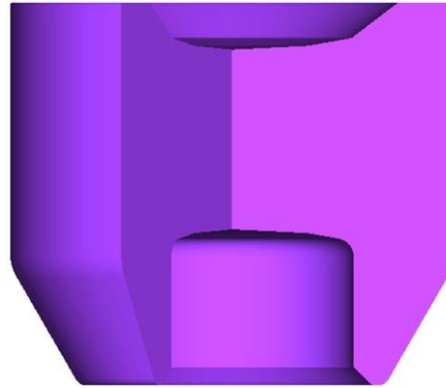


Figure 4.5 Station 2 geometry

At the first station, a hole 8.50 mm in length was formed during the backward extrusion. When this sample was formed at the second station, as can be seen in the image below, folding in the hole was detected. For this reason, the hole length was reduced to 6.00 mm at the first station. After this revision, the folding problem was eliminated. Image of the folding area is given below Figure 4.6.

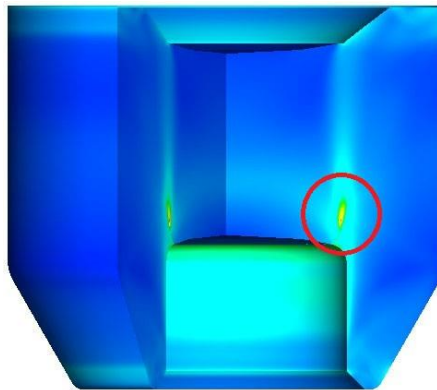


Figure 4.6 Station 2 folding detection

4.2.4 Station 3: Hexagon Forming

At this station, the hexagonal form begins to be given. Just like the second station, the sample arriving at this station is also rotated 180 degrees thanks to the transfer

system. Initially, the length of the hexagon formed by the extrusion method is kept short. Performing a longer extrusion would lead to significantly more material flow and, consequently, an increase in the maximum principal stresses on the die. This would cause the die to break during short cycles. The image of the desired geometry to be achieved after the 3rd station is given below Figure 4.7.

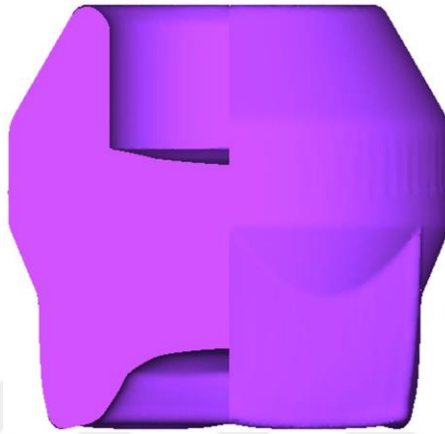


Figure 4.7 Station 3 geometry

4.2.5 Station 4: Hexagon Extension

At the station 4, it is planned to extend the hexagonal form, which was started at the previous station. While the hexagon form is extended, the hole on the inside is also extended in the same way as below Figure 4.8. To achieve this, a spring-loaded die system is needed.

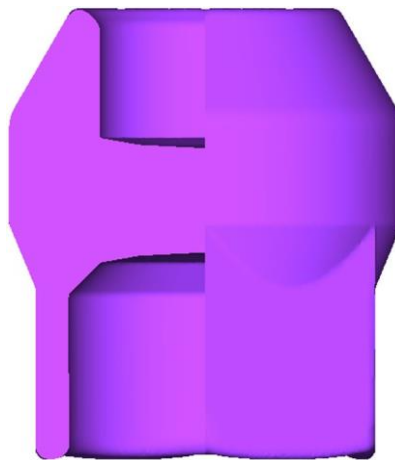


Figure 4.8 Station 4 geometry

4.2.6 Station 5: Flange Completing

The fifth station is the station where the product is brought to its final dimensions but its scrap is not thrown away. At this station, the base of the hexagon must sit completely on the base of the die and countersinks must be created. The conical section, prepared two stations before, is inflated here to form a flange. The most important issue at this station is that the flange does not make a double angle. For this reason, the positions of fixed and moving tooling systems must be adjusted very precisely. The image of the desired geometry to be achieved after the 5th station is given below Figure 4.9.

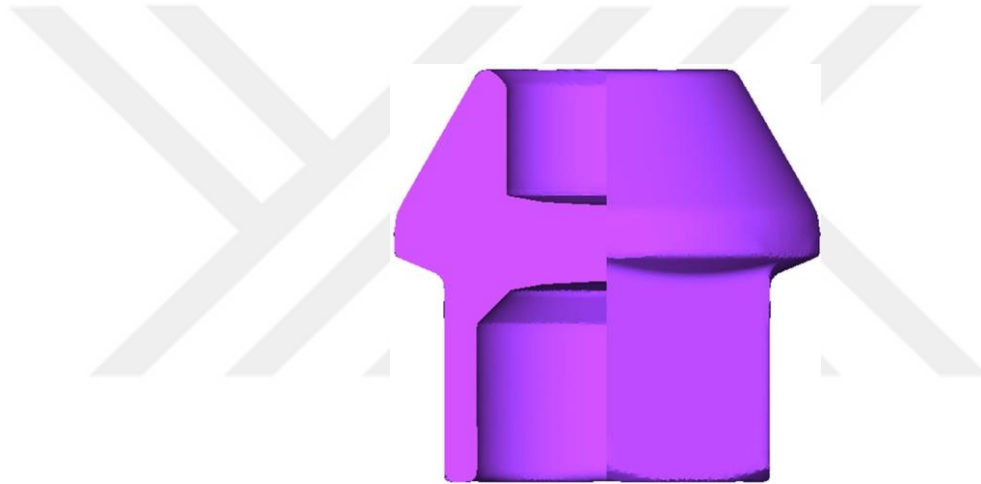


Figure 4.9 Station 5 geometry

4.2.7 Station 6: Piercing

This station is the final station of the cold forging. The scrap part is removed from the part by the shear force with the help of the punch element in the moving tooling system. The important thing here is to obtain a shearing surface with a diameter difference of 0.05 mm without creating a rank. The geometries obtained in the final product after the forming simulations conducted for all stations are presented in the Figure 4.10 and Figure 4.11. It is observed that the dimensions and tolerances are within the desired specifications.

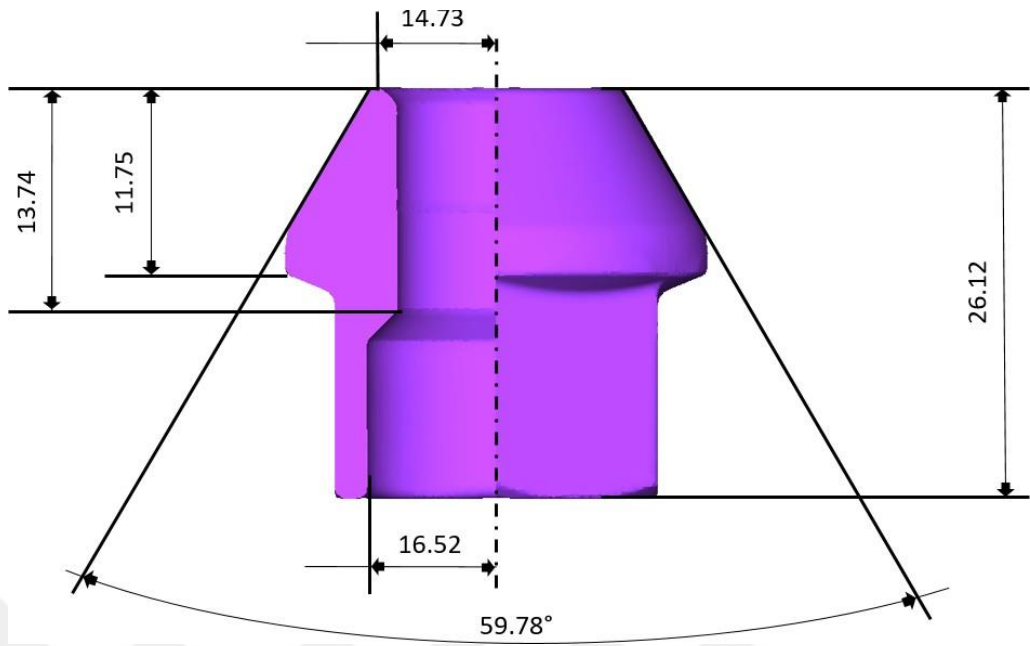


Figure 4.10 Station 6 geometry results

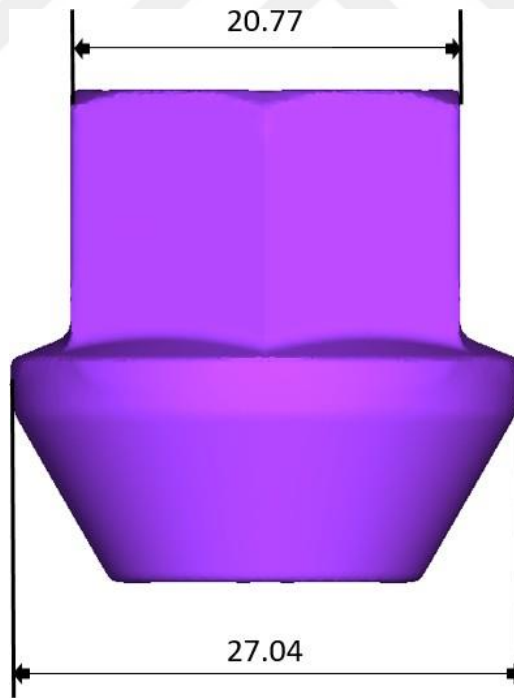


Figure 4.11 Station 6 geometry results

4.3 Cold Forging Simulation

As mentioned before, the first step in manufacturability analysis of a part begins with cold forging simulation. After the station designs are determined and the tooling designs of all stations are drawn in the AutoCAD 2012 and Inventor 2012 programs, “stp” files of the toolings are uploaded to the Simufact program. These tooling components are defined as undeformable for forming analysis.

Since the products to obtain at the first and second stations are axisymmetric, the forming analysis of these stations was set up to be two-dimensional. Analysis time has been shortened with this method. An average of 3,500 elements was used in both stations and element type determined as quads. At other stations, a three-dimensional analysis was established due to products to obtain are non-axisymmetric. 90° part of the workpiece was simulated and hexahedral element type was used. An average of 35.000 elements was used for all of these forming simulations. Mesh details are given below Figure 4.12.

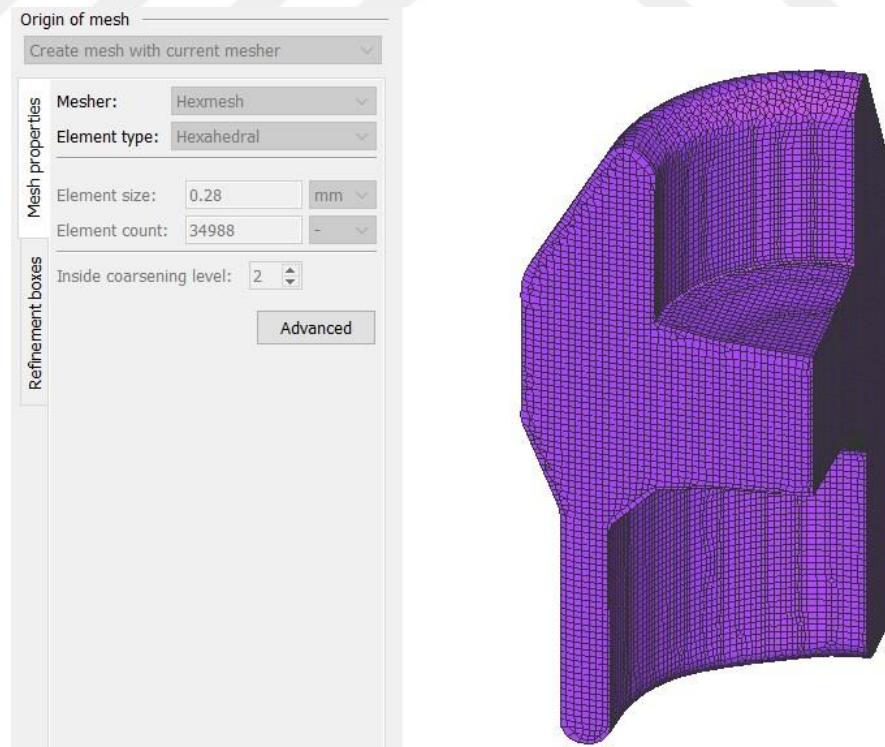


Figure 4.12 Mesh details

4.3.1 Material Flow Analysis

According to the material flow simulation results shared below figures, no material flow values exceeding the limits have been detected. It is observed that the forming occurs in a uniform manner across all stations. It can be seen that the highest values are under the flange and on the side of the hole extension. Since high material flows occur in these areas, high hardness values are also expected due to strain hardening.

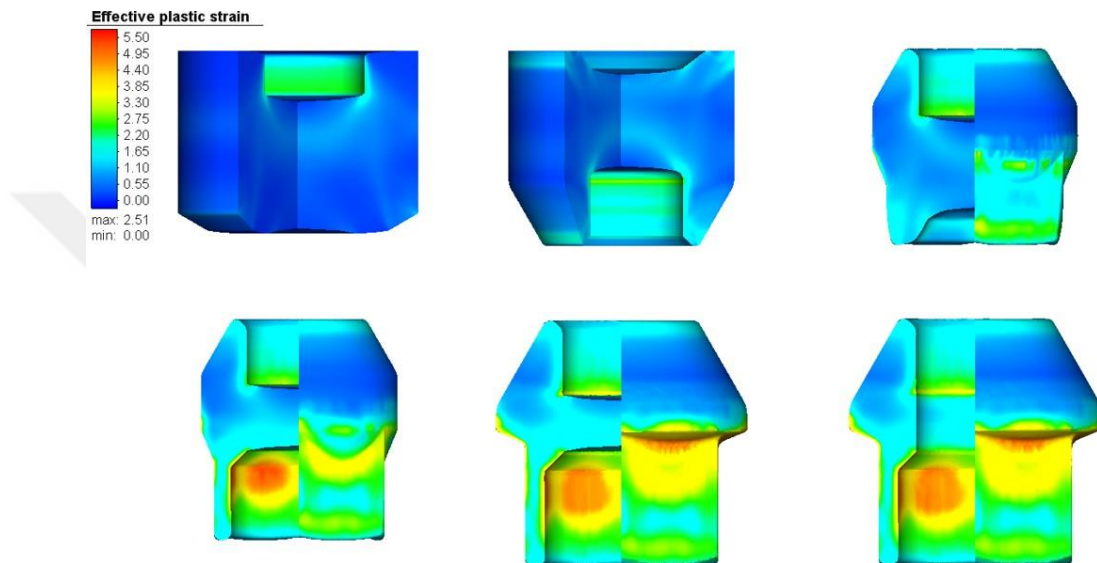


Figure 4.13 Material flow

4.3.2 Numerical Damage Detection

Formability of steels is possible up to ductile fracture limits. In order for the workpiece to be shaped in the desired design, these limits must be determined correctly. For this reason, there are many studies in the literature to estimate ductile fracture limits (Aksen et al., 2020). There are studies by McClintock (1968), Rice and Tracey (1969) assume that cylindrical and spherical cavities grow and swell under load. Proposing a porous plasticity model, Gurson (1977) determined the cavities volume ratio within the material as a parameter. He suggested that ductile fracture occurs in materials that reach this value under a certain load. Cockroft and Latham (1968) defined a function based on tensile stress and plastic strain increment.

In the determination of the Cockcroft-Latham critical damage values for materials, a commonly used method in the literature involves identifying the crack initiation point in compression tests and then calculating the damage value corresponding to this point through simulations. Although different geometries have been tried in compression tests, it is quite difficult to determine the onset of cracks in tests carried out with low and medium carbon steels used in cold forging production. At the Norm Fastener R&D Center, studies have been conducted in recent years to determine the critical damage values of raw materials used in bolt production. These studies involved tests on cylindrical, conical, and flanged samples. However, crack formation was not observed in many of the raw materials tested due to ductility of the materials. Although these investigations resulted in identifying a safe zone where no cracks were observed in the raw materials, the Cockcroft-Latham critical damage value could not be determined.

In this study, the critical damage limit was determined as 0.75 in the light of previous studies. In the simulation study, no region was seen above this value and thus, it was determined that no crack formation would be observed in the part. Image of the damage detection results of 5th station is given below Figure 4.14.

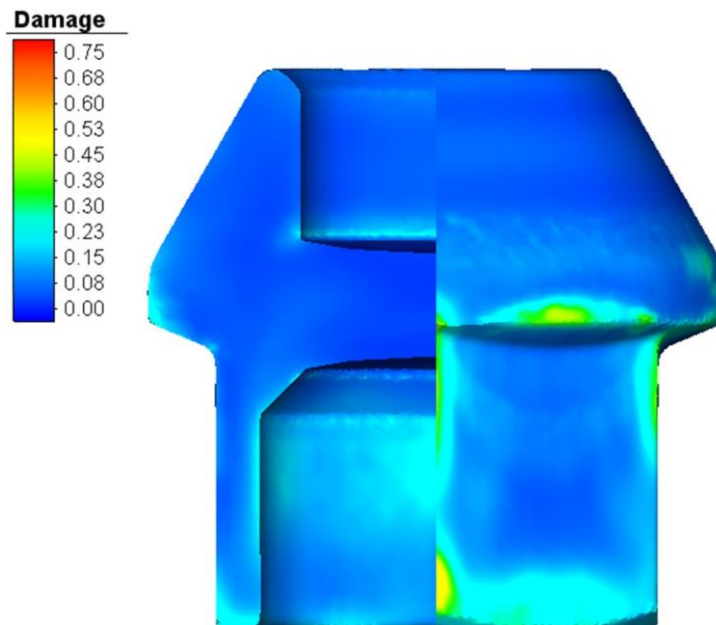


Figure 4.14 Numerical damage detection results

4.3.3 Hardness Analysis

The initial hardness value of the 17MnB3 material is defined as 110 Hv. This value is the concept of strain hardening after cold forming was mentioned in the previous sections. Various approaches have been developed to obtain the strain hardening value resulting from strain. The hardness equations of Tabor, Tekkaya and Tekkaya-Yavuz are as follows (Yavuz, 2001). This theoretical calculation method has a margin of error of less than 10% between experimental results and this value is at an acceptable level (Tekkaya & Lange, 2000).

Tabor

$$H_v * 9,81 = 2,9 * \sigma \quad (4.1)$$

Tekkaya

$$H_v * 9,81 = 2,475 * \sigma \quad (4.2)$$

Tekkaya & Yavuz

$$H_v * 9,81 = 2,527 * \sigma \quad (4.3)$$

Y (yield stress corresponding to a certain strain value) in the formula expresses the material flow stress. As seen in the visuals of the material flow analysis below, high hardness values are also observed in regions with high flow. The part will be applied to a heat treatment process to achieve the proof load value requested by the customer and to achieve a uniform hardness value on all sides. Hardness distribution of the samples are given below Figure 4.15.

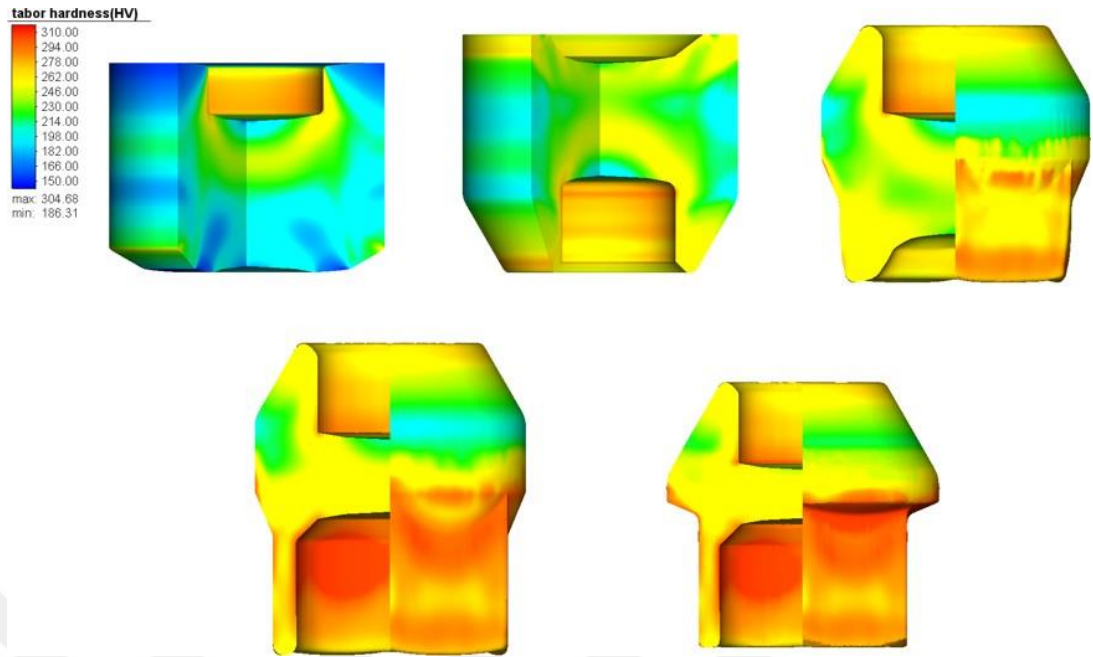


Figure 4.15 Hardness analysis

4.3.4 Folding Detection

Folding detection is the one of the other outputs that obtained from the Simufact program. When the simulation detects a folding area, it gives an error. Folding is an undesirable formation in cold forming. Folding formation affects the material flow at the next station and may cause the risk of crack. In this study, folding detection is observed on the second station as below Figure 4.16.

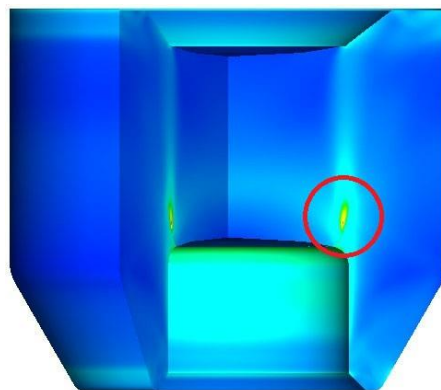


Figure 4.16 Folding detection example

4.3.5 Temperature Analysis

The initial temperatures of the workpiece and toolings were determined as room temperature, 20°C. The temperature of the part increases due to high friction and dislocation movements. These temperature values can also be seen in the simulation outputs. Areas reaching temperatures of up to 450°C have been detected, and these areas are the regions exposed to friction between the workpiece and the dies.

4.3.6 Forging Load

In the simulation program, the forging loads can also be obtained as outputs as below Figure 4.17. It is observed that the total forging load is 294 tons, when we examine the forging loads on a station-by-station basis. It has been determined that this is below the 300-ton forging load limit of the South Korean-made Hyodong 637 machine, and it has been concluded that the production of the wheel nut on this machine is suitable.

- Total forging load: 294 ton
- Machine limit: 300 ton

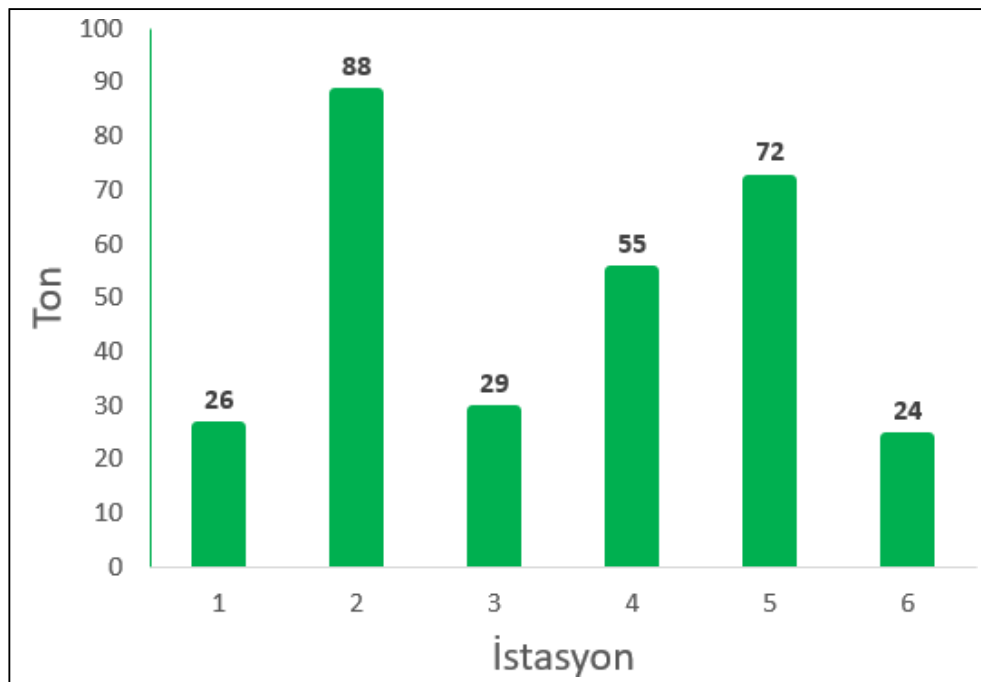


Figure 4.17 Forging load graphic

4.4 Tooling Design

After the forming analysis shows any nonconformity at the station design, the next stage, which is the tooling design study, can be carried out. When designing the toolings, some details should be take into account such as stroke length of the machine, tooling slot geometry and transfer system with the light of this informations. The stations deemed critical are the stations with the highest forging load output or material movement that we obtained from the forming simulation. For these stations, simulation is carried out again with the help of the Simufact program. Simulation study is carried out by marking the tooling as deformable rather than rigid and specify convenient materials.

One of the crucial steps in tooling design is the selection of convenient materials. In tooling systems composed of various elements, each component is made from different materials chosen based on the performance expected from it. For instance, die core materials, which are in contact with the workpiece material and subjected to high compressive stress and wear, are often selected to be tungsten carbide produced via powder metallurgy. On the other hand, the casings that hold the dies together are typically made from cold work tool steels. This careful selection ensures that each component of the tooling system can withstand its specific operational challenges effectively. A brief and general list of the materials of the components used in the toolings is given in the Table 4.2.

Table 4.2 Material of tooling components (Tschaetsch, 2006)

Material		Assembly hardness HRC	Used for				R _e [N/mm ²]
Name	No.		Punch	Die	Rein- forcement	Ejector	
S6-5-2 (M2)	1.3343	62 to 64	xx	xx		xx	2100
S18-0-1 (B18)	1.3355	59 to 62	xx	x			2100
S6-5-3 (M4)	1.3344	62 to 64	xx				2200
X 165 CrMoV 12	1.2762	60 to 62	x	x		x	2000
X 40 CrMoV 51	1.2344	50 to 56		x	xx	x	1200- 1400
42 CrMo 4	1.7225	30 to 34			xx	x	700-900
G40		1100 Hv	x	x			
G50		1100 Hv		x			
G60		950 Hv	x	xx			

The die cores are made of tungsten carbide (WC), produced using powder metallurgy techniques. They possess a range of unique features, with their most significant ability being resistance to wear. When compared to steel, its compressive strength is also higher than other metals or alloys. Its wear resistance is up to 100 times higher, and its thermal expansion is half that of steel. Additionally, tungsten carbide is resistant to thermal shock and oxidation up to 650°C. Carbide compositions also have extraordinary resistance to surface friction and welding (General Carbide Corp., 2008) Since carbides are chemically almost inert, they are ideal for wear applications in abrasive environments. As nut production is performed at high speeds, such as nearly

one part per second, the impact on the die core makes the toughness of the carbide cutting edge a significant factor. Although carbide materials exhibit brittle behavior, toughness can be enhanced by increasing the cobalt binder content.

Tungsten carbide die cores are produced by EDM (Electrical Discharge Machining) also known as Electroerosion production method. Electroerosion is a manufacturing method in which material is removed by melting or evaporating from the workpiece surface, thanks to an electrical spark that is continuously controlled and occurs as a result of a series of repetitive electrical discharges in very short periods of time, and the instantaneous high temperatures it creates. Although the electro-erosion method uses electrical energy as energy, it is in the category of thermal processing methods since the material removal process is carried out with thermal energy (Jameson, 2001).

The EDM production method, which is widely used in the processing of hard materials, plays an important role in producing complex geometries on workpieces with good surface roughness values. In the electroerosion method, a (usually) “-” charged electrode (cathode) is used as a tool, a (usually) “+” charged electrode (anode) is used as the workpiece, and a chamber filled with liquid (usually a dielectric hydrocarbon) containing both of them is attached to the tool (Figure 4.18). A moving head and a machine table are used to guide the workpiece. Although a variety of different types of EDM machines are manufactured, wire EDM and dip EDM machines are the most common types (Poyrazoğlu, 1994)

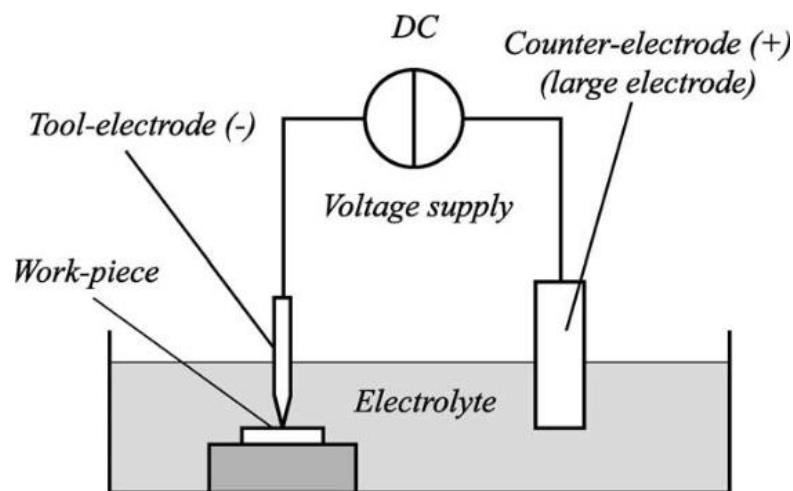


Figure 4.18 Schematic of EDM process (Wüthrich & Fascio, 2005)

One of the most important problems encountered in cold forging processes is the damage and breakage that occurs in the forging dies at low cycle due to abrasion caused by high forging forces and friction conditions. Stress-induced fractures and fatigue fractures occurring under dynamic cyclic loads are quite common in tooling components (Skov-Hansen et al., 1999). The abrasions that occur on the tooling surface during service periods cause the formation of micro cracks on these surfaces, causing the tooling to break suddenly. Fatigue fractures are cracks that progress according to the stress topography, starting from the point where the highest stress occurs during the forging process, and are very difficult to detect visually (Cosenza et al., 2004). Therefore, foreseeing these problems with the help of simulation programs and taking action is very important in terms of cost (Wagner et al., 2006). When designing a tooling, determining the correct shrink fitting ratio between the die case and the core die is of critical importance to increase the life of the dies (Kılıçaslan & İnce, 2016).

After the toolings are designed and the 2D drawings are completed, an unique codes are given for each tooling component. The tooling design project is completed by creating assembly drawings of the tooling components with the given codes.

4.5 Die Load Analysis

After the forming analyzes are completed, die load analysis is performed to examine the maximum and minimum principal stresses acting on the tooling components of critical stations and to increase their life cycle. Thanks to die load analysis, the life cycle of the dies can be increased with minor revisions in the tooling design, material determination can be made more accurately, and the forming design approach can be reviewed if necessary. When setting up this analysis, unlike the forming simulation, tooling components are also selected as deformable. A material is assigned to all components and divided into meshes with a certain number of elements.

In this study, die load analysis was carried out based on the fixed tooling system of the fifth station. It was decided to carry out the analysis at this station because most of the hexagonal extensions would be made here.

The segmented dies, consisting of six symmetrical parts, and the lower die were selected as CTE50A material, a tungsten carbide cobalt. CTE50A, with its high strength and wear resistance properties, is an appropriate choice for the die material in contact with the material. X40CrMoV51, a hot work tool steel, was chosen as the case component, with a shrink fitting rate set at 0.5%. The compressive strength value of the CTE50A material stated in the catalog of Ceratizit, a manufacturer of wear-resistant and hard material products for cutting tools, is 3200 MPa. Minimum principal stress pattern is given below Figure 4.19 and the variation of minimum principal stress on the die which is stated with red arrow is given below Figure 4.20. This graphic shows the minimum principal stress applied to the die throughout the press cycle and demonstrates that it does not exceed the 3200 MPa limit value.

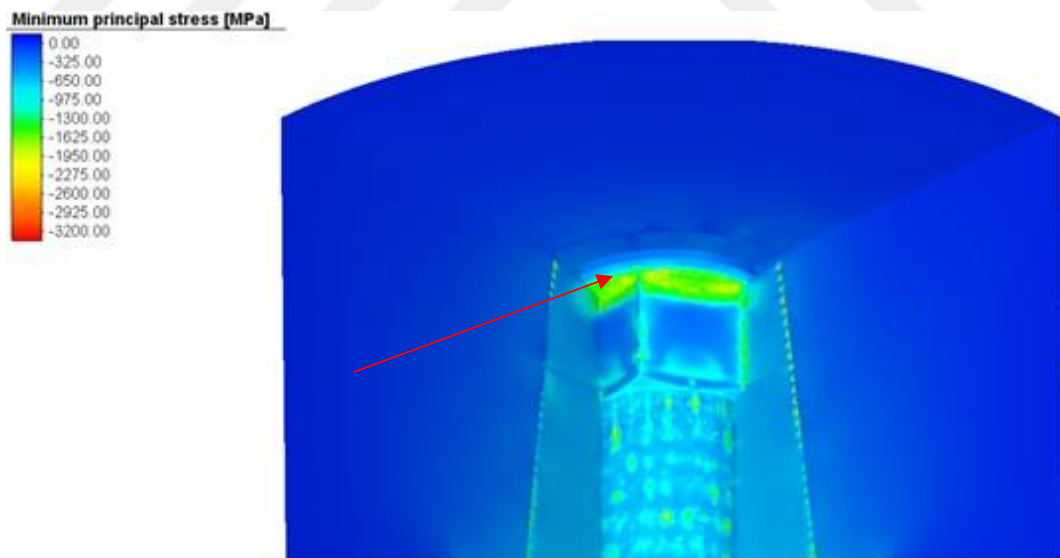


Figure 4.19 Minimum principal stress of 5th station

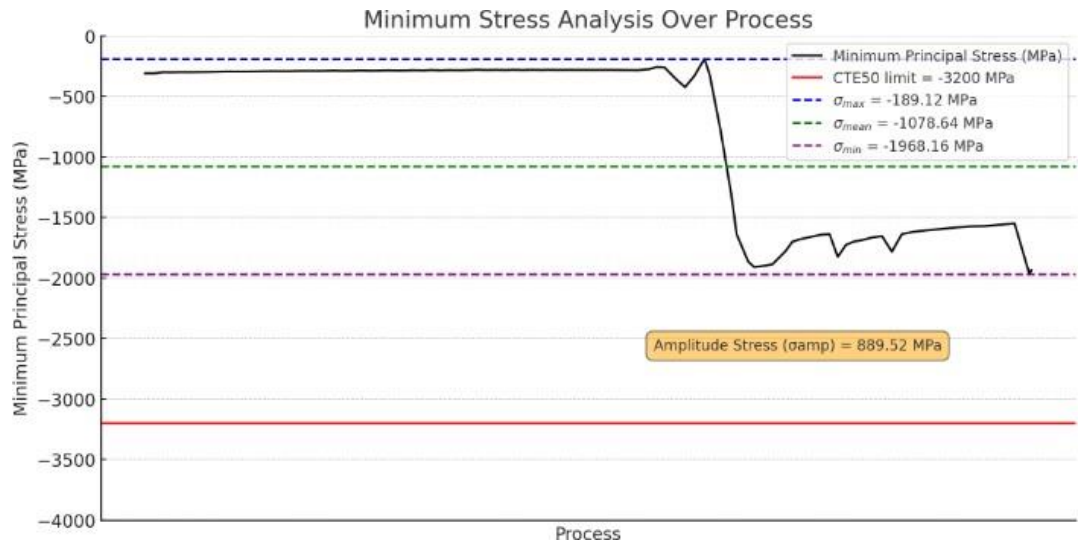


Figure 4.20 Minimum principal stresses on the die

Maximum principal stress pattern is given below Figure 4.21 and the variation of minimum principal stress on the die which is stated with red arrow is given below Figure 4.22. This graphic shows the minimum principal stress applied to the die throughout the press cycle and demonstrates that it does not exceed the 700 MPa limit value.

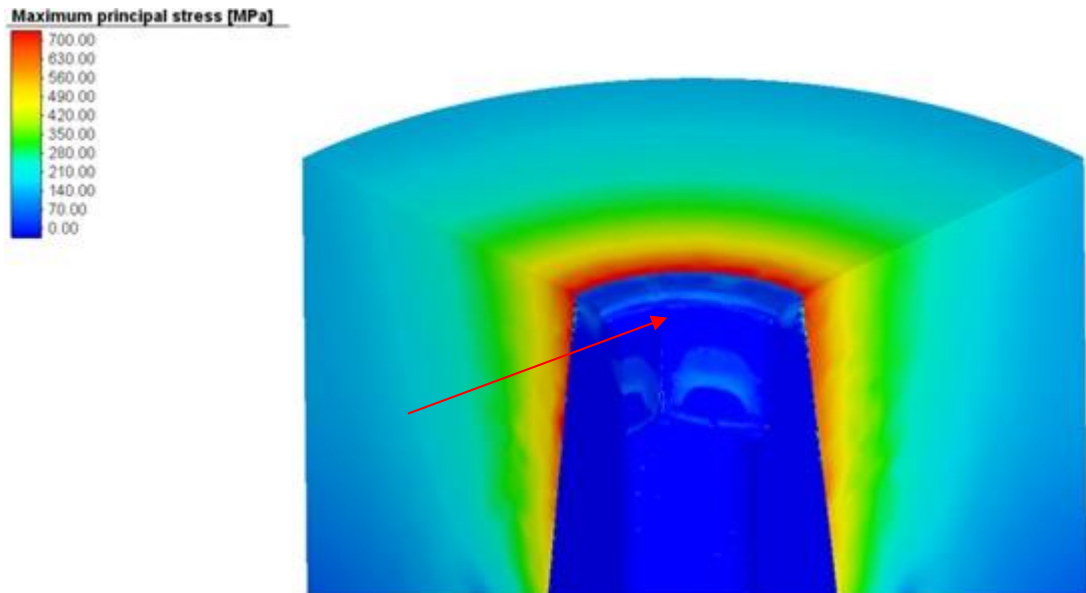


Figure 4.21 Maximum principal stress of 5th station

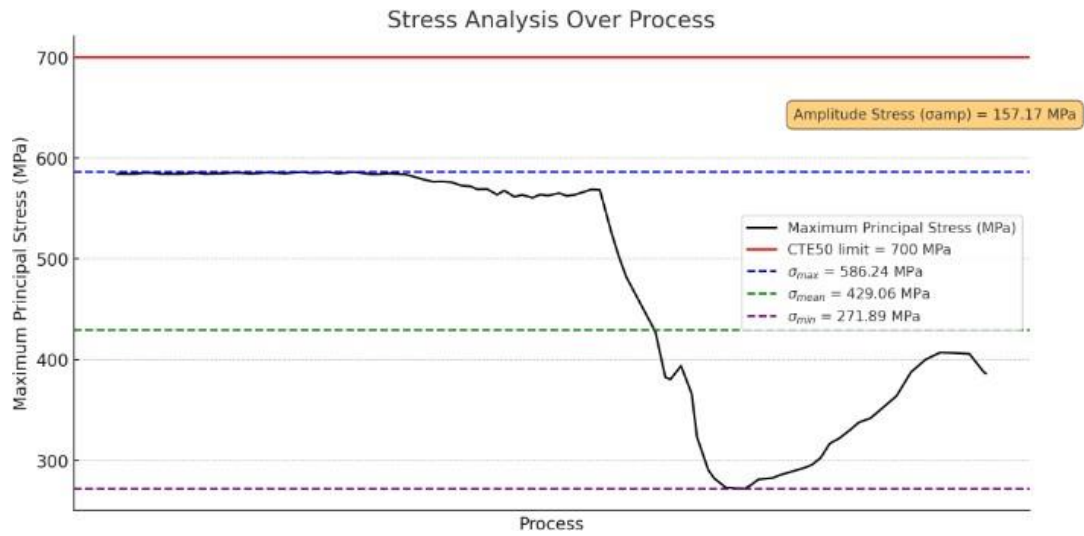


Figure 4.22 Maximum principal stresses on the die

As we can see the Figure 4.22 and 4.20, it is seen that the maximum and minimum principal stresses on the 5th station die core during the process period are within the strength limits of the its material. As a result of this analysis, it was concluded that the shaping simulation outputs and tooling design were appropriate and the tooling life would be sufficient for long cycles.

CHAPTER FIVE

CONCLUSION

This study has been conducted to examine the manufacturability of wheel nuts, which are notoriously challenging to produce through cold forming, and to develop a production approach. In the fastener industry, where there is a significant increase in market share for specialized and geometrically complex parts like wheel nuts, companies need to enhance their know-how in manufacturability to meet these demands. On the other hand, achieving accurate production in a single trial reduces costs, advancing the manufacturer's competitiveness. This value-added knowledge, which provides advantages in terms of both timing and cost, represents one of the most significant assets for companies. Furthermore, since wheel nuts are classified as safety components, it is imperative to unconditionally meet all the expected geometric and performance criteria. Motivated by these factors, this study proposes a design approach for producing wheel nuts with challenging geometry through cold forming, analyzed using the finite element method.

The initial station design encountered a folding issue at the second station, prompting a revision of the first station design. By retracting the moving tooling system (punch) by approximately 2.50 mm, the backflow rate was reduced. This revision eliminated the folding issue at the second station. Subsequent stations achieved the expected forming, and the final station produced the desired geometry within nominal dimensions.

After the successful results in the forming simulation, the material flow analysis was examined and it was seen that high deformation values were not obtained. Results show that the strain distribution is almost equal at each station. In addition, the maximum hardness range of each station sample was observed by performing Tabor hardness transformation. The hardness distribution observed in correlation with the deformation values was found to be within the desired limits. The fact that no value exceeds the critical damage limit is observed at any station shows that the forming design has been established correctly. The absence of any folding in the final station design indicated no potential for surface defects or cracks, and the temperature analysis not exceeding expected values suggested that the part's surface would achieve the

desired surface quality. Finally, the total forging loads were examined and it was determined that the forging load was within the limits of the selected Hyodong 637 machine. In the light of this information, it was concluded that the formation analysis was completed successfully and the next step was the die load analysis.

The die load analysis was set up on the fixed tooling system of the fifth station. This station was chosen for analysis due to the high forging load and the backward extension of the hex length through backflow occurring at this station. Anticipating high stresses, the die components were meticulously designed and transferred to the Simufact simulation program. Differently from the forming analysis, the tooling components were selected to be deformable, and each was assigned a material.

The segmented dies, consisting of six symmetrical parts, and the lower die were selected as CTE50A material, a tungsten carbide cobalt. CTE50A, with its high strength and wear resistance properties, is an appropriate choice for the die material in contact with the material. X40 CrMoV 51, a hot work tool steel, was chosen as the case component, with a shrink fitting rate set at 0.5%.

The die load analysis simulation study revealed that the maximum and minimum principal stresses applied to the die were within the material limits. Potential wear on the die core was considered negligible due to the precise machining of the die's surface roughness and the application of PVD coating. Additionally, thermal stresses that could develop on the die were also disregarded. As a result, the tooling design was deemed suitable without the need for any revisions, and the study was successfully completed.

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