CHAPTER II

An Overview of the Substantial Outputs of Forging Processes and the Generation of Loads Affected by Forging Parameters in Closed-Die

İsmail GÜRBÜZ[1]
Seyit Murat Altunç[2]
Abdulmecit GÜLDAŞ[3]

1. Introduction

The Metal Forming term is defined by a group of manufacturing methods that transform a formless material or a material with simple geometry into a beneficial part without changing mass or composition. Metal parts manufacturing is split into five general areas in a simplified way; (1) primary forming (Casting, Melt Extrusion, Die Casting, and Metal Powder Pressing), (2) Metal forming processes (Rolling, Extrusion, Cold and Hot

[1] Gazi Üniversitesi Fen Bilimleri Enstitüsü, İmalat Müh. Bölümü, Teknikokullar, Ankara-Türkiye
ORCİD ID:0000-0002-1339-3427, ismailgrbz9@gmail.com
[2] Evimetal İnox Yapı Çözümleri Tasarım Merkezi, Arnavutköy-İstanbul,
ORCID ID: 0009-0006-6154-2817, murat@evimetal.com.tr
[3] Gazi Üniversitesi Teknoloji Fakültesi, İmalat Müh. Bölümü, Teknikokullar, Ankara-Türkiye
ORCID ID: 0000-0002-1865-2272, aguldas@gazi.edu.tr

Forging, Bending), (3) Chip removal forming (Cutting, Turning, Milling and Broaching), (4) Heat treatment (Anodizing and Surface Hardening), (5) Joining processes (Welding, Soldering, Riveting, Shrinking, Mechanical Assembly).

Forging, (Dieter, 1986)which is considered one of the oldest metalworking arts, is one of the most important manufacturing processes in which a metal part in its simple initial form, such as rods, sheets, billets, and/or ingots, is formed into the desired shape by plastic deformation. It is also suitable for the production of individual sample parts as well as for mass production. Forging plays a significant role in the metal forming industry as it reduces the required machining processes and allows complex parts to be produced with the desired grain flow in forged parts. Because the ideal grain flow in the final products has been provided, they show better mechanical and metallurgical characteristics than parts manufactured by casting and machining processes (Groover, 2010) (Chen, et al., 2017) (Jo, Jeong, Lee, Moon, & Hwang, 2021). In addition to that, beneficial grain flow procures a longer fatigue life than parts manufactured by casting and machining (Chen, et al., 2017). The grain flow that occurs in parts manufactured by different manufacturing processes is shown symbolically in Figure 1.

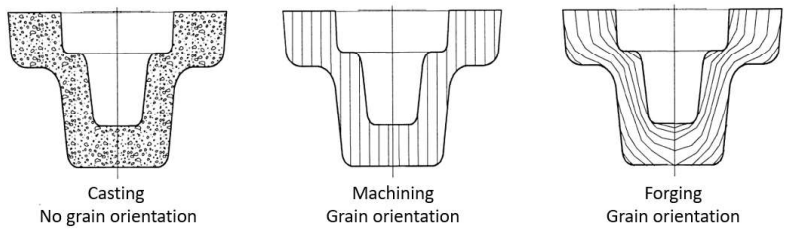


Figure 1: The grain orientation in different manufacturing methods.

2. Forging

Forging classification

Fundamentally, forging consists of a group of manufacturing processes with deformation stages. The other stages are the separation and assembly processes. Forging processes are classified by machine type, workpiece type, forming temperature, and die set type.

Machine type

The forging process is classified by machine type into 3 main groups (press forging, hammer forging, and forming on the forging roller). The equipment used in forging (presses and hammers) affects the forging process as they impress strain rate and temperature conditions. Thus, they determine the manufacturing rate.

The demands of a specific forging technique need to align with the features of a specific forging device, including its load capacity, energy, time requirements, and precision. T. Altan et al. explained in detail the working principles and characteristics of traditional and special machine types used in forging (Altan, Ngaile, & Shen, Cold and Hot Forgings: Fundamentals and Applications, 2005).

Material type

The metals used in forging can be divided into ferrous (carbon steels, alloy steels, and stainless steels) and non-ferrous metals (aluminum, magnesium, and titanium alloys) according to their type. In the forging industry, ferrous steels are generally used extensively. However, with the increase in demand for forged non-ferrous metal products, especially in aviation and automotive, the

use of non-ferrous metal products in forging is increasing rapidly. The main reasons for this increase in demand are the lightness, long life, durability, and environmental friendliness of the forged non-ferrous final product (Cavaliere, 2004).

Forming temperature

The temperature level and how it spreads are determined by the initial temperatures of the material and the dies, the friction-generated heat, and the heat exchange among the deformed material, dies, and the surroundings. It's noted that 90-95% of the energy used in forming processes is converted into heat (Atlan, Oh, & Gegel, 1983). Forging processes are divided into 3 groups bases on temperature; Cold forging, Hot Forging, and Warm Forging (Lange K.). General temperature values for three different forging operations are illustrated in Figure 2.

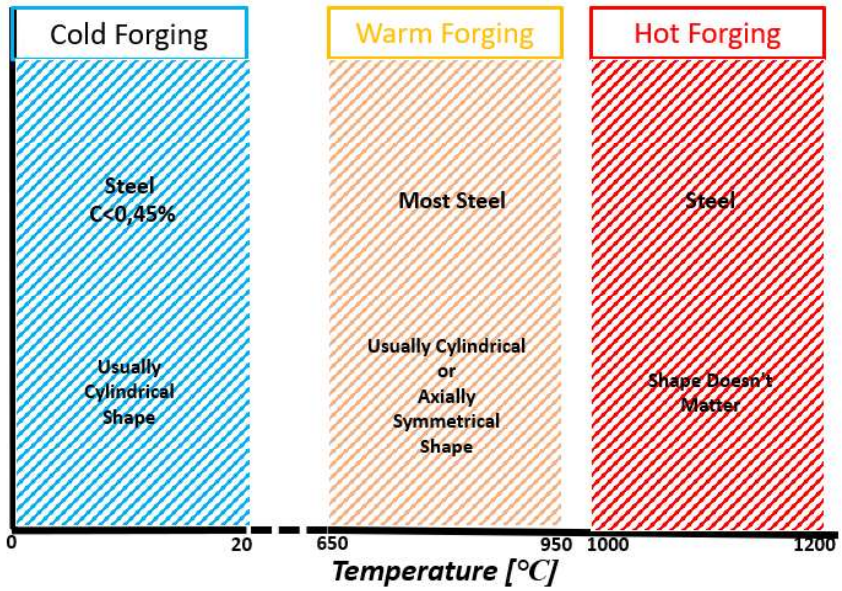


Figure 2: Forming temperature ranges

Cold forging

Initially, the workpiece temperature is room temperature in cold forging. The forging process, in the design of the cold forging manufacturing process, may be considered a complex system that contains a workpiece that is affected by tribological and environmental conditions, and implicit interactions between tool and press. K.Lange indicates that the center of the system is the good surface conditions of a workpiece with a simple initial shape and the forging operation which enables the final product with a complex shape and correct dimensions (Lange K. , 1992). The advantages of cold forging compared to rival manufacturing processes are high material utilization, improved material properties, and an unaffected grain flow. The other advantages are also accuracy and high surface quality of manufactured compounds (Tekkaya & Hering, 2019) (Ishinaga, 1997) (Yanagimoto, Sugiyama, Yanagida, Iwamura, & Ishizuka, 2009). One of the most important factors in providing these advantages is the dislocations formed by high flow stress in the forged part. However, this high flow stress requires a high operation load, and only a limited number of patterns may be manufactured (Jo, jeong, Lee, Moon, & Hwang, 2021).

Hot forging

Hot forging is carried out in a range of higher than recrystallization temperatures of the material to decrease flow stress and increase workpiece formability. After forming, which is carried out at higher than reforming temperatures, workpieces do not take place a permanent strain hardening (Lange K.). Heat treatment is necessary for the workpiece to obtain the appropriate strength (Wernicke, et al., 2021). Even in this situation, high mechanical

loads come into existence during forming. High-forming load estimation is not possible because of Thermo-Elastic-Plastic effects and complex interactions between the tool and workpiece system (Behrens & Odening, 2009) (Maier, et al., 2019). Failure mechanisms for hot forging processes may be stated as corrosion, surface crack extension, plastic strain deposition, mechanical thermal fatigue, and thermal shocks. Despite the formability in hot forging being better than other forging processes, die corrosion is faster due to higher temperatures and compound pressure. Fast die corrosion negatively affects the die life, causing rising costs and decreasing manufacturing speed. For this reason, estimation of the die corrosion is critical for die life estimation (Davoudi, Nejad, Koloor, & Petru, 2021). Elastic springback caused by high thermo-mechanical stresses occurs after forging, leading to deviations from the actual geometry to undesirable geometry, and shrinkage behavior (Behrens, et al., 2020)

Warm forging

During warm forging, the workpiece temperature is above room temperature and under the recrystallization temperature. The process may be accepted as a precise forming application that enables high-quality component manufacturing (Forcellese & Gabrielli, 2000). Intermediate temperature forging of high carbon and alloy steels is favored over cold forging due to its benefits, including reduced flow stress, enhanced ductility, minimized workpiece hardening, and improved toughness of the forged components (Fujikava, Yoshioka, & Shimamura, 1992) (Hirscvogel & Dommelen, 1992) (S.Sheljaskov, 1994). Compared to hot forging, warm forging provides better material utilization, improved surface quality, and high dimensional accuracy (Shivpuri, Babu, Kini,

Pauskar, & Deshpande, 1994). In this context, the technique merges the accuracy of cold forging with the low yield stress and high formability characteristic of hot forging (Xinbo, Hongsheng, & Zhiliang, 2003). However, warm forging is more inconvenient than both traditional methods in terms of working conditions and environmental compatibility (Sheljaskov, 1994). In addition, die/tool corrosion is significant in warm forging. If the shape of the product desired to be obtained at the end of the operation is complex, the physical process that indicates the operation (metal flow, material characterization, and product qualification) is complicated and may not be analyzed systematically (Shivpuri, Babu, Kini, Pauskar, & Deshpande, 1994). Like in any of the three forging methods, understanding the metal's flow stress at warm forging temperatures is crucial for planning the process, designing the dies, selecting die materials, and determining press capacity.

Die set type

Forging operations are generally non-stationary operations that occur consequent indirect pressure under three-dimensional stress and deformation conditions. There are several forging methods (flash/flashless closed die forging, open die forging, electric forging, forward/backward extrusion, radial forging, etc.) used in the industry depending on the type of die set, forging can be categorized into two primary groups: open die forging and closed die forging.

Open die forging

In the most general definition, in the open die forging method, simple tools are used that have no concern with the final workpiece shape. Open die forging is a forming operation of hot metal with a hammer aid on a flat or simply contoured surface. The

cross-section of the hot workpiece is reduced by compressing it between the upper die or hammer connected to a ram and a lower die connected to the press bed, and the length of the workpiece is increased by repeated and alternating forging. To minimize the number of machining required to obtain cylindrical steel components made in small quantities from large masses, such as turbine rotors, shafts, or rolling rolls, workpiece deformation is carried out in an open-die forging press to achieve approximate final geometry. (Choi, Chun, Tyne, & Moon, 2006). Open die forging is frequently conducted not only to shape the workpiece into its desired final form but also to enhance its mechanical properties by achieving a uniformly distributed fine grain size throughout the workpiece. (Wolfgarten, Rudolph, & Hirt, 2020). The tool sizes are relatively small in comparison to the overall dimensions of the forged workpieces. Because only a portion of the workpiece undergoes deformation at any given moment during forging, the necessary forging loads are lower than those needed to deform the entire workpiece. The primary purpose of this type of incremental forging process is to progressively compress or layer the material until it attains the ultimate desired shape. However, it is complicated to calculate the material flows in both the axial and lateral directions after each forming step of the workpiece. For this reason, to achieve the appropriate dimensional accuracy in the workpiece, geometric changes in the workpiece must be constantly observed and monitored by the operator who will perform the forming process, taking into account the flow behavior of the material (Aksakal, Osman, & Bramley, 2008) (Aksakal, Osman, & Bramley, 1997). It is a well-known fact that metal flow is affected by friction in forging processes. Metal flow is significantly affected by friction due to

using lubricants is difficult because of high temperatures in open-die forging. Therefore, the effect of friction in open die forging has attracted the attention of many researchers. R. Lakshmipathy and R. In their study, Sagar attempted to prevent the deterioration of the lubrication between the die and the workpiece by changing the surface topography of the die forging with a better-performance open die (Lakshmipathy & Sagar, 1992). E. Ghassemali et al. investigated the impact of lubricants with varying friction coefficients on material performance during the open die micro forging procedure (Ghassemali, Tan, Wah, Lim, & Jarfors, 2014).

The quality of open die forging relies on various control factors such as die width, die configuration, die overlap, die staging, ingot shape, temperature gradient, draft design, transition program, and more.

Closed die forging

In closed die forging, tools that are closely related to the desired end product shape are used. Closed die forging is divided into two (with flash/flashless) in itself. Closed die forging systems with flash and flashless are shown in Figure 3 in simplified form.

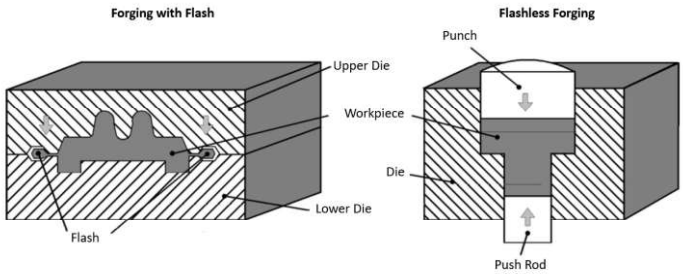


Figure 3: Simplified representation of flash and flashless closed die forging

The quality of the part forged with the closed die depends on many parameters (process design, forging load, pre-die design, material flow stress, friction, equipment, etc.) (Shamasundar, 2003).

Closed die forging with flash

Closed die type forging with flash is the forming process of a simple shaped (usually round or square bar) hot metal part in the form of a billet by plastic deformation in a die, usually consisting of two parts. During forming, waste material flows into the gutters outside the forging boundary of the die separation line. The flash geometry should fill the gutters when the two dies come into contact in the separation plane (Biswas & Rao, 1985). The flash gutter acts as a drain valve for the excess pressure that arises in closed dies. This gutter also acts as a brake to slow down the outflow of metal to allow it to be filled in the desired configuration (ASM HandBook, 1988). Closed forging dies can be made with one or more gutters, depending on the shape and dimensions of the workpieces to be forged. These gutters may be divided into several types according to their roles (forging finishing, pre-forging, cutting, etc.), and the workpiece shapes obtained with each gutter represent the forging stages (Luca, 2017).

As in other forging processes, it is important to know and control the flow behavior of the material in forging processes with flash to effectively fill the die gutter, surface quality, optimum load, and die wear and to avoid defects caused by material flow. In closed die forging with flash, the material flow mainly depends on 5 parameters (geometry of the flash gutter, initial and intermediate billet geometry, flash percentage, heat transfer between the tool and the billet) (Atlan, Oh, & Gegel, 1983).

Since material waste is one of the most crucial properties affecting the cost of forging, the correct calculation of flash gutter is critical in reducing the cost of forging (Sleeckx & Kruth, 1992). In forging with flash, flash gutters may be expressed in three basic geometries (parallel, wedged, and V-notch). G. Samolyk and Z. Peter, in their work, analyzed the effect of geometric parameters of the V-notched flash gutter on the forging process. They also conducted calculations aiming to ascertain the most advantageous measurements of the gutter based on the forging load and the degree of die gutter filling with metal. (Samolyk & Pater, 2005). F.F-Sanee and A.H. Hosseini investigated the impact of flash allowance and billet sizes on both forging load and material flow for two standard round components. One component had a vertical axis of symmetry (aligned with the ram direction of motion), while the other had a horizontal axis of symmetry. (F-Saniee & Hosseini, 2006).

In closed die hot forging, the quality of the finished part is widely determined by the design of the pre-die and the quality of the pre-shape. The purpose of the pre-die design is to achieve an optimal die shape, which allows the die gutter to be filled with effective forging force. (Dehghani & Jaferi, 2010) Furthermore, the correlation between the pre-forming volume and the final forging volume significantly influences the quality of the end product. When the pre-die geometry is intricate, the volume distribution within the pre-die becomes crucial to guarantee adequate metal flow during the final forging process. Thus, achieving precision forging necessitates the use of an accurate pre-die. (ASM HandBook, 1988).

Flashless closed die forging

This forming operation has the advantage of lower material consumption and minimal machining tolerance due to the absence of flash in the final product. The purpose of this forming operation is to produce parts that are net shape or at least near net shape. This manufacturing method can be described as close tolerance forging (ASM HandBook, 1988). In the flashless closed die forging type, it is executed by permanently deforming a metal part in the form of a billet at room temperature or below the recrystallization temperature of the material with the help of a punch in a volume-controlled manner and filling it into the die gutter. In this forging process, the punch and die can consist of one or more parts and no material loss occurs. Flashless forged parts have an improved strength due to an uninterrupted grain flow (Stonis, Rüther, & Behrens, 2015).

Closed die cold forging is an extremely challenging metal forming application compared to other forging methods due to the high forming loads caused by the high flow stress of billet material. High die stresses due to high forming loads (surface pressure up to 3000 MPa (Geiger, Arbak, & Engel, 2008) (Ku & Kang, 2014)) cause wear on the application tools and reduce their service life. In addition, the success of cold forging processes depends on the properties of the tool material (high wear resistance, high strength, and high toughness) and its design. In addition, high operational loads cause elastic deformations of the operating systems, affecting the quality of the final product.

Forging defects

When improper forming conditions are used in forging operations, forging defects often occur in the workpiece due to

complex deformation and complicated material flow. The most common forging defects are inadequate filling, cracks, surface defects, buckling, flowline protrusions, and swirls (Arentoft & Wanheim, 1997). These are widely known defects in forging operations, and it is significant to eliminate them to improve product, process design, and forming quality.

Buckling defect

In die forging processes, buckling (folding) defect is one of the most common plastic flow defects. Figure 4 shows the buckling defect that occurs in an axisymmetric part manufactured using the cold forging method.



Figure 4: The buckling defect in an axisymmetric part manufactured with the cold forging method. (W.L. Chan,2009)

Flow-induced buckling defect prediction is crucial in product and design and has attracted the attention of many researchers. P. F. In their work, Gao et al. have developed a versatile approach to the prediction of buckling defects that is substantial for workpiece and forming design and improves the forming quality during the die-forging process (Gao, et al., 2019). W.L.Chan et al. proposed a dynamic change in tool geometry to control the buckling defect (Chan, Fu, Lu, & Chan, 2009). R. Balendra et al., in their studies, identified flow-related defects in the main configurations of injection forging with experiments to improve the efficiency of the injection

forging design of tubular materials. They found that forging defects such as plastic deformation instability of the workpiece, buckling, and improper axial/radial flow rate are due to different flow mechanisms of the materials. They also developed a pre-shaping procedure to prevent bucklings from developing (Balendra & Qin, 2000).

Metal flow lines

The formation of metal flow lines among forging defects is due to the quality of the surfaces the toolset and the workpiece contact with, the coefficient of friction, and the die geometry. In mechanical parts manufactured by hot forging, where high strength and structural reliability are expected, M. K. Razali et al. emphasized the importance of friction effects in closed-die hot forging and carried out experimental and finite element method studies on the shaping of S45C steel with three-stage hot forging. They concluded that metal flow lines are greatly affected by friction conditions and that friction optimization improves metal flow lines (Razali, Kim, Irani, Kim, & Joun, 2021).

Side surface crack

In forging processes, the flow direction and arrangement of the material play an important role in part quality. Y. H. Moon et al., in their studies, because the flow pattern of the material during forging may cause a side surface crack/error, developed velocity fields and power terms with upper bound analysis for double-ram axisymmetric forging. In the first of their two-part articles, they present the terms velocity domains and individual powers, derived based on flow patterns. In their second article, they present the criteria they have determined for side surface defects based on the

upper bond solution (Moon, Van Tyne, & Gordon, 2000) (Moon, Van Tyne, & Gordon, 2000). A.B.Abdullah et al. examined the effect of the conicity angle and distance to the edge on defect formation based on the flow model and stress distribution of the material, which will affect the quality and accuracy of the pin-shaped by cold embossing, with 2D simulations (Abdullah, Sapuan, Samad, T.Khaleed, & Aziz, 2013).

Inadequate filling

Complete filling of the forging die is significant for forging operations. Figure 5 shows the inadequate filling error that occurred in the lever arm.

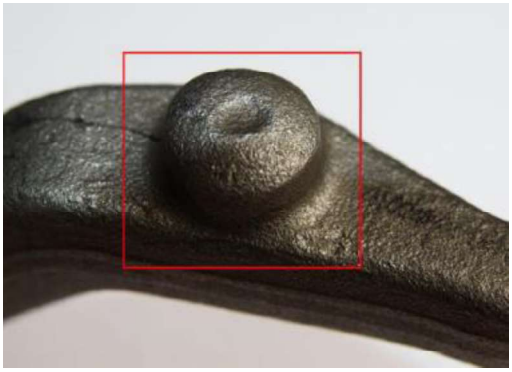


Figure 5: Lever arm inadequate filling error (M. Hawryluk et al. 2015)

The air gaps formed between the toolset and the workpiece are one of the substantial parameters that cause the die cannot be filled. Other important parameters in this defect formation may be shown as inaccurate pre-die design and incorrect material flow. M. Hawryluk et al. worked on the modeling of inadequate fillings (caused by air pockets between the workpiece and the tool) by the finite element method, which is seen as one of the major problems

in the closed die forging process. In their study, they observed the incorrect flow of material with the lever arm forging simulation. They also saw that the pre-die position had a significant impact on the proper filling of the die, and the correct die position helped to remove defects in the workpiece significantly with the lever arm forging simulation. In addition, in the lever arm forging simulation, they identified the incorrect flow of the material as the cause of the forging defect (Hawryluk & Jakubik, 2015). A. Kocanda et al. how the positioning of the die gap affects metal flow and the distribution of lateral forces within the die during the hot forging of aircraft engine turbine blades, utilizing simulation software based on the finite volume method. They also pointed to the effect of the torsional moment on the die offset brought about by these lateral forces (Kocanda, Czyzewski, & Mehdi, 2009). Y.Can et al. performed experimental investigations on conventional closed die forging, examining how the aspect ratios and indentation of the workpiece influence both forging load and die filling. They concluded that increased indentation and aspect ratio helped with better die filling overall. They also observed that they affect billet and punch diameters and punch ratios forging loads and die fill rates (Can, Altinbalik, & Akata, 2004). H. Ssemakula et al. have developed an alternative method of manufacturing large copper barrel lids with a much lower forging force for a forging company specializing in forging heavy parts. The main focus of their work is on the distribution of forming parameters such as load requirement, filling of the die gutter, and effective strain within the workpiece at different forming stages and temperatures (Ssemakula, Stahlberg, & Öberg, 2006).

Microstructure

It is known that the material to be shaped using the forging method undergoes significant changes from the operation parameters (temperature, strain, and strain rate). M. O. Alniak et al. noted alterations in the microstructure resulting from plastic deformation in hot isostatically pressed (HIPed) P/M Rene 95 under isothermal conditions. Their research revealed that the microstructure transitions into a consistent coaxial fine-grained micro-duplex structure, at which point the flow forces become uniform. At this point, the ongoing deformation does not produce any further changes in grain size or flow strength. In this constant deformation state, the micro-duplex grain size and flow strength remain unaffected by the initial microstructure but are influenced by the strain rate at a specific temperature. When the strain rate decreases and/or the temperature rises, the steady-state grain size increases while the stable flow power decreases. Their study demonstrated that the microstructure undergoes significant changes during forging, and the grain size of both initially fine-grained and coarse-grained compacts is influenced by the applied strain rate, forging temperature, and strain. (Alniak & Bedir, 2006). Figure 6 shows how the material microstructure is affected by temperature and strain rate.

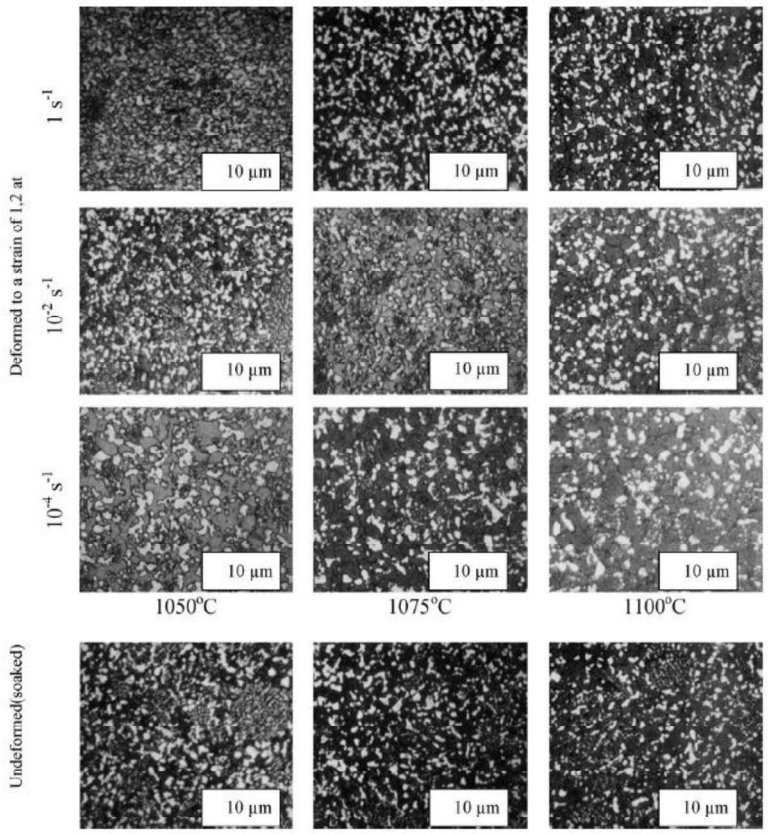


Figure 6: The microstructural evolution of the material is affected by temperature and strain rate during the forging operation (M. O. Alniak et al. 2006)

In this context, many studies have been carried out aimed at how the structural evolution of the material takes place and controlling it in forging operations. H-G. Yan et al. examined the microstructure and mechanical characteristics of the ZK21 alloy by conducting a multi-stage forging process at various strain rates in their research. (Yan, et al., 2012). W. Weronski et al. analyzed grain growth by finite element method, which leads to a decrease in the mechanical properties of parts shaped by forging aluminum alloys.

The overlap of theoretical studies with industry practice has shown that it is possible to predict structural defects in the forging operations of aluminum alloys by the finite element method (Weronski, Gontarz, & Pater, 1999). M. J. Tan et al. investigated the interactive effect of grain size and sample sizes on material flow and microstructural evolution in a staged open-die micro-forming process (Tan, Ghassemali, Wah, Jarfors, & Lim, 2013).

T. Henke et al. propose a strategy that allows incorporating microstructure evolution uncertainties in material behavior into a microstructural model in their paper. They applied this model to the hot forging process design. They showed the probability distribution of the grain size value is asymmetrical and predicts the formation of grain sizes with a grand deviation from the most likely grain size (Henke, Bambach, & Hirt, 2013). G. Banaszek et al. studied stress density heterogeneity, material flow discontinuity, and elimination of metallurgical defects in free hot forging operations. They observed that the shapes and geometries of the tools contribute positively to the reduction of metallurgical defects on the workpiece by obtaining a uniform deformation character in the early stages of forging. They also found they are favorable for improving the homogeneity of stress concentrations over a forging cross-section. Besides, they observed significant controllability of the flow kinematics of the material with appropriate tool shape and appropriate forging technological parameters (Banaszek & Stefanik, 2006).

W.Li et al. observed the viscoplastic behavior of the AA7050 grade material as well as the temperature-dependent flow stress behavior of the material under various deformation conditions by

applying a series of compression tests with a physical simulator (Gleeble 3800). Additionally, they employed electron scattering diffraction technology to investigate the grain orientation map of the material and to examine potential dynamic recrystallization and grain size distribution during deformation. Their research aims to determine the optimal parameters for hot forging by analyzing the evolution of grain size during the process, and to offer guidance for the industrial manufacturing process of AA7050. (Li, et al., 2018). A.K. Padap et al. aimed to understand the microstructural improvement mechanisms that occur in the multiaxial warm forging stage of AISI 1016 steel in their study. In their paper, they utilized optical microscopy and electron-backscattered diffraction findings to examine the predominant mechanisms at different stress stages. They conducted an extensive investigation into the structural changes occurring in both ferrite and perlite components. (Padap, Chaudhari, Pancholi, & Nath, 2010).

Die fatigue

As in all manufacturing processes, it is substantial to have sustainability, energy, and waste saving, therefore reducing environmental pollution in the forging method. Forging dies significantly affect the quality and cost of the forgings produced, and thus production sustainability as they exhibit an unstable and relatively short lifespan. In forging processes, the die cost may cover 15% to 35% of the total cost. M. Bayramoğlu et al. think that a 15% reduction in the total cost of the forging process may be achieved if the die life is increased by 100% (Bayramoğlu, Polat, & Geren, 2008). For this reason, studies to increase the durability of forging dies are the focus of attention of many researchers. While the main factors of die fatigue in hot forging are considered to be abrasive

wear and plastic deformation, one of the main causes of die fatigue in cold forging can be considered as fatigue cracks (Varquez, Hannan, & Altan, 2000). According to M. Hawryluk's literature search, forging tools indicate that the reasons for the failure of the tools used in hot forging are loss of dimension and fatigue cracks, which are a result of abrasive wear and plastic deformation (Hawryluk, 2016). They have discussed the wear mechanisms that affect the durability of hot forging tools through a comprehensive literature review and have extensively examined the most popular methods used to increase tool durability (Wildomski & Gronostajski, 2020).

A.A. Emamverdian et al. present methods for checking die tools and potentially extending die life, in addition to an extensive literature review of hot forging tool failures, including abrasion (abrasive wear, adhesive wear, oxidation, and thermal fatigue cracking), mechanical fatigue cracking, and plastic deformation, and related machining methods, including surface treatment (nitriding) in their studies (Emamverdian, Sun, Cao, Pruncu, & Wang, 2021). According to research, destructive mechanisms involved in die wear in hot forging processes (abrasive wear, adhesive wear, fatigue cracking, and plastic deformation) are also effective mechanisms in the wear of cold forging dies. However, it can be said that the main reason for the low tool strength used in cold forging is the high yield point of the material and the large forming loads (Cwikla & Tofil, 2019). In their study, M. Dalbosco et al. aimed to improve the fatigue life of an automotive part die manufactured by the cold forging method (Dalbosco, Lopes, Schmitt, & Pinotti, 2021). I. Valfolomeev et al. investigated the initiation and dispersion of fabrication defects in high-performance rotor steel under fatigue load

in their study (Varfolomeev, Moroz, Diegele, Kadau"K, & Amann, 2017). H. Y. Kim et al. aimed to obtain quantitative information in terms of material flow, die pressure, and temperature in the hot closed die forging process in their study. They considered using the information obtained in the design of pre-forming processes to reduce the forging load and extend the die life (Kim, Kim, & Kim, 1994).

Operation planning and scheduling

As with other metal forming processes, forging requires estimating the maximum load, forming energy, and die stresses in the planning and programming of the operation. Maximum load and forming energy are the two basic parameters determining the press size and maximum production rate (Altan, O'Connell, Painter, & Maul, 1996). One of the most important parameters required for estimating these variables is the flow stress of the material. The effects on the flow stress of the metal can be divided into factors that are unrelated to deformation (chemical composition, metallurgical structure, etc.) and factors directly related to deformation (deformation temperature, strain, strain rate). The degree of dependence of the flow stress on the temperature may vary for different materials (Altan & Boulger, 1973). Flow stress is affected by temperature and strain rate. In hot forming processes of metals (Hot Forging), if the forging temperature is above the recrystallization temperature of the workpiece, the effect of strain on flow stress is insignificant. However, the effect of strain-velocity ratio on flow stress becomes substantial. T. Altan et al., in their study, mentioned that in conventional hot forging, specifically non-isothermal forging, temperature fluctuations within the deformed part impact metal flow and forging load. Additionally, they

highlighted that the temperatures are significantly influenced by the operational characteristics of the forging machines employed. (Altan, Varden, Im, & Shen, 1988).

In cold forging, the impact of the strain rate ratio on flow stress is minimal. (Altan, Ngaile, & Shen, 2005). In general, forging and forming operation(s) are planned with the assumption that the thermal effect is negligible for steels developed in accordance with cold forging operations. However, during operation, inherently high-strength materials can generate too much viscous heating, causing the operating temperature to rise to around 600°C (Eom, et al., 2014). In this case, there is a decrease in flow stress and forming load, especially in aluminum alloys and high-strength steels that generate a lot of heat during forming (Joun, Chung, & Hong, 2019) (Kim, Yoo, & Joun, 2019) (Byun, Lee, Park, Seo, & Joun, 2020). In addition, in forging processes, due to the effect of friction, the constraints of the die geometry, and the inhomogeneity of deformation, related stress, and forces are high. In cold forging, tools endure substantial loads, potentially leading to excessive friction between the workpieces and the tools. This friction can influence various aspects such as the deformation load, metal flow, deformation uniformity, internal structure and surface quality of the product, and die wear. Hence, it's crucial to comprehend, assess, and manage friction effectively. (Hu, Yin, & Zhao, 2017).

Finite element method

In the late 1960s, the development of simulation technology with the finite element method began in the field of forging. In the 1970s and early 1980s, two-dimensional steady-state simulations were carried out, such as round bar drawing/extrusion and plane

strain plate rolling that did not require re-meshing (Lee & Kobayashi, 1973) (Oh, Chen, & Kobayashi, 1979). Especially in the aerospace part development phase, hot forging metal flow simulations were applied for 2D non-stationary state with manual re-meshing (Kim, Yagi, & Yamanaka, 2000).

Today, the finite element method is used extensively in the planning of metal forming operations. Biba et al. described the advantages of using FEM to analyze forging processes in their study (Biba, Stebounov, & Lishiny, 2001). To get effective results from simulation software, it is known the importance of accurate physical modeling of the operation(s) and the correct entry of the mechanical and thermal characteristics of the material into the system. Material flow curves serve as the primary data input for simulating metal forming processes. According to T. Altan et al., to ensure accurate finite element analysis, the flow curves of the material must encompass the process range being studied in terms of strain, strain rate, and temperature. (Altan & Vazquez, 1996). I. Gürbüz et al. studied creating simulation infrastructure to reduce die-lapping processes for mass production in the automotive industry. By fully characterizing the material mechanical properties, friction coefficients, and die elastic properties through a series of mechanical tests, they have shown that the negative deviations that may arise from mechanical conditions between the simulation environment and the physical environment are minimized, with the compatibility of simulation and physical data (Gürbüz, Altınel, & Karadoğan, 2013).

3. Forging (operation) load

The effects of forging loads applied in the forging operations on product quality and operation systems during and/or after forming have been the subject of study for many researchers, as well as the parameters that the forging load is affected during the process. In this article, the studies of researchers focusing on the operational load in closed die forging forming processes regardless of the forming temperature are examined.

Parameters affected by operational load

The most substantial parameter required for estimating the maximum load and forming energy, which determines the maximum manufacturing rate in all metal forming operations, is the correct determination of the flow stress of the material. We have mentioned the parameters that flow stress is affected by forging operation types under the operation planning and programming heading of the article. This chapter focuses on the work of researchers who want to observe the impact of the flow stress of the material and the parameters directly related to deformation on the forging load.

About flow stress and deformation (temperature, strain, strain rate)

When the forging literature is examined, it is understood that the deviations in the load distribution that occur in forging operations are affected at most by the flow stress distribution of the material. Many researchers revealed that the flow stress of the material is directly affected by the parameters directly related to deformation (temperature, strain, and strain rate). P. Bereczki et al. examined how the strain rate affects flow stress development in Al 6082M grade alloy material during multiaxial forging, using a physical simulator

(Gleeble 3800) in their research. They found that the development of cyclic flow curves is non-monotonic, showing a notable decrease in flow tension as the forging direction changes. Their analysis of the strain rate effect led them to conclude that the kinetics of strain hardening varied depending on the applied strain rate. Also, as the strain rate increases, the saturation of the flow stress indicates that it occurs in the higher accumulated strain. However, they concluded that as the strain rate increases, it leads to an increase in the degree of strain softening between the forging passes (Bereczki, Krallics, & Renko, 2019).

H.J. Lee et al. present a new material flow strain model by improving the closed-form function model for the carbon steel S25C, which exhibits typical dynamic strain aging, in their research (Lee, Razali, Lee, & Joun, 2021). As a result of studies, it has been revealed that the flow stress of the material is affected by hardening mechanisms, as well as factors directly related to deformation. S. Nouri et al. developed a model in the flow stress studies of the alloy of three hardening mechanisms (solid solution, inhibiting the movement of dislocations, and density increase of statistically stored dislocations) that affect the hardening behavior of the alloy during plastic deformation of Al 2024 grade alloy. They applied this model to the finite element model to evaluate the development of the flow stress of the alloy after multiaxial forging (Nouri, Kazeminezhad, & Shadkam, 2020). Z. Xiao et al. investigated the effect of multi-stage forging forming parameters (degree of deformation, strain rate, number of stages, adiabatic thermal temperature) on the quality of products using a physical simulator (Gleeble 3500). With the results, they showed that the strain rate effect on microstructure and mechanical properties is low. They also emphasized that the number

of stages and the degree of deformation have a remarkable effect on the microstructure (Xiao, et al., 2015).

M. Irani and A. K. Taheri, in their study, determined the optimum temperature of a low-carbon steel in a precision forging operation (Irani & Taheri , 2008). R. Sirinivasan et al. investigated the effects of strain rate, workpiece temperature, and operation duration on deformation load in an experimental and simulation environment in which the die, workpiece, and ambient temperatures are different from each other (non-isothermal). Their research demonstrates that at extremely slow strain rates, the initial temperature may not notably impact deformation loads. Conversely, at very high strain rates, where there's insufficient time for substantial heat transfer to the surroundings, the behavior may resemble that observed in isothermal deformation. At slow strain rates, with prolonged deformation times, the workpiece temperature can stabilize. In such cases, the deformation load rises with the strain rate. However, at high strain rates, workpiece temperatures do not stabilize. Consequently, deformation loads can decrease at higher strain rates. (Srinivasan, Balathandayuthapani, & Yan, 2005).

C. D. Lang et al. have recently considered recent advances in electrically assisted manufacturing and have investigated the usability of this innovative approach in forging through a series of tests, based on the knowledge that it reduces flow strain and accordingly deformation force. With the test results in their studies, they exhibited the advantages of electrically assisted manufacturing in forging (decrease in flow voltage and increase in hardness, etc.) and disadvantages (increase in spring back) (Lang, et al., 2020). P. Vo et al. investigated the flow behavior and microstructural

development of IMI834 close to titanium under typical ingot cracking process conditions in their study. They also developed a comprehensive flow stress model valid in dual-phase temperature regimes for general close alloys. They validated the model for various alloys using experimental and literature data (Vo, Jahazi, Yue, & Bocher, 2007).

Tribology

In metal forming processes, since the friction behavior between the die and the workpiece is one of the most significant parameters affecting metal flow, surface quality, and tool life, it has been the focus of attention of many researchers (Nielsen & Bay, 2017). In closed-die hot forging operations, the effects of high friction coefficients due to the high temperature and lubrication difficulties, in addition to die constraints on forming and operations are known. On the other hand, in cold forging, friction conditions become highly demanding because of the significant surface expansion and normal pressures at the interface between the tool and workpiece, despite the use of advanced lubrication systems (Andreas & Merklein, 2014). T.Altan, M. O'Connell et al. wanted to establish a guide for estimating accumulation loads and energies when creating accumulation with a closed die without flash in their study. They also investigated the sensitivity of the forging load to friction, part size, and average material stress using the finite element method (Altan, O'Connell, Painter, & Maul, 1996). Snape et al. investigated the change in the coefficient of friction in the area where the die interface contacts the workpiece using the finite element method. In their study, they observed that the estimated maximum forging load is highly sensitive to changes in the coefficient of friction (Snape, Clift, & Bramley, 1998). In another study, they observed that the

change in friction coefficient had a significant effect on strain and maximum forging load. The flow stress and friction between the empty die interfaces are found to have a significant effect on forging (Snape, Clift, & Bramley, 2002). T. Gangopadlyhyay et al. developed an expert fuzzy logic calculation-based system to estimate forging load and axial stress in their work on the knowledge that empty die interface friction has a significant effect on forging load and axial stresses and creates turbidity for the estimation of these parameters. (Gangopadhyay, Pratihar, & Basak, 2011)

C. Gilbert et al. concentrated on devising an analytical expression to compute forging forces during the compression of bimetallic components, focusing on an assembly comprising a ring made of AISI 1045 steel and a cylinder made of AISI 1015 steel. They aimed to enhance the calculation of forming loads in two-metal ring-cylinder assemblies by refining analytical models previously developed by M. Plancak et al. (Plancak, Kacmarcik, Vilotic, & Krsulja, 2012). Building upon earlier simplified models rooted in the Coulomb friction model, they devised two new analytical models incorporating the shear friction model to provide a more accurate simulation and approach to the real-world problem (Gilbert, Bernal, & Camacho, 2015). Q. Zhang et al. investigated the effect of friction and material flow change by comparing traditional cold forging and oscillating cold forging methods with experiments and simulations. With the results of simulations and experiments, they concluded that oscillating cold forging reduces the operational load by about 25% compared to traditional cold forging operations and contributes positively to friction. They also attributed the reason why the forged part surface quality is better than traditional cold forging to the fact

that low friction causes less metal accumulation (Zhang, Ben, & Yang, 2016).

N. Bay et al. determined frictional strain with typical lubricants for aluminum, steel, and stainless steel with a simulative tribology test system for varying normal pressure, surface expansion, slip length, and tool/workpiece interface temperature. The study results showed that friction was strongly influenced by normal pressure and tool/workpiece interface temperature, while other process parameters studied observed a small effect on friction (Bay, Eriksen, Tan, & Wibom, 2011). C. In their study, Hu et al. aimed to develop an alternative test to minimize the uneven deformations of the inner hole and hence measurement difficulties that occur in the ring compression test, which is often used to characterize the frictional behavior that necessarily occurs at the interface of the workpiece and the die or tool in metal forming. With the developed test method, by simply controlling the angle of inclination of the outer protrusion, they observed that the friction behavior at the workpiece and tool interface could be quantitatively evaluated (Hu, Ou, & Zhao, 2015). In another study, they examined the effect of tool surfaces obtained by machining an aluminum alloy differently in the cold forging process on friction conditions through two different test methods (Hu, Ding, Ou, & Zhao, 2018). In another study, they proposed a novel test based on combined forward and backward extrusion to determine the friction factor in cold forging (Hu, Yin, & Zhao, 2017).

K.H. Jung et al. determined the friction coefficients of Al2024 and 6061-o materials by size-reduced type test (Jung, Lee, Kim, Kang, & Im, 2012). M.S. Joun et al. examined the similarities

and differences between Coulomb's law of friction and the law of friction of constant shear by comparing finite element solutions involving friction-sensitive metal forming processes (accumulation processes with different aspect ratios, strip rolling, ring gear forging, multi-step extrusion, as well as pipe contraction and expansion) (Joun, Moon, Choi, Lee, & Jun, 2009).

Parameters affected by operational load

Die fatigue

N. Karunathilaka et al. investigated how cyclic contact pressure exerted on the tool surface during the forging process impacts the fatigue of the tool material. The samples were subjected to low, medium, and high forging pressures, and it was observed that the tensile strength and fatigue life of the samples forged with low and medium contact pressures increased compared to the non-forging sample. In contrast, the forging sample decreased with higher contact pressure.

Based on the assumption of sample homogeneity, they determined that the strength and fatigue life of the tool steel fluctuate according to the contact pressure applied to the tools during the forging process. (Karunathilaka, Tada, Uemori, Hanamitsu, & Kawato, 2018).

Pre-die design

In forging processes (especially complex parts), the geometric design of the pre-die has a great influence on the forging load and material waste. M. Sedighi et al. have tried to present a suitable algorithm for the practical pre-die design of complex parts (Sedighi & Tokmechi, 2008). V. A. Pandya et al. aimed to observe the effect of the pre-die size on the stress and forging force on the

die during the closed-die forging of anchor clamp and transport pin used in a transmission line with the help of finite element analysis and to minimize die stress and forging force (Pandya & George, 2021) (Pandya & George, Effect of preform design on forging load and effective stress during closed die hot forging process of pin, 2020). A. Halouani et al. developed an optimization method that uses a free-surface method based on the final product shape for performing tool design in multi-stage cold forging processes. This optimization method aims to minimize the equivalent plastic stress and punch force during the forging process (Halouani, Li, Boussad, & Guo, 2012). H. S. Park et al. worked on the initial design and optimization of the pre-die shape for the bevel gear (Park, Ayu, & Kumar, 2018). N. Biba et al. developed the pre-existing isothermal surfaces method for pre-forging dies and developed special software to provide automatic bidirectional geometry data transfer between finite element method simulation software and computer-aided modeling program. They have applied this method in several forging cases. In the application results, they observed a reduction in surface defects and material waste (Biba, Vlasov, Krivenko, Duzhev, & Stebunov, 2020).

Elastic deformation (press-die-workpiece)

Studies conducted by many researchers have shown that the quality of the final product obtained by forging is affected by many factors, such as the material properties of the workpiece and the tool, the elastic deformation behavior of the tools/dies, and the lubricant state between the workpiece and the tool. In addition to these studies, the effects of forging load on the system and part have been the focus of attention for many researchers. V. Krusic et al. analyzed the effect of the distribution of key input parameters (Mass, Flow Stress,

Friction, and Press Hardness) of four different forging processes (Backward Cup Extrusion, Upsetting, Closed Die Forging, and Forward Rod Extrusion) on the dimensional accuracy of the product and tool life for typical cold forging operations. In the study, it was stated that in backward cup extrusion and upsetting systems, the deviation in load distribution was mostly affected by the flow stress distribution of the material, and friction had a significant effect on the effective stress in the die. In addition, it has been stated that two of the most substantial parameters affecting dimensional accuracy in this system are the distribution of material values and press stiffness conditions. In closed-die forging, it has been noted that while the workpiece mass distribution has a great impact on dimensional accuracy, in the same process, the system load is most affected by the press stiffness, flow stress, and flow stress parameter. In the forward bar extrusion process, the distribution of the flow stress parameter and the press stiffness affected the dimensional accuracy of the product, while the system load was affected by the flow stress parameter and friction. In addition, it is emphasized that the effective stress distribution in the die is affected by flow stress and press stiffness. In addition, in the study, the effect of press stiffness on forging dies was investigated by working with presses with two different stiffnesses. It is emphasized that the stiff press increases the elastic deformation in the forging dies, and accordingly, the stiff press reduces the tool life (Krusic, Masera, Pristovsek, & Rodic, 2009).

In another study, V Krusic et al. studied both experimentally and analytically the effect of workpiece-tool-press and tool loads on product quality and optimization of these parameters in the multi-stage forging process (Krusic, Arentoft, Masera, Pristovsek, &

Rodic, 2011). H. Ou et al. investigated the effect of press and die deflections on the final product form in the forging of blade profiles using the finite element method. The results revealed distinct patterns and magnitudes of die surface deviations due to die and press elasticity. They also concluded that it is significant to consider press elasticity if achievable accuracy is to be improved in forging blade components (Ou & Armstrong, 2006). A. Chen et al. studied single-stage injection forging with a particular tool design as an alternative to traditional multi-stage forging processes for automobile fastener production. They have developed axisymmetric models to analyze forging force and energy requirements. Injection forging requires more load to complete the forming process compared to multi-stage forging. This excess load needed during forming will affect adversely effects on the tool's life and dimensional accuracy. However, the featured element in the study is the forming energy needed in injection forging is less than in multi-stage forging. In terms of forming errors, dimensional errors may be controlled by reducing the forming load at each stage of multi-stage forging (Chen, Qin, Chen, & Choy, 2017).

H.G. Zhang et al. created software to simulate the impact of process loads on press deflections in multi-stage forging procedures. In all stages single-stage, two-stage, and three-stage forgings performed on a vertical crank press may require several adjustment iterations before the correct settings are reached. This occurs because adjusting one station affects the forming load there, altering press/tool distortion and consequently, closing heights at other stations. Throughout production, wear on the intermediate-stage tool can enlarge the die cavity volume, leading to shorter workpieces. Adjusting the corresponding load can alter the dimensions of the

workpiece in the finishing die, thereby diminishing part accuracy. They worked to create a mathematical model of press/tool deviations that occur in multi-stage forging operations. By using a computer program developed from this model, they tried to predict the effect of variables such as workpiece dimensions, clamping height, press, and tool stiffness on product accuracy, and to minimize the press/tool setting times required at all stages of forging operations. The program validated its output through one-stage, two-stage, and three-stage physical forging experiments performed on a vertical crank press (Zhang & Dean, 1993). F. Jovane et al. devised a computerized method to aid users in assessing the appropriateness of forming sequences for multi-stage cold forging of rotationally symmetrical workpieces. The program is equipped with features such as automated analysis of sequences for forging both solid and hollow parts, identification of the specific processes within each step, assessment of load peak distribution across various forming stages, and estimation of the strain distribution accumulated in the final part with cavities. The most important meaning of using the program as a module of an integrated CAD system for cold forging is to perform a complete manufacturability check on the process planner and provide an appropriate tool to determine the optimal forging sequence. The benefits that can arise from the implementation of the program are the design of performing sequences consistent with the mechanical properties of the final product and the correct use of presses and tools (Jovane, BAriani, Benuzzi, & Knight, 1987).

R. Hino et al. studied a simulation-based optimization technique that aims to reduce the number of forming operations with multi-stage forging. This optimization technique has been applied in

the progressive reduction of the three-stage forging process of an axisymmetric aluminum billet. First, the focus is on forming load optimization, as the forming load increases significantly in the final stages of the forging processes, which negatively affects the quality of the surface that responds to this increased forming load. The second and third focuses were on breakage prevention and gap optimization, respectively (Hino, Sasaki, Yoshida, & Toropov, 2008). L. Capan et al. considered that the two metal forming methods were similar to each other because defects occurred in the material under the punch in backward cup extrusion by round-shaped closed die forging with flash, and the remaining material moved along the die walls. In their study, they calculated the required press force by dividing the workpieces into accretion areas for these two metals forming methods and also considering the die wall angles. They concluded that the backward extrusion method may be used to calculate the press load of round-shaped forgings (Capan & Baran, 2000). J. B. Renko et al. compared the results of a finite element method-based program with tests with a physical simulator (Gleeble 3800) for a multi-axis forging operation. They observed that the required operation load obtained from the virtual data was 5kN higher than the physical tests on average, and in both methods, the required operation load in the first forging stage was the highest and the required operation load in the second stage was the lowest. In addition, they observed that in the third stage and subsequent forging stages, the required operation load converged to the force-displacement curves from above in odd-numbered operations, while the required operation load converged from the bottom in even-numbered operations. As a result, they suggest that the incompatibility of physical tests and virtual data is due to the

applied linear hardening material model, which cannot handle the nonlinear structure of multi-axis forging (Renko & Krallics).

H.Ou et al. conducted simulations using finite element simulation to analyze the material flow during the forging process of wing sections (Aerofoil), forging force history, contact pressure distribution between the die and the component, and examined the elastic deflections of forging dies. They also proposed changing die profiles in response to die deviations based on compensation of elastic behavior of die and nominal dimensions of the forging dies. By using finite element analysis, they tried to minimize the form errors of the airfoil sections due to the die elasticity. They concluded that the precision forging of aerofoil sections enables the quantitative estimation of die elasticity and the technique of compensating for component-form errors to achieve the manufacturing net-shaped parts (Ou & Balendra, 1998). S.Y. Hsia ve P.Y. Shih investigated precisely how die wear, die stress, die interaction, and workpiece stresses are related in fastener manufacturing dies by finite element analysis method. In addition, in their study, they used different samples to evaluate the flow stress-strain curve and friction coefficient (Hsia & Shih, 2015).

4. Results

According to detailed literature research, it can be applied using more than one method in the manufacturing processes of metal components. When forging processes are carried out under less-than-ideal conditions, forging defects are inevitable. Examining and eliminating these defects as much as possible is critical in terms of the forging process and the final product to be reached as a result of this process.

During the application of the forging process, tribological and geometric effects and deformation should be considered as well as the operation load and die stresses.

The finite element method, which offers the opportunity to combine today's technologies with traditional manufacturing methods, is used extensively in the examination, development, and optimization of the forging process.

When the studies conducted to date are examined, it is clearly understood that many parameters affect the mechanical properties, dimensional accuracy, surface quality, formability, and operation planning of the workpiece in the forging process, which is the focus of this article. It is understood from research that forging operation loads are an important operational input that affects the ideal mechanical properties, dimensional accuracy, ideal surface quality, and ideal die tool life expected from the forged final product. In addition, it is understood that forming loads play a key role in the ideal forming energy and appropriate press/tool selection. Thus, it may be deduced that the requirement for the forming loads to be estimated and in the ideal range has a significant impact on the effective applicability of forging operations. In this context, the parameters affected by this substantial operational input have been of interest and studied in detail by many researchers. From the studies, it is understood that the flow stress of the material, die limitations, the effect of friction between the die and the workpiece, thermal effects, strain-rate, and press/tool hardness are important active parameters. When the studies conducted to date are examined, it is seen that while the forming load estimation, idealization, affected parameters, and factors in the first forming

stage of single-stage forging processes or multi-stage forging processes have been studied in detail and intensively, not much work has been done on the forming load estimation, idealization, affected parameters and factors in other stages of multi-stage forging operations.

Bibliography

Abdullah, A., Sapuan, S. M., Samad, Z., T.Khaleed, H. M., & Aziz, N. A. (2013). Numerical investigation of geometrical defect in cold forging of an AUV blade pin head. *Journal of Manufacturing Processes*(15), 141-150.

Aksakal, B., Osman, F. H., & Bramley, A. N. (1997). Upper-bound analysis for the automation of open-die forging. *Journal of Materials Processing Technology*(71), 215-223.

Aksakal, B., Osman, F. H., & Bramley, A. N. (2008). Determination of experimental axial and sideways metal flow in open die forging. *Materials and Design*(29), 576-583.

Alniak, M. O., & Bedir, F. (2006). Change in grain size and flow strength in P/M Rene 95 under isothermal forging conditions. *Materials Science and Engineering B*(130), 254-263.

Altan, T., & Boulger, F. W. (1973). Flow Stress of Metals and Its Applications in Metal Forming. *Journals of Engineering for Industry*, 1009-1019.

Altan, T., & Vazquez, V. (1996). Numerical Process Simulation for Tool and Process Design in Bulk Metal Forming. *Scientific Technical Committee Paper Discussion Sessions, CIRP*(45), 599-615.

Altan, T., Ngaile, G., & Shen, G. (2005). *Cold and Hot Forgings: Fundamentals and Applications.* ASM International.

Altan, T., O'Connell, M., Painter, B., & Maul, G. (1996). Flashless closed-die upset forging-load estimation for . *Journal of Materials Processing Technology*(59), 81-94.

Altan, T., Varden, O., Im, Y. T., & Shen, G. (1988). Investigation of Metal Flow in Non-Isothermal Forging Using Ring and Spike Tests. *Annals of the ClRP* (37).

Andreas, K., & Merklein, M. (2014). Influence of surface integrity on the tribological performance of cold forging tools. *Procedia CIRP*(13), 61-66.

Arentoft, M., & Wanheim, T. (1997). *Journal of Materials Processing Technology*(69), 227-232.

ASM HandBook. (1988). ASM INTERNATIONAL.

Atlan, T., Oh, S. I., & Gegel, H. (1983). Metal Forming-Fundamentals and. *American Society of Metals (ASM)*.

Balendra, R., & Qin, Y. (2000). Identi®cation and classification of Fow-dependent defects. *Journal of Materials Processing Technology in the injection forging of solid billets*(106), 199-203.

Banaszek, G., & Stefanik, A. (2006). Theoretical and laboratory modelling of the closure of . *Journal of Materials Processing Technology metallurgical defects during forming of a forging*(177), 238-242.

Bay, N., Eriksen, M., Tan, X., & Wibom, O. (2011). A friction model for cold forging of aluminum, steel and stainless steel provided with conversion coating and solid film lubricant. *CIRP Annals - Manufacturing Technology*(60), 303-306.

Bayramoğlu, M., Polat, H., & Geren, N. (2008). Cost and performance evaluation of different surface treated dies for hot

forging process. *Journal Of Materials Processing Technology*(205), 394-403.

Behrens, B. A., & Odening, D. (2009). PROCESS AND TOOL DESIGN FOR PRECISION FORGING OF GEARED COMPONENTS . *International Journal of Material Forming*(2), 125-128.

Behrens, B.-A., Volk , W., Maier, D., Scandola, L., Ott, M., Brunotte, K., . . . Till, M. (2020). A Combined Numerical and Experimental Investigation on Deterministic Deviations in Hot Forging Processes. *Procedia manufacturing*(47), 295-300.

Bereczki, P., Krallics, G., & Renko, J. (2019). The effect of strain rate under multiple forging on the mechanical and microstructural properties. *Procedia Manufacturing*(37), 253-260.

Biba, N., Stebounov, S., & Lishiny, A. (2001). Cost Effective Implementation of Forging Simulation. *Journal of Materials Processing Technology*(113), 34-39.

Biba, N., Vlasov, A., Krivenko, D., Duzhev, A., & Stebunov, S. (2020). Closed Die Forging Preform Shape Design Using Isothermal Surfaces Method. *Procedia Manufacturing*(47), 268-273.

Biswas, S., & Rao, K. J. (1985). Flow of metal into the flash gap in the last stages of a plane-strain closed-die forging operation. *Journal of Mechanical Working Technology*(11), 319-331.

Byun, J. B., Lee, H. J., Park, J. B., Seo, I. D., & Joun, M. S. (2020). Fully Coupled Finite Element Analysis of an Automatic Multi-Stage Cold Forging Process. *Trans. Tech. Publication Ltd.*(311), 88-93.

Can, Y., Altinbalik, M. T., & Akata, H. E. (2004). An investigation on forging loads and metal flow in conventional closed-die forging of preforms obtained by open-die indentation. *Indian Journal of Engineering & Material Sciences*(11), 487-492.

Capan, L., & Baran, O. (2000). Calculation method of the press force in a round shaped closed-die forging based on similarities to indirect extrusion. *Journal of Materials Processing Technology*(102), 230-233.

Cavaliere, P. (2004). Isothermal forging of AA2618 reinforced with 20% of alumina particles. *Composites: Part A Applied Secience and Manufacturing*(35), 619-629.

Chan, W., Fu, M. W., Lu, J., & Chan, L. C. (2009). Simulation-enabled study of folding defect formation and avoidance in axisymmetrical flanged components. *Journal of Materials Processing Technology, 209*(11), 5077-5086.

Chen, Q., Hu, H., Lin, J., Huang, S., Wu, Y., Shu, D., . . . Mingbo, Y. (2017). Multi-stage cold forging process for H68 brass cylindrical shell part with deep blind hole: simulation and experiment. *Int J Adv ManufTechnol*.

Chen, S., Qin, Y., Chen, J. G., & Choy, C.-M. (2017). A forging method for reducing process steps in the forming of automotive fasteners. *International Journal of MEchanical Sciences*.

Choi, S., Chun, M. S., Tyne, C. V., & Moon, Y. H. (2006). Optimization of open die forging of round shapes using FEM analysis. *Journal of Materials Processing Technology*(172), 88-95.

Cwikla, A., & Tofil, A. (2019). Analysis of wear of cold forging dies using the technique of focal differentiation microscopy. *IEEE*, 629-632.

Dalbosco, M., Lopes, G. S., Schmitt, P. D., & Pinotti, L. (2021). Improving fatigue life of cold forging dies by finite element analysis: A case study. *Journal of Manufacturing Processes*(64), 349-355.

Davoudi, M., Nejad, A. F., Koloor, S. R., & Petru, M. (2021). Investigation of effective geometrical parameters on wear of hot forging die. *Journals of Materials Research And Technology*(15), 5221-5231.

Dehghani, K., & Jaferi, A. (2010). Finite element stress analysis of forging dies to improve their fatigue life. *Material Science-Poland, 28*(1).

Dieter, G. E. (1986). *Mechanical Metallurgy.* Singapore: McGraw-Hill.

Emamverdian, A. A., Sun, Y., Cao, C., Pruncu, C., & Wang, Y. (2021). Current failure mechanisms and treatment methods of hot forging tools (dies) - a review. *Engineering Failure Analysis*(129).

Eom, J., Son, Y. H., Jeong, S. W., Ahn, S. T., Jang, S. M., Yoon, D. J., & Joun, M. S. (2014). Effect of strain hardening capability on plastic deformation behaviors of material during metal forming. *Materials and Design*(54), 1010-1018.

Forcellese, A., & Gabrielli, F. (2000). Warm forging of aluminium alloys: a new approach for time . *International Journal of Machine Tools & Manufacture compression of the forging sequence*(40), 1285-1297.

F-Saniee, F., & Hosseini, A. H. (2006). The effects of flash allowance and bar size on forming load and metal flow in closed die forging. *Journal of Materials Processing Technology*(177), 261-265.

Fujikava, S., Yoshioka, H., & Shimamura, S. (1992). Cold- and warm-forging applications in the automotive industry. *Journal of Materials Processing Technology*(35), 317-342.

Gangopadhyay, T., Pratihar, D. K., & Basak, I. (2011). Expert system to predict forging load and axial stress. *Applied Soft Computing*(11), 744-753.

Gao, P., Fei, M. y., Yan, X. G., Wang, S. B., Li, Y. K., Xing, L., . . . Keyim, Z. (2019). Prediction of the folding defect in die forging: A versatile approach for three typical types of folding defects. *Journal of Manufacturing Processes*(39), 181-191.

Geiger, M., Arbak, M., & Engel, U. (2008). Material adapted tool design in cold forging exemplified by powder metallurgical tool steels and industrial ceramics. *German Academic Society for Production Engineering*(2), 409-415.

Ghassemali, E., Tan, M. J., Wah, C. B., Lim, A. V., & Jarfors, A. W. (2014). Friction effects during open-die micro-forging/extrusion processes: an upper bound approach. *Procedia Engineering*(81), 1915-1920.

Gilbert, C., Bernal, C., & Camacho, A. M. (2015). Improved analytical model for the calculation of forging forces during compression of bimetallic axial assemblies. *Procedia Engineering*(132), 298-305.

Groover, M. P. (2010). *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems.* John Wiley & Sons, 2010.

Gürbüz, I., Altınel, S. A., & Karadoğan, C. (2013). PRACTICAL TECNIQUES in VIRTUAL TRYOUT for AUTOMOTIVE SHEET METAL FORMING. *7. International Design and Production of Machines and Dies/Mold.* Antalya.

Halouani, A., Li, Y. M., Boussad, A., & Guo, Y. Q. (2012). Optimization of cold forging perform tools using Pseudo Inverse Approach. *Trans. Nonferrous Met. Soc. China*(22), 207-213.

Hawryluk, M. (2016). Review of selected methods of increasing the life of forging tools in hot die forging processes. *Archives Of Civil Mechanical Engineering , 16*, 845-866.

Hawryluk, M., & Jakubik, J. (2015). Analysis of forging defects for selected industrial die forging processes. *Engineering Failure Analysis*.

Henke, T., Bambach, M., & Hirt, G. (2013). Quantification of uncertainties in grain size predictions of a microstructure-based flow stress model and application to gear wheel forging. *CIRP Annals - Manufacturing Technology*(62), 287-290.

Hino, R., Sasaki, A., Yoshida, F., & Toropov, V. V. (2008). A new algorithm for reduction of number of press-forming stages in. *International Journal of Mechanical Sciences forging processes using numerical optimization and FE simulation*(50), 974-983.

Hirscvogel, M., & Dommelen, H. V. (1992). Some applications of cold and warm forging. *Journal of Materials Processing Technology*(35), 343-356.

Hsia, S.-Y., & Shih, P.-Y. (2015). Wear Improvement of Tools in the Cold Forging Process for Long Hex Flange Nuts. *Materials*(8), 6640-6657.

Hu, C., Ding, T., Ou, H., & Zhao, Z. (2018). Effect of tooling surface on friction conditions in cold forging of an aluminum alloy. *Tribology International*.

Hu, C., Ou, H., & Zhao, Z. (2015). An alternative evaluation method for friction condition in cold forging by ring with boss compression test. *Journal of Materials Processing Technology*(15).

Hu, C., Yin, Q., & Zhao, Z. (2017). A novel method for determining friction in cold forging of complex parts using a steady combined forward and backward extrusion test. *Journal of Materials Processing Technology*.

Irani, M., & Taheri , A. K. (2008). Effect of forging temperature on homogeneity of microstructure and hardness of precision forged steel spur gear. *Materials Chemistry and Physics*(112), 1099-1105.

Ishinaga, N. (1997). An advanced press design for cold forging. *Journal of Materials Processing Technology*(71), 100-104.

Jo, A. R., jeong, M. S., Lee, S. K., Moon, Y. H., & Hwang, S. K. (2021). Multi-Stage Cold Forging Process for Manufacturing a High-Strength One-Body Input Shaft. *MDPI*(14), 532.

Jo, A. R., Jeong, M. S., Lee, S. K., Moon, Y. H., & Hwang, S. K. (2021). Multi-Stage Cold Forging Process for Manufacturing a High-Strength One-Body Input Shaft. *Multidisipliner Digital Publishing Institute*(14), 532.

Joun, M. S., Moon, H. G., Choi, L., Lee, M. C., & Jun, B. Y. (2009). Effects offrictionlawsonmetalformingprocesses. *TribologyInternational*(42), 311-319.

Joun, M., Chung, W. J., & Hong, S. M. (2019). Macroscopic Modelling of Metal Forming Processes by FEM. *Jinseam Media*.

Jovane, F., BAriani, P., Benuzzi, E., & Knight, W. A. (1987). Computer Aided Design of Multi-Stage Cold Forging Process: Load Peaks and Strain Distribution Evaluation. *Annals of the CIRP.*

Jung, K. H., Lee, H. C., Kim, D. K., Kang, S. H., & Im, Y. T. (2012). Friction measurement by the tip test for cold forging. *Wear*(286-287), 19-26.

Karunathilaka, N., Tada, N., Uemori, T., Hanamitsu, R., & Kawato, M. (2018). Effect of contact pressure applied on tool surface during cold forging on fatigue life of tool. *Procedia Manufacturing*(15), 488-495.

Kim, H. Y., Kim, J. J., & Kim, N. (1994). Physical and numerical modeling of hot closed-die forging to reduce forging load and die wear. *Journal of Materials Processing Technology*(42), 401-420.

Kim, H., Yagi, T., & Yamanaka, M. (2000). FE simulation as a must tool in cold/warm forging process and tool design. *Journal of Materials Processing Technology*(98), 143-149.

Kim, K., Yoo, J. D., & Joun, M. S. (2019). FE prediction of temperature variation of material and dies with number of strokes in aluminum yoke cold forging. *Proc. Kor. Soc. Tech. Plast. Conf.*, (pp. 105-106).

Kocanda, A., Czyzewski, P., & Mehdi, K. H. (2009). Numerical analysis of lateral forces in a die for turbine blade forging. *ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING, 9*(4).

Krusic, V., Arentoft, M., Masera, S., Pristovsek, A., & Rodic, T. (2011). A combined approach to determine workpiece-tool-press deflections and tool loads in multistage cold-forging. *Journal of Materials Processing Technology*(211), 35-42.

Krusic, V., Masera, S., Pristovsek, A., & Rodic, T. (2009). Adjustment of stochastic responses of typical cold forging systems. *Journal of Materials Processing Technology*(209), 4983-4993.

Ku, T.-W., & Kang, B.-S. (2014). Hardness-controlled tool fabrication and application to cold forging of inner race with skewed ball grooves. *International Journal Of Manufacturing Technology*(74), 1337-1354.

Lakshmipathy, R., & Sagar, R. (1992). EFFECT OF DIE SURFACE TOPOGRAPHY ON DIE-WORK INTERFACIAL FRICTION IN OPEN DIE FORGING. *Int. J. Mach. Tools Manufact, 32*(5), 685-693.

Lang, C. D., Hasbrouck, C. R., Hankeys, A. S., Lynch, P. C., Allison, B. D., & Roth, J. T. (2020). Electrically-Assisted Manufacturing for Reduction in Forging Forces of Bearing Steels. *Procedia Manufacturing*(48), 349-357.

Lange, K. (1992). Some aspects of the development of cold forging to a high-tech precision technology. *Journal of Materials Processing Technology*(35), 245-257.

Lange, K. (n.d.). *Handbook of Metal Forming.* Michigan: Society of Manufacturing Engineers.

Lee, C., & Kobayashi, S. (1973). New Solutions to Rigid-Plastic Deformation Problems Using a Matrix Method. *Trans. ASME, J. Eng. Ind*(95), 865-873.

Lee, H., Razali, M. K., Lee, K. H., & Joun, M. S. (2021). Flow stress characterization of carbon steel S25C in the temperature range of cold forming with an emphasis on dynamic strain aging. *Materials Today Communications*(28).

Li, W., Liu, Y., Luan, Q., Li, Y., Gu, B., & Shi, Z. (2018). A study of thermomechanical behaviour and grain size evolution of AA7050 under hot forging conditions. *International Journal of Lightweight Materials and Manufacture*.

Luca, D. (2017). A numerical solution for a closed die forging process. *Matec Web Conferences.*

Maier, D., Hartmann, C., till, M., Büdenbender, C., Behrens, B., & Volk, W. (2019). Data-Driven Compensation for Bulk Formed Parts Based on Material Point Tracking. *Key Engineering Materials*(794), 277-284.

Moon, Y. H., Van Tyne, C. J., & Gordon, W. A. (2000). An upper bound analysis of a process-induced side-surface defect in forgings Part 1: The velocity fields and power terms. (99), pp. 169-178.

Moon, Y. H., Van Tyne, C. J., & Gordon, W. A. (2000). An upper bound analysis of a process-induced side-surface defect in forgings Part 2: Characteristics and criteria curves. *Journal of Materials Processing Technology*(99), 179-184.

Nielsen, C. V., & Bay, N. (2017). Overview of friction modelling in metal forming processes. *Procedia Engineering*(207), 2257-2262.

Nouri, S., Kazeminezhad, M., & Shadkam, A. (2020). Flow stress of 2024 aluminum alloy during multi-directional forging process and natural aging after plastic deformation. *Materials Chemistry And Physics*.

Oh, S. I., Chen, C. C., & Kobayashi, S. (1979). Ductile Fracture in Axisymmetric Extrusion and Drawing—Part 2: Workability in Extrusion and Drawing. *Trans. ASME, J. Eng. Ind*(101), 36-44.

Ou, H., & Armstrong, C. G. (2006). Evaluating the effect of press and die elasticity in forging of aerofoil sections using finite element simulation. *Finite Elements in Analysis and Design*(42), 856-867.

Ou, H., & Balendra, R. (1998). Die-elasticity for precision forging of aerofoil sections using finite element simulation. *Journal of Materials Processing Technology*(76), 56-61.

Padap, A., Chaudhari, G. P., Pancholi, V., & Nath, S. K. (2010). Warm multiaxial forging of AISI 1016 steel. *Materials and Design*(31), 3816-3824.

Pandya, V. A., & George, P. M. (2020). Effect of preform design on forging load and effective stress during closed die hot forging process of pin. *Materials Today, Proceedings*.

Pandya, V. A., & George, P. M. (2021). Analysis of die stress and forging force for DIN 1.2714 die material during closed die

forging of anchor shackle. *Materials Today, Proceedings*(45), 4695-4701.

Park, H. S., Ayu, F. R., & Kumar, S. (2018). Preform Optimization for Bevel Gear of Warm Forging Process. *Procedia CIRP*(72), 340-345.

Plancak, M., Kacmarcik, I., Vilotic, D., & Krsulja, M. (2012). Compression of bimetallic components–analytical and experimental investigation. *International Journals Of Engineering*(10), 1584-2665.

Razali, M. K., Kim, S. W., Irani, M., Kim, M. C., & Joun, M. S. (2021). Practical quantification of the effects of flow stress, friction, microstructural properties, and the tribological environment on macro- and micro-structure formation during hot forging. *Tribology International*(164).

Renko, J. B., & Krallics, G. (n.d.). Comparison of physical and virtual simulation of multi-axial forging processes on EN-AW 6082 aluminium alloy. *Materials Today*.

S.Sheljaskov. (1994). Current level of development of warm forging technology. *Journal of Materials Processing Technology*(46), 3-18.

Samolyk, G., & Pater, Z. (2005). Use of SLFET for design of flash gap with V-notched lands in a closed-die forging. *Journal of Materials Processing Technology*(162-163), 558-563.

Sedighi, M., & Tokmechi, S. (2008). A new approach to preform design in forging process of complex parts. *journal of materials processing technology*(197), 314-324.

Shamasundar, S. (2003). Process simulation based optimization of precision forging process. *International Seminar on Precision Forging.* Nagoya, Japan.

Sheljaskov, S. (1994). Current level of development of warm forging technology. *Journal of Materials Processing Technolog*(46), 3-18.

Shivpuri, R., Babu, S., Kini, S., Pauskar, P., & Deshpande, A. (1994). Recent advances in cold and warm forging process modeling techniques: selected examples. *Journal of Materials Processing Technology*(46), 253-274.

Sleeckx, E., & Kruth, J. P. (1992). Review of flash design rules for closed-die forgings. *Journal of Materials Processing Technology*(31), 119-134.

Snape, G., Clift, S., & Bramley, A. (2002). Parametric sensitivity analyses for FEA of hot steel forging. *Materials Processing Technology*(125-126), 353-360.

Snape, R. G., Clift, S. E., & Bramley, A. N. (1998). Sensitivity of finite element analysis of forging to input parameters. *Materials Processing Technology*(82), 21-26.

Srinivasan, R., Balathandayuthapani, M., & Yan, W. (2005). Temperature changes and loads during hot-die forging of a gamma titanium–aluminide alloy. *Journal of Materials Processing Technology*(160), 321-334.

Ssemakula, H., Stahlberg, U., & Öberg, K. (2006). Close-die forging of large Cu-lids by a method of low force requirement. *Journal of Materials Processing Technology*(178), 119-127.

Stonis, M., Rüther, T., & Behrens, B.-A. (2015). Analysis of Material Characteristics and Forging Parameters for Flashless Forged Aluminum-Matrix Composites. *Materials And Manufacturing Process*(29), 140-145.

Tan, M.-J., Ghassemali, E., Wah, C. B., Jarfors, A. E., & Lim, S. (2013). Grainsizeandworkpiecedimensioneffectsonmaterial flow in anopen-diemicro-forging/extrusionprocess. *Materials Science & Engineering A*(582), 379-388.

Tekkaya, A. E., & Hering, O. (2019). Damage-induced performance variations of cold forged parts. *Journals of Materials Processing Technology*(19).

Varfolomeev, I., Moroz, S., Diegele, D., Kadau"K, & Amann, C. (2017). Study on fatigue crack initiation and propagation from forging defects. *Procedia Structural Integrity*(7), 359-367.

Varquez, V., Hannan, D., & Altan, T. (2000). Tool life in cold forging – an example of design improvement to increase service life. *Journal of Materials Processing Technology*(98), 90-96.

Vo, P., Jahazi, M., Yue, S., & Bocher, P. (2007). *Materials Science and Engineering A*(447), 99-110.

Wernicke, S., Hahn, M., Detzel , A., Tillmann, W., Stangier, D., Dias, N. L., & Tekkaya, A. E. (2021). Force reduction by electrical assistance in incremental sheet-bulk metal forming of gears. *Journal of Materials Processing Tech.*(296).

Weronski, W., Gontarz, A., & Pater, Z. (1999). The reasons for structural defects arising in forgings of aluminium alloys analysed using the ®nite element method. *Journal of Materials Processing Technology*(92-93), 50-53.

Wildomski, P., & Gronostajski, Z. (2020). Comprehensive Review of Methods for Increasing the Durability of Hot Forging Tools. *Procedia Manufacturing*(47), 349-355.

Wilson, F. (1965). *Die Design Handbook 2nd ed.* McGraw-Hill and Society of Manufacturing Engineers.

Wolfgarten, M., Rudolph, F., & Hirt, G. (2020). Analysis of process forces and geometrical correlations for open-die forging with superimposed manipulator displacements. *Journal of Materials Processing Tech.*(276).

Xiao, Z., Liu, H., Liu, B., Sun, H., Liu, D., & Liu, G. (2015). The effect of forming parameter on multi-stage cold forging with 20MnTiB steel. *Int J Adv Manuf Technol*.

Xinbo, L., Hongsheng, X., & Zhiliang, Z. (2003). Flow stress of carbon steel 08F in temperature range of warm-forging. *Journal of Materials Processing Technology*(139), 543-546.

Yan, H.-G., Wu, Y. Z., Chen, J. H., Du, Y. G., Zhu, S. Q., & Su, B. (2012). Microstructure and mechanical properties of ZK21 magnesium alloy fabricated by multiple forging at different strain rates. *Materials Science & Engineering A*(556), 164-169.

Yanagimoto, J., Sugiyama, S., Yanagida, A., Iwamura, N., & Ishizuka, M. (2009). Control of ultrafine microstructure by single-pass heavy deformation and cold forging of metal. *journal of materials processing technology*(209), 679-685.

Zhang, H. G., & Dean, T. A. (1993). COMPUTER MODELLING OF TOOL LOADS AND PRESS/TOOL DEFLECTIONS IN MULTISTAGE FORGING. *Int. J. Mach. Tools Manufact, 35*(1), 61-69.

Zhang, Q., Ben, N., & Yang, K. (2016). Effect of variational friction and elastic deformation of die on oscillating cold forging for spline shaft. *Journal of Materials Processing Technology*.