



Analysis of Deformation Rate and Hardness of Forged Automotive Parts

¹Huang-Li Wang, ^{2,*}Kuo-Da Chou, ³Ming-Shan Lai

¹Graduate Institute of Manufacturing Technology/National Taipei University of Technology, Taipei City, Taiwan, ROC.

²Department of Vehicle Engineering/National Formosa University, Yunlin County, Taiwan, Republic of China

³Department of Mechanical Engineering/National Taipei University of Technology, Taipei City, Taiwan Republic of China, Email: ¹le5890606@gmail.com, ²kdchou@nfu.edu.tw, ³S0980334003@gmail.com

*Corresponding Author: Kuo-Da Chou, (kdchou@nfu.edu.tw)

Abstract- Key Lock parts in automotive Electronic Power Steering (EPS) systems must possess mechanical properties such as fatigue resistance, high toughness, and high strength. Therefore, forging is not only suitable for meeting the performance requirements of EPS but also offers cost advantages. However, the hollowness, narrow grooves and densely packed teeth of Key Lock parts restrict material flow and cause uneven stress distribution within the parts, making forging a significant challenge. This paper uses S35C medium carbon steel as raw material and compares the following three different forging methods: cold forging, warm forging, and hot forging, through actual die-cutting to understand the impact of different forging methods and the forging deformation rate between different process passes on surface hardness. Experimental results show that, observed under an optical microscope, the grain size is coarsest after hot forging, followed by warm forging, and finest after cold forging. Hardness increases with increasing forging deformation rate; cold forging yields the highest hardness, followed by warm forging, and hot forging yields the lowest. In terms of dimensional accuracy, cold forging has the best precision, followed by warm forging. Hot forging requires additional processing to meet the dimensional requirements due to thermal expansion and contraction. These experiments provide manufacturers with insights to help them choose the appropriate process to meet their specific needs.

Keywords: Forging, Deformation Rate, Hardness.

1. Introduction

With changing economic patterns and the arrival of a consumer-oriented era, products on the market are trending towards low quantities, greater variety, and more refined products, resulting in increasingly shorter product lifecycles. Take the automotive industry as an example: models receive minor updates every one to two years, and major updates every three years. With shorter product lifecycles and competitions from regions with lower labor costs, the automotive part industry is facing increasing pressure. Therefore, manufacturers must adopt more cost-effective production methods while enhancing the mechanical properties of finished products to respond to industrial challenges. Forging is a metal forming process through compression, it can be further categorized into cold forging, warm forging and hot forging. Cold forging is a form of cold processing, which is the phenomenon that a ductile metal undergoes plastic deformation, leading to improved hardness and toughness due to the dislocation [1]. Hot forging is primarily used for processing large machine parts and materials with higher work hardening index. The forging temperature must be maintained above the recrystallization temperature of the material. Compared with cold forging, it can increase the plasticity of the metal and reduce the forging pressure, but it tends to produce oxide scale and difficult to control the dimension [2]. Warm forging is an improved process that combines the advantages of both hot and cold forging. The material is heated but it has not reached the temperature required for phase transformation. The required load is lower than that of cold forging and there is no high-temperature oxidation scale, while dimension can be better controlled [3-4]. The advantages and disadvantages of cold forging, warm forging and hot forging are compared as follows [5]:

Table 1. Comparison of different forging methods

	Cold Forging	Warm Forging	Hot Forging
Forging Temperature	Normal Temperature	150~800°C	800°C and above
Forging Mold	a. Open Mold, b. Semi-closed, c. Closed	a. Open Mold, b. Semi-closed, c. Closed	a. Semi-closed
Mold Durability	Low	Normal	High
Mold Precision	High	Normal	Low
Mold Cost	High	Normal	Low
Forging Load	High	Normal	Low
Forging Stress	High	Normal	Low

Deformation Resistance of Material	High	Normal	Low
Preprocessing of Material	Soft or Spheroidizing Annealing Required	Depends on Temperature	Not Required

Forging allows control over metal flow and grain structure, resulting in finer, more homogeneous materials with excellent fatigue resistance, impact resistance, and toughness. Forged parts can significantly enhance the mechanical strength and toughness of materials. Other processing methods, such as casting, 3D metal printing, and electrical discharge machining (EDM), are unable to alter the grain structure of the raw material. Therefore, under the same material conditions, their mechanical properties cannot compare with those achieved through forging. Furthermore, forging offers rapid production, making it a common method for manufacturing mechanical parts that must withstand high loads and frequent usage. It is widely used in industries like the automotive parts manufacturing, aerospace engineering, including the production of forged parts of warheads, rockets, weapons, and military equipment in the defense industry. Although forged products can improve material toughness, but achieving specific hardness requirements often requires heat treatment methods that modify the internal microstructure of the material. Surface hardness can also be increased through surface sandblasting or polishing, which alter the surface microstructure. These are common methods used to increase hardness. But these post-processes for hardening increase production time and manufacturing costs. In today's highly competitive automotive industry where rapid mass production is essential, reducing processing steps directly increases competitiveness. The purpose of this paper is to validate the feasibility of increasing product hardness without the use of post-processing treatments through a practical case. The forged part of this experiment is the Key Lock part in an automotive EPS (shown in Figure 1). Through CAE simulation software, Deform 3D, each pass is analyzed and the output tonnage of the forging machine is observed. As well as the overall internal stress distribution [6] and forging deformation rate, to assess whether the process and mold design are feasible. Then an actual part is forged, its hardness is measured and compared among cold forging, warm forging, and hot forging processes, along with its dimensions. Providing manufacturers a reference for selecting the appropriate method according to their requirements.



Figure 1. Electronic Power Steering (EPS) [7]

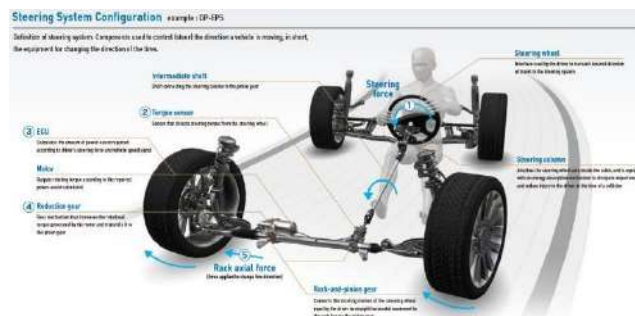


Figure 2. Key Lock part

II. Literature Review

This paper discusses multi-pass forging, in which cold forging can produce products with excellent dimensions, surface finish, and strength. However, due to its high pressure, the requirements for mold strength are considerably higher. Therefore, mold design technology must be applied to reduce the load or increase the strength. Literature review can help learn from the experience of predecessors, reduce the number of trial runs, lower the costs, and reduce the development process.

In 2003, Dong-Kyun Min et al. [8] proposed a new method to improve mechanical properties and lower production costs through precision cold forging. The research object was a steering yoke. The study used the plastic finite element method to reduce development time and mold costs. Practical considerations in the manufacturing stage were also studied, such as hardness in heat treatment and coating conditions in lubrication. Forging is a metal forming process through compression, it can be further categorized into cold forging, warm forging and hot forging. Cold forging is a form of cold processing, which is the phenomenon that a ductile metal undergoes plastic deformation, leading to improved hardness and toughness due to the dislocation [9]. Hot forging is primarily used for processing large machine parts and materials with higher work hardening index. The forging temperature must be maintained above the recrystallization temperature of the material. Compared with cold forging, it can increase the plasticity of the metal and reduce the forging pressure, but it tends to produce oxide scale and difficult to control the dimension [10]. Warm forging is an improved process that

combines the advantages of both hot and cold forging. The material is heated but it has not reached the temperature required for phase transformation. The required load is lower than that of cold forging and there is no high-temperature oxidation scale, while dimension can be better controlled [11-13].

De-Le Shi and Yi Xiong [14] pointed out that during plastic deformation, the material structure and stress redistribution can be used to reduce stress concentration (reduction of area) in the case of local plastic deformation, rather than uniform plastic deformation (elongation). The balance between work hardening and mechanical properties can be found through experiments. Due to the plastic deformation caused during the forming process, the hardness of cold forged parts increases. Hardness affects the forgeability of parts and their mechanical properties during usage. In this study, a method was proposed to optimize the shape of the preform and the mold to minimize the variation in hardness distribution. This method can be applied to reverse extrusion. A finite element model of the mechanical behavior of materials during processing was developed to predict the effective strain distribution in the parts. The hardness distribution was determined using the analytical relationship between effective strain and hardness [15].

In 2003, Wan-Jun Cheng [16] systematically analyzed the causes of cold forging fracture, proposed a method to improve the quality of cold forgings, and studied the ultimate strain of upsetting under different heat treatment states. Considering the important property of hydrostatic stress components in restraining the toughness fracture of materials, a fracture criterion for cold forging materials was proposed from the perspective of energy. The experimental verification results show that the criterion can be used for fracture prediction of cold forged metal and as a guide for the compilation of cold forging process and the adjustment of the mold.

In 2012, Xian-Ming Zhang [17] introduced the types, selection principles, process performance and selection requirements of cold forging mold materials, which acts as a guide for engineers and technicians engaged in the design and manufacture of cold forging molds.

In 2011, De-Jun Kong [18] analyzed the application of cold forging parts in the automotive industry, introduced the structure and application of prestressed combined molds and prestressed strip-wound molds, summarized the materials of cold forging molds, and elaborated the development trend of cold forging molds by analyzing the current status of cold forging mold design and manufacturing worldwide.

In 2018, Juliana Zottis et al. [19] proposed experiments based on hardness measurement and application of numerical analysis methods, for strain distribution evaluation and mechanical properties of tensile products. Additionally, the influence of mold misalignment and non-uniform friction was considered in the finite element simulation, to determine the influence, hardness and residual stress distribution after drawing. Furthermore, by using available equations from the literature, once the flow stress is determined, the possibility of predicting hardness of the effective plastic strain can be explored. These two methods are used to calculate hardness distribution of strain simulation values during cold drawing. Microhardness values measured from the experiments of cold-drawn bars showed a good correlation.

While the aforementioned literature explored the relationship between hardness and stress, but they did not specifically examine the relationship between forging deformation rate and hardness in cold, warm, and hot forging. The Key Lock part tested in this paper has characteristics such as hollowness, narrow grooves, and densely packed teeth, resulting in restricted material flow paths and uneven internal stress distribution of the part. Cold forging must overcome the load of the mold, while hot forging is more difficult to control in terms of dimensions, especially the part tested in this experiment comes with teeth features.

III. Experiment Structure

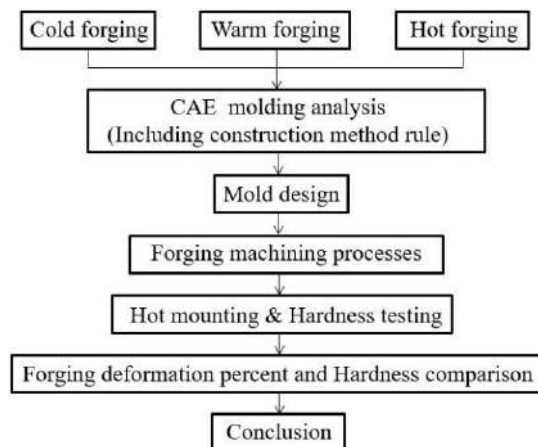


Figure 3. Experiment flowchart

The material used in this experiment was SCM415 low-carbon chromium-molybdenum alloy structural steel, a commonly used steel with a wide range of applications. Its characteristics include extremely high wear resistance after surface carburizing treatment, while the central part maintains high toughness to withstand impact loads. It is suitable for parts requiring high toughness and wear resistance. The main compositions and mechanical properties are shown in Table 2.

Table 2. SCM415 Main compositions and mechanical properties

MAIN COMPONENTS								
C	Si	Mn	S	P	Ni	Cr	Mo	Cu
0.13~0.18 %	0.15~0.35 %	0.6~0.85 %	≤0.03 %	≤0.03 %	≤0.25 %	0.9~1.2 %	0.15~0.3 %	≤0.3 %
MECHANICAL PROPERTY								
Tensile Strength	Yield Strength	Elongation		Reduction of Area		Hardness		
> 830 N/mm ²	--	> 16%		> 40%		235~321HB		

3.1 Material Pretreatment

Before the experiment, the material must go through spheroidizing annealing, phosphate coating, and saponification. Spheroidizing annealing reduces the material's hardness and other mechanical properties, while also reducing forging impact and increasing mold life. Phosphate coating and saponification improve the material's ductility and create a lubricating layer on the surface. During forging, the material is shaped by a strong impact force, generating high friction with the mold surface, while temperature rises rapidly. Therefore, lubrication is crucial to the quality of the forged product, especially during cold or warm forging. Using phosphate coating and saponification reduces metal flow resistance and deformation load. It also controls surface quality and ensures uniform fluidity of the metal surface, reducing the occurrence of workpiece sticking. Lastly it decreases surface friction between the material and the mold, this allows for smoother demolding and extends mold life.

3.2 Experiment Equipment

The equipment used in this experiment was a vertical 650T forging machine, the specifications of which are shown in Figure 4. The hardness testing machine is shown in Figure 5, and the measured values are expressed using the Vickers hardness test (HV).



Figure 4. Vertical 650T Forging Machine and Specification



Figure 5. Hardness Testing Machine

3.3 CAE Simulation Analysis Software

This paper uses Deform-3D as the CAE simulation software for the finite element method. Deform-3D is a finite element system based on processing simulation, an ideal tool for simulating 3D material flow and easy to use. It has a powerful simulation engine capable of analyzing the coupled large deformations and thermal characteristics of multiple related objects during metal forming process, providing comprehensive analytical

data, including material and temperature flow during the forming process. Deform-3D has a variety of applications, including forging, extrusion, rolling, free forging, shearing, bending, and other forming processes.

3.4 Method Planning

After CAE simulation analysis, and considered factors such as mold cost, mold design restrictions, mold load, equipment ejection specifications, low forming stress, and the capable forging tonnage of the equipment, the forging process is shown in Figure 6.

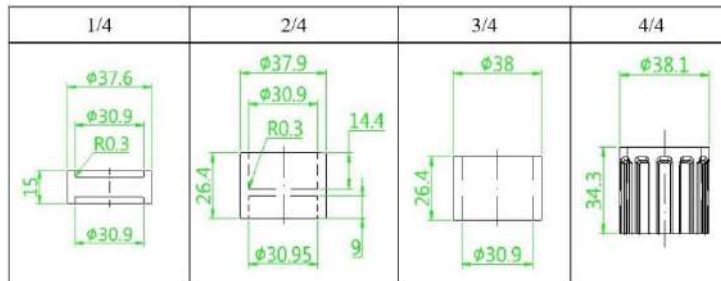


Figure 6. Method planning

Figure 6 shows the cold forging process. However, thermal expansion of the raw materials must be considered for hot forging. The mold heats up as well, therefore the thermal expansion of the mold must also be calculated to avoid the forged part from becoming too large or too small after cooling. The hot forging temperature in this experiment was approximately 900°C, the warm forging temperature was approximately 500°C, and the cold forging was carried out at room temperature. The expansion coefficient of the experimental material SCM415 was $11\sim 22 \times 10^{-6}/^{\circ}\text{C}$ (depending on the processing temperature), and the expansion coefficient of the mold material SKD61 was $10.5\sim 13 \times 10^{-6}/^{\circ}\text{C}$ (depending on the processing temperature). The shrinkage rate of the forging was calculated as shown in formula (1).

$$\text{Shrinkage Rate} = (\alpha_f \times \Delta T_f) - (\alpha_d \times \Delta T_d) \quad (1)$$

α_f = Coefficient of thermal expansion of experimental material SCM415 = $22 \times 10^{-6}/^{\circ}\text{C}$ (900°C)
 α_d = Coefficient of thermal expansion of mold material SKD61 = $13 \times 10^{-6}/^{\circ}\text{C}$ (900°C)
 ΔT_f = 900°C - 25°C = 875°C
 ΔT_d = 250°C - 25°C = 225°C
 $\text{Shrinkage Rate} = [(22 \times 10^{-6})(875)] - [(13 \times 10^{-6})(225)] = 0.01925 - 0.002925 = 0.016325 \quad (2)$

Assume the mold dimension is designed to fit the final product, when a forged part cools down to 25°C from 900°C during the forging process, due to contraction the final forged part will be smaller than the original design. Therefore, expansion is required to be added during mold design. So that a 900°C material is forged in an enlarged mold, and when the forged part cools down to 25°C, it will be the desired product dimension. Additionally, mold is heated up to about 250°C normally, so the mold will increase in dimension due to expansion. This increased dimension of the mold will also increase the dimension of the 900°C forged part, so will the dimension of the forged part when cooled to 25°C. Which leads to difficult shaping afterwards or increased processing time. Thus, the thermal expansion of the mold must be removed when designing the mold. As can be seen from formula (2), the mold design size for hot forging should be increased by about 1.6%.

IV. Results and Discussion



Figure 7. Key Lock -1



Figure 7. Key Lock -2

The deformation rate of forging is defined by simulating the deformation of each pass using CAE (as shown in Figure 6). The forming load of the equipment for each pass and the three forging methods is shown in Table 2. Several key trends and characteristics can be seen from Table 2:

1. From the 4 passes data, it can be observed that in the same pass, the lower processing temperature, the higher the forging force required. This is consistent with the physical properties of metals having better plasticity and low strength at higher temperatures.
2. The passes with larger deformation, the forging force is also greater. This means that the force must be increased to form the shape in passes with greater plastic deformation. Therefore, passes with greater forging force also exert a greater force on the mold. Thus, in mass production, for passes with larger forging forces, the mold must be made with a more durable material and surface treatment to avoid a short mold life. Additionally, more lubricant must be applied during the forging process of the pass.
3. The fourth pass represents the final forming or finishing stage of the product, which requires an enormous force to fill the mold or reach the final size. Therefore, the forging force is the highest among all passes. However, during hot forging, due to the thermal expansion and contraction of raw materials and molds, formula (1) must be used to calculate the shrinkage rate of the forged part to ensure the dimensional accuracy of hot forging.

Table 3. Deformation and Equipment Forming Load

Stage	Deformation Rate	Cold Forging Forming Load (kN)	Warm Forging Forming Load (kN)	Hot Forging Forming Load (kN)
Stage-1	12 %	890	842	261
Stage-2	30 %	1140	972	418
Stage-3	7 %	620	599	162
Stage-4	51 %	2872	2787	2006

The positions for hardness testing of the forged parts and the three forging methods are shown in figure 9. After steps like cutting, cold mounting, grinding and polishing, hardness testing is then carried out. The hardness test values are shown in Table 3.

Table 3. Hardness test value

Hardness (HV)			
	Cold Forging	Warm Forging	Hot Forging
A1	318.75	288.85	214.55
A2	314.37	273.26	198.63
A3	332.69	279.84	203.22
B1	344.88	296.52	225.44
B2	332.77	309.16	225.63
B3	345.46	304.71	220.77
C1	385.74	356.33	249.62
C2	386.24	360.14	254.26
C3	378.53	353.49	262.35
Average	348.83	313.59	228.27

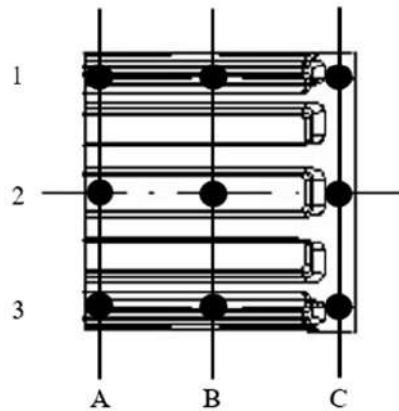


Figure 9. Hardness test position

Under the same deformation rate, the hardness of cold forging results the highest. It can be seen from figure 10 that the forming load of cold forging is higher than other forging methods as well. Increased intensity of metal processing will lead to work hardening, and the increase of strain hardening, strength, tensile strength, and yield strength will result in increased deformation resistance, causing higher required forging deformation load. In contrast, hot processed metals soften due to recovery and recrystallization during deformation, thus requiring less processing load per unit volume compared to cold processing. Figure 11 also shows that, at the same forging deformation rate, the hardness of the three forging methods is directly proportional to the forming load.

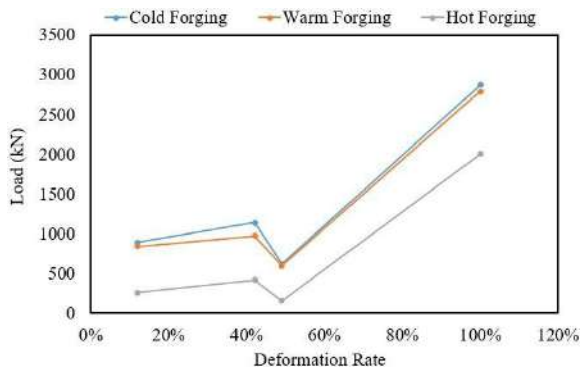


Figure 10. Deformation Rate and Forming Load

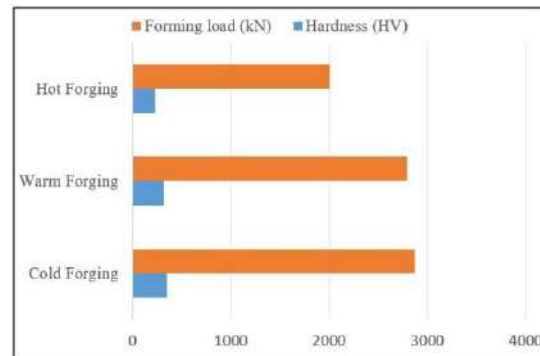


Figure 11. Hardness and Forming Load

Figure 12-14 shows the metallographic analysis of three forging methods. The experimental results show that the metal material flows uniformly and the forging flow lines are smoothly distributed. No defects such as misalignment or folding were observed, indicating that the CAE simulation of each pass is appropriate. If there are defects in the forging flow lines, the product may fracture at the defect after long-term usage. It can be seen that the material structure is more compact after extrusion, thereby improving the mechanical properties.

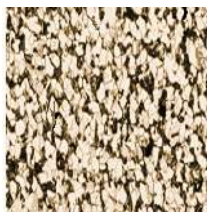


Figure 12. Cold Forging Metallography (× 200)

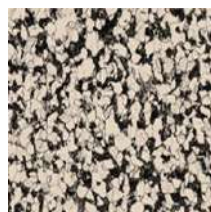


Figure 13. Warm Forging Metallography (× 200)



Figure 14. Hot Forging Metallography (× 200)



V.. Conclusion

The product tested in this paper has characteristics such as hollowness, narrow grooves, and densely packed teeth, which restrict the material flow path and cause internal uneven stress distribution, making forging highly challenging. This paper compares three forging methods through actual die-cutting and analyzes the forging deformation rate, processing load, and hardness. Providing manufacturers a reference for selecting the appropriate forging method according to cost, hardness, and strength. Each of the three forging methods has its own advantages and disadvantages. This paper has value in promotion and application for practical development.

1. The hardness of part A is greater than that of part B, and part B is greater than that of part C. It is determined that the deformation and forming load are greatest at part A, which is consistent with the trend of CAE simulation results.
2. The effect of different forging deformation rates on hardness can be seen from the experimental results. It shows that regardless of whether it is cold forging, warm forging or hot forging, the higher the forging deformation rate, the higher the hardness.
3. Regardless of the forging method, the hardness of the forging is directly proportional to the forming load.
4. From the 4 passes data, it can be observed that in the same pass, the lower processing temperature, the higher the forging force required. This is consistent with the physical properties of metals having better plasticity and low strength at higher temperatures.
5. The changes in the metallographic structure of the material before and after forming are observed through an optical microscope. And it can be seen that the grains were coarsest after hot forging, followed by those after warm forging, and the grains were finest after cold forging, which was consistent with the results of CAE simulation of forging flow lines.
6. The passes with larger deformation, the forging force is also greater. This means that the force must be increased to form the shape in passes with greater plastic deformation. Therefore, passes with greater forging force also exert a greater force on the mold. Thus, in mass production, for passes with larger forging forces, the mold must be made with a more durable material and surface treatment to avoid a short mold life. Additionally, more lubricant must be applied during the forging process of the pass.
7. In cold forging, it can achieve higher hardness and strength, but position of stress concentration must still be considered to prevent excessive deformation. Which may cause the phosphate coating on the surface of the material to wear down, potentially leading to defects like fracture or overflow of the forged part, as well as wearing out the mold or reducing its life.

VI. Conflict of Interest: The authors declare that they have no conflicts of interest.

VII. Grant/Funding: The authors received no financial support or funding for the research, authorship, and/or publication of this article.

References

1. ASM International, Forming and Forging, 9th Edition Metals Handbook, 14th ed. USA;1998.
2. ZHANG, Ying-jian, HUI, Wei-jun, DONG, Han, Hot Forging Simulation Analysis and Application of Microalloyed Steel Crankshaft, *Journal of Iron and Steel Research* 2007;14:5:189-194.
3. Wu Shichun, Warm forging of stainless steels, *Journal of Mechanical Working Technology* 1982;6:4:333-345.
4. A. Behren and H. Just, Extension of the forming limits in cold and warm forging by the FE based fracture analysis with the untegrated damage model of effective stresses, *Journal of Materials Processing Technology* 2002;125:126:235-241.
5. ASM: Metals Handbook, ninth ed., Heat Treating, ASM International, Metals Park, OH;1981.
6. J. Walters, W. T. Wu, A. Arvind, G. Li, D. Lambert and J. Tang, "Recent development of process simulation for industrial applications," *Journal of Materials Processing Technology* 2000; 98:205-211.
7. Website : <https://www.jtekt.co.jp/e/>
8. Dong-Kyun Min, Min-Eung Kim, A study on precision cold forging process improvements for the steering yoke of automobiles by the rigid-plastic finite-element method, *Journal of Materials Processing Technology* 2003;138:339-342.
9. Mahendra G. Rathi, Nilesh A. Jakhade, An Overview of Forging Processes with Their Defects, *International Journal of Scientific and Research Publications* 2014;4:6:1-7.
10. Quang-Cheng Hsu, Rong-Shean Lee, Cold forging process design based on the induction of analytical knowledge, *Journal of Materials Processing Technology* 1997;69:1-3:264-272.
11. ZHANG, Ying-jian, HUI, Wei-jun, DONG, Han, Hot Forging Simulation Analysis and Application of Microalloyed Steel Crankshaft, *Journal of Iron and Steel Research* 2007;14:5:189-194.
12. Wu Shichun, Warm forging of stainless steels, *Journal of Mechanical Working Technology* 1982;6:4:333-345.



13. F. T. Mahi, D. Schmoekkel, Metal Forming (Warm): Comparison with Hot and Cold Forming, *Encyclopedia of Materials: Science and Technology (Second Edition)* 2001;5437-5438.
14. Deke Shi, Yi Xiong, Effect of Work Hardening of Materials on Fracture, *Ordinance Material Science and Engineering* 1990:1-4.
15. Haluk Tumer, Fazil O. Sonmez, Optimum shape design of die and perform for improved hardness distribution in cold forged parts, *Journal of Materials Processing Technology* 2009;209:3:1538-1549.
16. Cheng Wanjun, Huang Liangju, Liu Huàmin, Predication of Cracking of Metal Cold Forging, *Automobile Technology* 2003;11:27-28.
17. Zhang Xian-Ming, Development and Application of Cold Forging Die Materials, *Die & Mould* 2012.
18. Kong Dejun, Wang Qiang, Cai Dongmei, Chen Kongjun, Status and Development of the Cold Forging Die, *Journal of Netshape Forming Engineering* 2001;3;1:46-51.
19. Juliana Zottis, Carla Adriana Theis Soares Diehl, Alexandre da Silva Rocha, Evaluation of experimentally observed asymmetric distributions of hardness strain and residual stress in cold drawn bars by FEM-simulation, *Journal of Materials Research and Technology* 2018;7:4:469-478.