

EXPERIMENTAL STUDY ON TOOL LIFE OF COLD FORGING
TOOLS MADE OF HIGH SPEED STEEL AND INVESTIGATION
OF TOOL LIFE IMPROVEMENT

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TABLE OF CONTENTS

Abstract

Chapter 1: Introduction	1
1.1. Research background.....	1
1.2. Research objectives.....	5
1.3. Structure of present thesis.....	5
References.....	7
 Chapter 2: Literature review	9
2.1. Forging.....	9
2.2. Cold forging tool material and new trends.....	11
2.3. Residual stress.....	13
2.4. Surface roughness.....	14
2.5. Lubrication systems use in cold forging.....	16
2.6. Surface treatments use for cold forging tools.....	18
2.7. Fatigue.....	22
References.....	25
 Chapter 3: Effect of lubrication and forging load on surface roughness, residual stress and deformation of cold forging tools	30
3.1. Introduction.....	30
3.2. Experimental procedure.....	30
3.2.1. Material, specimen preparation and lubricant.....	30
3.2.2. Experimental setup.....	32
3.2.3. Measurements.....	33
3.3. Results and discussion.....	34
3.3.1. Working surface and surface roughness.....	34
3.3.2. Residual stress.....	38
3.3.3. Deformation of specimens.....	39
3.3.4. Interrelation among evaluated parameters.....	43
3.4. Summary.....	49
References.....	50

Chapter 4: Effect of forging contact pressure applied to tool surface on fatigue life of high speed tool steel	51
4.1. Introduction	51
4.2. Experimental procedure	52
4.2.1. Testing materials and specimen preparation	52
4.2.2. Forging setup	53
4.2.3. Tensile and fatigue tests	55
4.2.4. Measurements	56
4.3. Results and discussion	57
4.3.1. Forging test	57
4.3.2. Tensile test	62
4.3.3. Fatigue test	64
4.4. Summary	68
References	69

Chapter 5: Effect of post-treatment polishing on fatigue life of precision shotpeened and micro-abrasive blasted high speed tool steel	70
5.1. Introduction	70
5.2. Experimental procedure	71
5.2.1. Testing materials and specimen preparation	71
5.2.2. Surface treatment and polishing	72
5.2.3. Tensile and fatigue tests	73
5.2.4. Measurements	74
5.3. Results and discussion	75
5.3.1. Specimen surface condition and surface roughness	75
5.3.2. Residual stress	79
5.3.3. Tensile strength and fatigue life	81
5.3.4. Relationship between surface roughness and residual stress with tensile strength	85
5.3.5. Relationship between surface roughness and residual stress with fatigue life	87
5.3.6. Cost efficiency of post-treatment polishing	89
5.4. Summary	94

References.....	95
Chapter 6: Conclusions	96
List of publications	98
Acknowledgements	100

ABSTRACT

This study discussed on the variation of the parameters (Residual stress, surface roughness, deformation) that affect the tool life of cold forging tools under different forging conditions, the effect of those parameter variations on fatigue life of tool steel and method to improve the fatigue life of tool steel.

The material used in this study was JIS SKH51 (AISI M2; DIN 1.3343), molybdenum based high-speed steel (HSS), which is commonly used in cold forging tool manufacturing. SKH51 is a tool steel that can achieve a high hardness of over 60 HRC and high compressive strength over 3000 MPa.

A specimen made of heat treated SKH51 (59-61 HRC) with a polished working surface was used as a punch for cold forging upsetting process. Cold forging upsetting process was carried out under 'with lubrication' and 'without lubrication' conditions with two different forging loads using low carbon steel SPCC sheet as the counter face. The forging loads were set to 150 kN and to 180 kN, which corresponded to contact pressure of 1910 MPa and 2290 MPa, respectively. A great influence of forging condition on the variation in surface compressive residual stress, surface roughness, and tool deformation during forging operation was observed. Surface compressive residual stress showed a positive relationship with the forging load for both lubrication conditions. The presence of lubricant in the forging process reduced the increase in compressive residual stress. A uniform variation of compressive residual stress on the working surface was not observed for higher forging load. Surface roughness was also showed a positive relationship with forging load for both lubrication conditions, and at high forging load, even variation of surface roughness on the working surface was not observed. Increase in surface roughness during forging was reduced by the presence of lubrication. A difference in tool deformation behavior and working surface deterioration was observed based on the lubrication condition during forging. The effect of lubrication on tool deformation was largely observed under high forging load. The downward displacement at the center of the punch working surface had a positive relationship with average height reduction. Results showed that both lubrication condition and forging load effect the variation of surface roughness. On the other hand, surface compressive residual stress variation largely depended on the forging load. The effect of the variation in the above parameters on forging tool life and forged part accuracy were discussed.

The magnitude of the contact pressure applied on cold forging tool on fatigue behavior of tool steel was investigated. Rectangular cross-sectioned dog bone shaped specimens made of JIS SKH51 were subjected to cyclic contact pressure by forging operation with three load values. The set load values were 150 kN, 300 kN, and 450 kN, which corresponded to 750 MPa, 1500 MPa, and 2250 MPa of contact pressure on the specimen surface, respectively. Tensile test and axial fatigue test was carried out for forged and unforged specimens. The fatigue test was carried out with minimum stress value of 48 MPa and maximum stress values of 1680 MPa, 1440 MPa, 1200 MPa, and 960 MPa. A positive relationship was observed between the dimensional change,

surface hardness, and the surface compressive residual stress with the contact pressure applied on the surface. No significant correlation was observed between surface roughness and the contact pressure. Furthermore, the tensile strength of the specimens forged with lower and medium contact pressures slightly increased with compared to the unforged specimen while the specimen forged with higher contact pressure slightly decreased. The results of the axial fatigue test showed that fatigue life improved when the specimen was forged with lower and medium contact pressures. Conversely, fatigue life decreased as the specimens forged with high contact pressure. Assuming that all specimens are homogeneous, it can be concluded that, the fatigue life of the tool steel varies depending on the contact pressure applied on tools during the forging process.

Mechanical surface treatments are widely used in cold forging tools to improve the tool life. This study investigated the effect of post-treatment polishing on fatigue life of WPC and micro-abrasive blasting treated tool steel using heat-treated SKH 51. Six types of surface conditions were used for the study. The ground specimens were surface treated with Wonder Process Craft (WPC) and Micro-abrasive blasting (MB). Dimension controlled surface polishing was performed on the ground, WPC, and MB treated specimens. MB treatment showed a higher surface roughness increase compared to WPC treatment, while polishing showed a decrease. Surface treatment increased the surface compressive residual stress. A significant difference was not observed on surface compressive residual stress based on the surface treatment type used. The residual stress variation in depth direction was investigated on ground and surface treated specimens. The maximum compressive residual stress of ground specimen was observed at the surface, while for surface treated specimens 1 μ m below the surface. The polishing on surface treated specimens showed a further increase in compressive residual stress while polishing on ground specimen showed a slight decrease. Surface hardness increase was observed due to surface treatment. Surface treatment and polishing on ground specimen showed a slight improvement in tensile strength. Fatigue life showed an improvement due to surface treatment and polishing on the ground specimen. Furthermore, post-treatment polishing showed a significant improvement in fatigue life for both types of surface treatments. Therefore, post-treatment polishing is recommended after mechanical surface treatment to improve the fatigue life of cold forging tools.

INTRODUCTION

1.1 Research background

Forging is defined as a manufacturing process that working the metal into a desired shape using localized compressive forces. In ancient times, people used forging for making coins, ornaments, weapons, etc. In the present world, forging process plays a major role in industrial metal manufacture, particularly in the extensive iron and steel manufacturing industries. Forging is not limited to iron and steel. Alloys of aluminum, magnesium, copper, titanium, and nickel are listed as other commonly forged metals. Steel forge is often a source of great output and high productivity. Parts produced by forging are stronger than casted or machined parts. Because forging alters the metal's grain structure with respect to the flow of the material during deforming processes and is enable to create favorable grain structure in a material, which increases the strength of forged parts. Therefore, the metal forging process gives distinct advantages to the mechanical properties of work produced. Based on the temperature that the forging process is performed, the forging process can be divided into three categories, hot, warm and cold. Hot forging is performed above re-crystallization temperatures, typically $0.6 T_m$, or above, where T_m is melting temperature of the metal. Warm forging is usually conducted at the temperature range of $0.3 T_m$ to $0.5 T_m$. Finally, cold forging is conducted below $0.3 T_m$, usually at room temperature [1]. There are advantages and disadvantages over each process. The cost of tools and setup increases when moving from hot, warm to cold forging, while the dimension accuracy, surface finish increases and post-forge processing cost decreases.

Cold forging has become one of the most common processes in the mass production of components [2], especially net or near net shape forging products. There are many advantages of cold forging as mentioned above. However, forging tools subject to extreme impact and loading conditions due to the low forming temperature in the cold forging process [3]. The tool life or service life of the forging tool has a tendency to decrease and lead to high tooling costs and reduced efficiency due to frequent tool replacement [4]. Cold forging tools are often subjected to a combination of abrasive wear and very high mechanical loads which create surface pressure up to 3000 MPa caused by high flow stress of billet material at room temperature [4, 5]. This high contact stress has a great effect on two tool damage mechanisms, wear and fatigue. Wear is caused by the combination of high contact stress and accumulation of sliding length and it affects

the accuracy and surface quality of the workpiece [6]. The cyclic loading leads to the fatigue of the tool material. Fatigue cracks appear even at the very early stage and may lead to disruption at the tool surface and thus to a failure of the tool [7].

Since tool cost directly associated with the economy and productivity of forging process, it is essential to optimize the tool life. Tool life can be enhanced by altering several parameters which influence the two damage mechanisms fatigue and wear. The most significant parameter is the type of tool material; this follows by the heat treatment of the tool material, tool layout, manufacturing method, etc... There are improvements in tool materials used for forging tool. Looking back to the history of evolution in tool material, producing of high speed steels started more than 100 years ago. This followed by the introduction of cemented carbides in 1920 and PM (Powder Metallurgy) steels only some decades ago, now this industry is developing materials like super clean PM grades and Nitrogen alloyed steel [8]. However, optimizing the tool life by tool design can be very tedious because in many cases it is still done by trial and error and highly depends on the experience of the tool designer. Therefore, simulation methods based on the finite element method (FEM) is widely use to analyze the forming process and tool loading. It is important to ensure that the material behavior in the simulation reflects the real material behavior and description by an appropriate material model as precisely as possible to achieve the results close to the actual situation by simulation.

The surface condition of the forging tool also greatly affects the tool life. Surface roughness is a component of surface texture and defined as the sum of the surface irregularities in relatively small distances incipient as a result of manufacturing method used in production [9]. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. Surface roughness considered as an important factor in fatigue strength design evaluation [10]. A correct surface polishing procedure and surface roughness level are among the most influential factors for a successful cold forging process with low friction and less cold welding tendencies. This leads to a significant influence on the life of the tools [8]. There are several other methods to improve the surface condition of tools other than the surface polishing. These include mechanical and thermochemical methods [2]. These processes aim to increase hardness, wear resistance and /or fatigue strength and load-bearing capacity of metal by creating a hard layer with compressive residual stress on or near the surface of tools [11]. The surface coating is widely used in cold forging tools to improve the wear resistance [8]. Earlier investigations have confirmed that the most effective and economical means of improving the tool life of mechanical components is to apply thin hard films such as oxide, nitride and carbide

films to the surface to withstand severe operating condition [12]. The selective surface treatment is another method to address the problem where both damage mechanisms, fatigue and wear act concurrently at a different location of forging tool [8]. Processes such as hard roller burnishing, surface heat treatment by laser and surface texturing are common methods of selective surface treatment.

Residual stress can be defined as the stresses existing within a body in the absence of external loading or thermal gradients. In other words, residual stresses in a structural material or component is the stress that exists in the object without the application of any service or other external loads. Residual stresses can occur in any mechanical structure through a variety of mechanisms including plastic deformations, temperature gradients during thermal cycles or structural changes with phase transformation. Residual stress measuring techniques are classified into three main groups, destructive, semi-destructive and non-destructive. The residual stresses generated by tool production and external stresses induced by the forming process have a major effect on tool life in cold forging [13].

Lubrication plays an important role in forging. The objective is to decrease friction and thus lower the deformation forces and increase tool life. Efficient lubricants assist in improving the product quality and tool life by reducing forging load and wear by preventing direct metallic contact between the tool and the workpiece [14]. Due to very high surface expansion and interface temperature, the lubricants used in cold forging are subjected to very severe conditions [15]. If the lubricant used is unable to withstand the conditions mentioned above, it will lead to product defects or tool failure. Different types of lubricant are used in cold forging. The selection of lubrication is based on the parameters such as the metal being formed, the application or process method, requirements of the worked metal before and after the process, etc. The most widely used lubrication system in the cold forging of carbon steels is zinc phosphate coating and soaping system. Other than the above method mineral oil, calcium aluminate coating, oxalate coating, copper coating, etc. are used as lubricants in cold forging. The lubricant type depends on material been forged and forging process [16].

Surface treatments are widely used on steels to improve wear resistance, change the tribological behavior, corrosion resistance, optical behavior, decorative behavior and matched interface behavior while retaining toughness of the core material using mechanical, thermal, chemical and electrochemical processes. A primary need for tool and die manufacturers is to identify the best combination of steel chemical composition together with thermal and surface treatments to achieve the best thermomechanical shock and wear resistance with fulfilling the

industrial need for good quality products and extended tool life [17]. The main aim of using surface treatment in forging tool manufacturing is to increase surface hardness and lowering the friction coefficient by improving tribological behavior. Such treatments should imply a correct balance between hardness and toughness to achieve suitable strength with limited crack susceptibility. Mechanical surface treatment and surface coating are the most common surface treatments used in cold forging tools to improve service life and product quality.

Fatigue is a word originated from the Latin word “fatigare” which gives the meaning “to tire”. Even though this word used to express the physical or mental weariness of people, it is commonly accepted term in engineering when talking about the material or structural failure due to cyclic load [18]. Since there are studies carried out for more than 160 years on fatigue of metals and metal structures, there is a good understanding has been achieved on the metal fatigue mechanisms [19, 20, 21]. The fatigue can be described as the progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fracture after a sufficient number of fluctuations [22]. Fatigue fractures are caused by the simultaneous action of cyclic stress, tensile stress and plastic strain. If anyone of these three is not present fatigue cracking will not initiate and propagate [22]. The nominal maximum stress that causes fatigue fracture may be much less than the strength of the material which is typically calls as ultimate tensile stress or yield stress limit. Factors such as metal microstructure, manufacturing process, component geometry, type of environment, and loading condition influence the fatigue life of material and components. Fatigue life, N_f can be described as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs [19]. The fatigue failure mainly divides into three stages, crack initiation, propagation and final fracture.

Fatigue failure is the major failure mode in the cold forging of complex parts with net shaped surfaces and tool life was forced to be much shorter by fatigue than by wear in the cases of failure [23]. High strength and hardness of tool material along with the requirement of net shape manufacturing limits the plastic deformation in tools. Therefore, high cycle fatigue phenomenon usually takes place [24]. Thermal fatigue failure or thermomechanical fatigue is the result of cyclic heating and cooling of the surface of the die at a temperature of 30-40% of the absolute melting point of the dies material. Furthermore, these thermal stresses are superimposed by the stresses that occur in the body due to applied cyclic external load in forging. In most cases, the fatigue crack initiates at the corners and propagates in the radial direction. Selection of proper tool material, improvements in tool design and manufacturing method, usage of

appropriate heat treatment patterns and surface treatment techniques will improve the fatigue life of forging tools.

1.2 Research objectives

Understanding the tool behavior during forging operations is important to predict the tool life and decide tool life improvement methods. Therefore, studying the in-service variation of parameters affect the tool life was one of the objectives of this research. Furthermore, it is important to understand how the tool behavior effect on the mechanical properties of the tool material to recognize the failure mode and life of the material. Therefore, understanding of behavior of the mechanical properties of high speed tool steel due to conditions change in the forging process, and investigation of tool life improvement methods were other objectives of this study. Following three experiments were done to fulfill the objectives of this research.

1. Effect of forging load and lubrication on residual stress, surface roughness and deformation of forging tools.
2. Effect of forging contact pressure applied to tool surface on fatigue life of high speed tool steel.
3. Effect of post-treatment polishing on fatigue life of precision shotpeened and micro-abrasive blasting treated high speed tool steel.

1.3 Structure of present thesis

Chapter 2 presents a literature review related on the research work done so far on forging tool failure, tool material, the effect of residual stress and surface roughness on forging tool life, lubrication and surface treatment used in cold forging and tool life improve methods.

Chapter 3 discusses the effect of lubrication and forging load on surface roughness, residual stress, and deformation of cold forging tools. Experimental procedure of conducting the upsetting process of the specimens made out of heat treated SKH 51 high-speed tool steel under different forging conditions is explained. The variations of surface roughness, residual stress with the number of forging cycles in different forging conditions are discussed. Furthermore, outer diameter, downward displacement at the center, and height change with the number of forging cycles in different forging conditions are discussed. This is followed by a discussion of the correlation between the above parameters and how these parameters effect on tool life and product quality.

Chapter 4 discusses the effect of the magnitude of the contact pressure applied on cold forging tool on fatigue behavior of tool steel. Experimental procedure of forging of the specimens made of heat treated SKH 51 high-speed tool steel, tensile test, and fatigue test are explained. The variation of surface roughness, residual stress, surface condition, and surface hardness with the magnitude of the contact pressure on specimen surface is discussed. Finally, based on the results of the tensile and fatigue tests done using forged specimens, the effect of the magnitude of contact pressure on tool life is discussed.

Chapter 5 discusses the effect of post-treatment polishing on the fatigue life of surface treated tool steel. This chapter explains on two mechanical surface treatment processes, WPC and micro blasting surface treatments. The experimental procedure of surface treating specimen made of heat treated SKH 51 high-speed tool steel is explained. This is followed by the explanation of tensile and fatigue test procedures. The variation of surface roughness, residual stress and surface hardness with different surface conditions are illustrated. This is followed by the results of tensile and fatigue tests. Finally, the effect of post-treatment polishing on cold forging tool life is discussed base on the tensile and fatigue test results.

Finally, Chapter 6 presents the conclusions drawn from the researches and suggestions for further research.

References

- [1] B. D. Stojanovic, V. V. Skorokhod, M. Nikolic: Advanced Science and Technology of Sintering, Springer, Boston, MA (1999).
- [2] G. H. Farrahi, H. Ghadbeigi: J. Mater. Process. Technol., 174 (2006) 318-324.
- [3] Y. Lee, F. Chen: J. Mater. Process. Technol., 113 (2001) 539-543.
- [4] M. Geiger, M. Arbak, U. Engel: Prod. Eng., 2 (2008) 409-415.
- [5] T. W. Ku, B. S. Kang: Int. J. Adv. Manf. Tech., 74 (2014) 1337-1354.
- [6] H. Wiśniewska-Weinert, V. Leshchynsky, M. Ignatev, J. Borowski, T. Wiśniewski: Tribologia, 5 (2011) 239-248.
- [7] K. Wagner, A. Putz, U. Engel: J. Mater. Process. Technol., 177 (2006) 206-209.
- [8] U. Engel, J. Groenbaek, C. Hinsel, T. Kroiß, M. Meidert, R. Neher, F. Räuchle, T. Schrader: UTFscience, 3 (2011) 1-24.
- [9] STN EN ISO 4287, Geometrical product Specification (GPS). Surface texture: Profile method – Terms, definitions and surface texture parameters (1999).
- [10] G. Deng, K. Nagamoto, Y. Nakano, T. Nakanishi: ICF12 Ottawa (CA), (2009) 1-8.
- [11] T. Bell: ASM Handbook, Heat Treating, ASM Int., Vol. 4, Materials Park, Ohio (1991).
- [12] Y. H. Guu, H. Hocheng: Mater. Sci. Eng. A., 318 (2001) 155-162.
- [13] K. H. Kloos: Z. Werkstofftech, 10 (1979) 293-302.
- [14] C. Caminaga, F. Neves, F. Gentile, S. Button: J. Mater. Process. Technol., 182 (2007) 432-439.
- [15] M. Gariety, G. Ngaile, T. Altan: Int. J. Mach. Tool. Manu., 47 (2007) 673-681.
- [16] T. Altan, G. Ngaile, G. Shen: Cold and Hot Forging: Fundamentals and Applications, ASM Int., Materials Park, Ohio (2005).
- [17] E. Bernqocchi, A. Ferrero, E. Gqriboldi, A. Korovkin, G. Ponlini: Metall. Sci. Technol., 14 (1) (1996) 3-11.
- [18] S. Suresh: Fatigue of Materials, 2nd edition, Cambridge University Press, Cambridge (1998).
- [19] R. I. Stephens, A. Fatemi, R. R. Stephens, H. O. Fuchs: Metal Fatigue in Engineering, John Wiley & Sons, Hoboken (2001).
- [20] W. Schütz: Eng. Fract. Mech., 54(2) (1996) 263-300.
- [21] M. Klesnil, P. Lukaš, H. Saunders: J. Mech. Design., 104(4) (1982) 680-681.
- [22] H. E. Boyer: Atlas of Fatigue Curves, ASM Int., Materials Park, Ohio (1986).
- [23] M. Knoerr, K. Lange, T. Altan: J. Mater. Process. Technol., 46 (1994) 57-71.

[24] M. A. Saroosh, H. C. Lee, Y. T. Im, S. W. Choi, D. L. Lee: J. Mater. Process. Technol., 191 (2007) 178-181.

LITERATURE REVIEW

2.1 Forging

Forging is a manufacturing process which comes under metal forming. Forming is a non-material removal process and defined by DIN 8580 [1] as manufacturing through the three-dimensional or plastic modification of shape while retaining its mass and material cohesion. Metal forming processes are categorized into several groups with respect to forming mechanisms (under compression or/and tensile condition, by bending, under shear condition), part to be formed (sheet, bulk), time-dependency and forming temperature (hot, warm, cold).

Forging defines as the process that a metal work piece is plastically deformed to the desired shape by application of compressive forces, at temperatures ranging from ambient to 1500°C and more [2]. Forging parts can be made from any forgeable metal such as alloys of aluminum, magnesium, copper, titanium, etc. with widely varying sizes and shapes. Products made of forging have a good reputation in the applications where tension, dynamic load, human safety, etc. are critical considerations and in many cases they are irreplaceable [3]. This is mainly due to the good mechanical performances and high reliability of forged components. Steel forge is often a source of high output and productivity. Most parts produced by forging are stronger than casted or machined parts. Because in forging, the metal will also alter the metal's grain structure with respect to the flow of the material during its deformation and this can be used to create favorable grain structure in a material significantly increasing the strength of forged parts. Furthermore, forged product has structural integrity meaning that it has no internal voids and porosity, having uniform mechanical properties and predictable response to heat treatment. Therefore the metal forging process gives distinct advantages in the mechanical properties of work produced.

Forging processes are divided into hot, warm and cold based on the billet temperature. Hot forging is the process where forging temperature is above the material's re-crystallization temperature. The recrystallization temperature defined as the temperature at which the new grains are formed in the metal. Warm forging is the process where forging temperature is below the material's re-crystallization temperature, but above 30% of the re-crystallization temperature. Warm forging has the combined advantage and disadvantages of cold and hot forging. The third category, cold forging, is where the forging temperature is below 30% of the re-crystallization

temperature (usually room temperature). Cold forging has become one of the most common processes in the mass production of components, especially in the net or near net shape forging products [4]. The process not only changes the shape but also improves the properties of the forged parts due to grain size refinement. Throughout history, cold forging or cold forming as a production process, seen a rising interest and become one of the most widely used methods of making parts. Cold forged parts are widely used in automotive, appliance, aerospace and construction industries. Work hardening, also called strain hardening, occurs during cold forming due to dislocations in the metallic crystal structure. A large amount of force is needed and sometimes multiple operations are required to achieve more complex shapes. With proper lubrication, however, tool life is significantly increased with compared to hot or warm forging. As additional advantages, mechanical properties of forged materials are greatly improved, the grain structure becomes stronger, many repetitions of hardening by heat treatment are not necessary due to the work hardening that occurs during the forging process and both ferrous and non-ferrous metals can be cold forged. Materials that can be cold forged include, but are not limited to carbon steel, brass, stainless steel aluminum nickel alloys, etc. The ability to forge these metals and the amount of possible deformation depends greatly on the chemical composition and annealed properties. Furthermore, properties such as hardness and ductility are critical properties in determining the formability of a metal.

The technical and social demand for the use of light metal and load adapted structure concepts have boomed to limit the use of scarce fossil energy and to be environmentally friendly. The interest in using downsized and weight reduced components, especially in automobile and aircraft industries leads to develop innovative materials and process technologies. To be competitive and profitable, forging industry should also address the technological issues include materials, die design and modeling, lubrication, process modeling and optimization software, process controls and sensors, real-time preventative maintenance, and primary and secondary processing equipment.

In metal forming, the research can be divided into three main categories, die design, process planning, and product performance. The researchers are taking the advantages of computer advancements to integrate CAD/CAM in the design of optimal tooling, FE capabilities and some of the others integrated with Rapid Prototyping (RP) in demonstrating and evaluating the forging process [5]. Bambach [6] stated that the current challenges and trends of metal forming could be summarized to three categories as forming of alloys with low workability, scale-independent individualization and cyber-physical systems. Furthermore, the trend to

introduce the smart tooling in the forming process will give an advantage to production. Smart tools are new forming tool concept proposed by Qin [7] which focused on reducing pressure, extending tool life, improve the part quality and enhance the flexibility of the tooling system. Studies have been carried out on compensate forging tool deformation during operation in tool design to achieve better tool life and product quality. Del Pozo et al. [8] studied the die deflection during the pressing process. They proposed a methodology for the accurate manufacturing of drawing dies based on the prediction of press/die deformation during operation. They stated that with their methodology the manual adjustment time and hand polishing time can be reduced by 30%. Rosochowski [9] proposed a design procedure for cold forming tools by taking into account the component spring back and die deflection during forming, mainly for the net shape forming process. Not only in the tooling side but also in lubricants used for forging shows new trends to improve the performance and minimize the environmental damage. Tsuchiya [10] stated that the invention of short-time conversion coating and development of a water-soluble lubricant enable retreatment midway through the process and reduce the cost. Furthermore, he explains different environment-friendly lubricants tested using ice and frost generated from the cooling of the die and lubricant that uses water with suspended wheat flour for forming titanium and stainless steel sheets.

Net-shape forging of complex parts such as helical gears, helical-tooth pinions, etc. requires new concepts in press and tooling design with consideration of a multitude of interacting variables. In order to increase the accuracy of the product and to extend the service life of the tools, press builders have developed different types of advance press machines, such as multi-slide and multi-action hydraulic press machines, multi-slide forging press machines, multi-action forming press machines and servo motor press machines [11].

2.2 Cold forging tool material and new trends

There are many types of tools used in forging processes and each tool has its role in the process. Even though similar types of tools are used in different forging processes, the properties and characteristic are different in each tool. Optimizing tool life is important because tool cost directly associated to the economy and productivity of the process. Tool life can be enhanced by altering several parameters which influence the two damage mechanisms, fatigue, and wear. The most significant parameter is the type of tool material; this will be followed by the heat treatment of the tool material, tool layout, manufacturing method, etc... The tool material for the forging

tools should be selected considering the abrasive wear, mechanical fatigue, thermal fatigue, and plastic deformation occurred in each forging process. Tool steels have been available since the turn of the nineteenth century, and are still the mainstay of tool materials. They are alloys of iron and carbon with additions of elements such as chromium, tungsten, molybdenum, titanium, and vanadium. These elements improve the properties of the steel and the response to heat treatment.

The success of the cold forging process depends on two main criteria, i.e., the selection of tool material and die design [12]. Therefore, tool material which has a significant impact on forging tool life has shown great improvements in recent years. Looking back from the history, starting with High Speed Steel (HSS) more than 100 years ago, with the introduction of cemented carbides in 1920 and PM steels only some decades ago, now this industry is developing materials like super clean PM grades and Nitrogen alloyed steel [13]. Recent improvements of the production process of the powder and sintering process itself have led to a homogeneous distribution of carbides with an increase in size and reduction of number and size of non-metallic inclusions [14]. Since carbide clusters and non-metallic inclusions are possible crack initiation site in PM steel, which causes fatigue fracture of tool later on during its life, any countermeasure against these will improve the fatigue resistance of material [15].

Cemented carbides are materials made by "cementing" very hard mono-carbide (WC) grains in a binder matrix of a tough alloy by liquid phase sintering. There is a trend of using carbides in forging tools due to its outstanding feature of withstanding for wear resistance, deformation, impact, heavy load, high pressure, corrosion, and high temperature. There are different researches undergo to find new main starting material to improve the material properties of cemented carbide. Kitamura et al. [16] have done a study on using $\text{Co}_3\text{W}_9\text{C}_4(\text{k})$ and $\text{Co}_2\text{W}_4\text{C}(\theta)$ as the main starting material instead of Tungsten carbide(WC). They have found out that the fracture toughness was increased by 10-15% than that of the conventional alloy at identical hardness, while the transverse-rupture strength was comparable with that of the conventional alloy.

New tool material for cold forging applications was developed using numerical simulation techniques (FEM) for the design and a powder metallurgical route (HIP) for the production. Based on the idea of finding an optimize microstructure of the two-phase material by simulating different distributions of hard particles within the metal matrix, Berns et al. [17] developed a double dispersive material. Wear resistance and bending strength of the new material is similar to standard dispersion material with the same volume fraction of particles, but fracture toughness is increased by about 30%.

There was a study done by Yurtdas et al. [18] where carbon fiber composite was used as the die material. They have used carbon fiber composite in the stress ring of the cold forging die instead of conventional tool steel to create high compressive stress on the die insert surface. Fiber reinforced polymer matrix composites are mostly used in engineering applications due to their excellent mechanical properties, high energy absorption capacity, fatigue strength, corrosion resistance, and high rigidity. The results of their study show that the tool life of the die varies base on the type of carbon fiber used as a stress ring when compared with results of conventional steel. However, the cost of manufacturing die will be increased when using carbon fiber.

2.3 Residual stress

Residual stress is the stress that exists within a material without application of an external load [19], or it can be described as the stress which remains in a stationary body at equilibrium with its surroundings. Practically, residual stresses can generate in a material during every step of processing. The origins of residual stresses in a component can be classified as mechanical, thermal, and chemical. Mechanically generated residual stresses are often a result of manufacturing processes that produce non-uniform plastic deformation. They may develop naturally during processing or treatment or may be introduced purposefully to produce a particular stress profile in a component. Thermally generated residual stresses are often the result of non-uniform heating or cooling operations. The chemically generated stresses can develop due to volume changes associated with chemical reactions, precipitation, or phase transformation. Chemical surface treatments and coatings can lead to the generation of significant residual stress gradients in the surface layers of the component. In general, compressive residual stress on the surface of a component is beneficial. It tends to increase fatigue life, slow crack propagation, and increase resistance to environmentally assisted cracking such as stress corrosion cracking and hydrogen induced cracking. Tensile residual stress in the surface of the component is generally undesirable as it decreases fatigue life, increases crack propagation and decreases resistance to environmentally assist cracking.

In cold forging, the interaction of residual stresses caused by tool machining and external stresses induced by the forming process has a significant influence on the limits of tool life [20]. Therefore measuring the residual stress in forging tools and take necessary actions is important to improve the tool life. Researches have used different measuring method to study the

residual stress states in forging tools. Ruud [21] discussed on non-destructive methods for residual stress measurement. He has reviewed the X-ray diffraction method, ultrasonic velocity method, and Barkhausen noise analysis as ways of measuring the residual stress of the material. Toumi et al., [22] had used synchrotron X-ray diffraction method to analyze the residual stress of stellite coated forging tool steel.

Compressive stresses have a positive impact on tool life [23]. Therefore, machining processes which induce compressive residual stresses are preferred when manufacturing forging tools. Grinding, EDM process, hard machining, polishing are some of the processes used in the final stages of forging tool manufacturing process. Czan et al. [24] have analyzed the residual stress of in subsurface layers after precision hard machining of forging tools by X-ray diffraction method and the residual stress had compressive character. Furthermore, Merklein et al. [25] studied about the influence of machining process on residual stresses in the surface of cemented carbides which is commonly used material for die inserts in forging tools. The results showed that electrical discharge machining (EDM) process induces tensile stresses in the top layer, while grinding is accompanied by compressive stresses. Additionally, they found that surface compressive stresses for grinding followed by polishing are higher than for EDM followed by polishing.

Different surface treatment methods are used in forging tool manufacturing to increase the compressive residual stress of the forging tool to improve the fatigue life of the tool. Such treatments are used to reinforce the work piece surface layer which is often subjected to the highest loading. Reinforcement is achieved by local plastic deformation of near-surface areas which leads to compressive residual stresses and work hardening. Shot peening, deep rolling, micro blasting, fine particle peening, etc. are some mechanical surface treatment processes used to increase the compressive residual stresses in forging tools.

2.4 Surface roughness

Surface topography is the local deviations of a surface from a perfectly flat plane. Surface roughness is the texture of an optical surface on a microscopic scale, as opposed to flatness, power, and irregularity which all relate to large scale (macroscopic) surface shape. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, it is defined as a rough surface; on the other hand, if the deviations are small, it is defined as a smooth surface. Roughness parameters can be calculated

in either two dimensional (2D) or three dimensional (3D) forms. Even though there are advancements in the 3D surface analysis recently, 2D profile analysis has still been widely used in science and engineering fields.

Surface roughness measurement parameters are broadly classified into four sub-groups, amplitude (height) parameters, spacing parameters, hybrid parameters, statistical analysis. Gadelmawla et al. [26] and Marteau et al. [27] stated that the arithmetic average height parameter (R_a) is the most widely used parameter for describing surface roughness, which is easy to define, easy to measure and gives a good general description of height variations. Mechanical profiler is the most common and traditional method of measuring surface roughness and it works by utilizing a micro-scale stylus to traverse across the metal surface to record the average roughness amplitude, R_a provides an indication of the peak to trough variation in “height” between adjacent topological features.

Surface roughness plays a significant role in forging for tool service life and forged product quality. Polishing and fine grinding are used as the final process in forging tool manufacturing to reduce the surface roughness of the working surfaces of the forging tools. Fatigue is one of the primary failure modes of forging tools due to cyclic load subjected during continues forging process. Ardi et al. [28] stated that a crude relationship between surface roughness and fatigue performance has long been recognized and in the absence of inherent defects such as inclusions or porosity, crack initiation mechanisms under cyclic loading will be dominated by plasticity concentrated around surface features. Obiukwu et al. [29] state that the surface finish parameters have a significant correlation between fatigue initiation life, final separation life, and the fatigue endurance limit. Lai et al. [30] studied on the effect of the microstructure and surface roughness of the fatigue strength of high strength steel. They found that in low cycle fatigue range the failure is dominated by the surface initiated fatigue fracture and in high cycle rage it is subsurface initiated fatigue failure. High cycle fatigue (HCF) phenomenon usually takes place in cold forging tool fatigue failure due to high strength and hardness of tool material used for cold forging tools along with the requirement of net shape manufacturing limits the chances of plastic deformation in tools [31]. When the applied stress levels are low to create bulk plastic yielding, surface roughness controls the fatigue endurance strength under high cycle fatigue (HCF) conditions [32]. Higher surface roughness in the forging tool will increase the friction between tool and workpiece. Negative impacts of high friction are among others energy dissipative effects, increased energy consumption and a reduced tool life due to increased wear and forming forces. Therefore, it is very important to control the surface

roughness of forging tools to create a negative impact on fatigue and wear failure to get an extended tool life. The effect of the roughness on the wear of cold forming tools was investigated while using punch made of AISI M2 hardened steel by Souza et al. [33]. The study showed that different tool regions have different types of wear and that the punches with high surface roughness were prematurely broken. Furthermore, they stated that these faults in punches were related to the initial topography of the tools. Syahrullail et al. [34] studied the effect of tool surface roughness on a cold extrusion process. They concluded that higher surface roughness increases the extrusion load and affects the material flow.

2.5 Lubrication systems use in cold forging

Lubrication plays a significant role in metal forming processes. Efficient lubricants assist in improving the product quality and tool life by reducing forging load and wear by preventing direct metallic contact between the tool and the workpiece [35]. The lubricants in metal forming are usually selected based on several factors such as the ability to retard corrosion, easy to apply and remove, lack of toxicity or odor, adaptability over a useful range of pressure, temperature and velocity, surface wetting characteristics, cost, and availability [36].

Due to very high surface expansion and interface temperature, the lubricant used in cold forging subjected to very severe conditions [37]. If the lubricant used is unable to withstand the conditions mentioned above, it will lead to product defects or tool failure. Different types of lubricant are used in cold forging. The selection of lubrication is based on the parameters such as the metal being formed, the application or process method, requirements of the worked metal before and after the process, etc. The most widely used lubrication system in the cold forging of carbon steels is zinc phosphate coating and soaping system. Other than the above method, mineral oil, calcium aluminate coating, oxalate coating, copper coating, etc. are used as lubricants in cold forging depending on the material been forged and forging process [38].

The zinc crystalline phosphatization associated to soap or MoS_2 lubricant significantly improves the friction conditions at the tool-workpiece interface [40]. However, this lubrication system requires many complex and costly production steps and has a high impact on the environment. The zinc phosphate is applied to the workpiece in many baths with different temperatures. Hence, much energy is necessary. Additionally, the waste of the baths is much worse, because it is contaminated with heavy metal sludge [41, 42]. With the global demand for the environmental friendly, energy serving and effective lubricants, many new approaches for the

lubrication in cold forging are introduced. The new methods can be divided into the following groups [43].

- New conversion coatings
 - Electrolytic phosphate coating
 - Microporous coating
- Lubrication without conversion coating
 - Single bath systems
 - Dual bath systems

Electrolytic phosphating eliminates many drawbacks of conventional zinc phosphate coating. This method enables to obtain a sludge free phosphating bath. Furthermore, the use of acid for pickling is avoided by electrochemical pickling, the treatment time is considerably shortened, and working environment is improved and makes it possible to phosphate high alloyed steels and stainless steel [43]. In this method, an electrolytically applied calcium phosphate [44] is used to replace the zinc phosphate layer. This procedure ensures a much more uniform and fine crystalline coating with smaller film thickness, which can be much better controlled since it is a linear function of current density and treatment time [45].

Tang et al. [46, 47] have developed a porous coating working as an alternative lubricant carrier to conventional zinc phosphate coating. A two-phase alloy of Sn and Zn is electrochemically deposited on the workpiece surface after which one of the two metals is selectively etched leaving a micro-porous layer (typically 5 μm of thickness) of the remaining metal on the workpiece surface. Furthermore, Utsunomiya et al. [48] have produced porous surfaces in steel by chemical reduction of the pre-oxidized surface.

Single bath lubrication systems have been developed in Japan and Germany as an alternative to lubrication with conversion coatings [43]. After descaling/shot blasting and hot water rinsing, the slugs are dipped in an aqueous bath containing inorganic salt and an organic lubricant. The slugs are subsequently dried after which they are ready for cold forging. This lubrication system is possible to use as an in-process lubrication system because the whole procedure takes about 2 min. Schoppe [49] and Yoshida et al. [50] developed a single bath lubrication system forming a coating of inorganic salt and wax while Groche and Koehler [51] have tested a single bath lubricant including a compound of salt and wax. Furthermore, Holz [52] reports that application of MoS_2 by tumbling of in powder form has more or less totally

been replaced by dipping in aqueous dispersion baths thus avoiding dust and noise problems and facilitating lubrication of hollow slugs.

The dual bath systems form a ground coating adhering to the slug surface and an over coating to reduce friction further. Two types of lubricants were applied, a white lubricant consisting of wax and metal soap, and black lubricant comprising of MoS_2 and graphite. Nakamura et al. [53, 54] have studied several alternatives to conventional coating including single as well as dual bath systems. Furthermore, Lazzarotto et al. [55] showed a methodology to the select lubricant oils in cold metal forming processes, from a wide range of products available on the market, because the lubricant has economic importance and its proper selection can save production costs.

Herrmann et al. [56] studied the effect of the structuring of tools used for the cold forming process' rotary swaging, under conditions either with or without lubrication and with different feeding velocities. The structuring was done in the reduction zone of the tool with different cosine structures to discharge the abrasive particles and control the axial reaction force. They found that the axial reduction force can be effectively reduced by using a structured tool and the use of lubrication. Hafis et al. [57] evaluated the effects of lubricant quantity on forming loads and surface finish under dry and lubricated conditions among die-work piece sliding surfaces in the cold work drawing process. They found that poor lubrication increases the forming load, reduces the shape precision, and increases the surface roughness of the product.

2.6 Surface treatments use for cold forging tools

Surface treatments are widely used on steel to improve wear resistance, define tribological behavior, corrosion resistance, optical behavior, decorative behavior and matched interface behavior while retaining toughness of the core material by mechanical, thermal, chemical and electrochemical processes. A primary need for tool and die manufacturers is to identify the best combination of steel chemical composition together with thermal and surface treatments to achieve the best thermomechanical shock and wear resistance with fulfilling the industrial need of good quality product and extended tool life [58]. Increasing surface hardness and lowering the friction coefficient by improving tribological behavior is the main aim of using surface treatment in forging tool manufacturing. Such treatments should imply a correct balance between hardness and toughness to achieve suitable strength with limited crack susceptibility. Mechanical surface treatment and surface coating are the most common surface treatment used

in cold forging tools.

The mechanical surface treatment is a process based on the elastic–plastic cold working of the surface. During this treatment, the surface layer is work-hardened and residual compressive stress is generated. Shot peening, micro blasting, fine particle peening are widely used mechanical surface treatment methods used in forging tools. Shot peening has been used for many years as a palliative on a number of problems affecting the surfaces of components in several industries [59]. Improvement of the fatigue life, hardness, wear, stress-corrosion cracking, etc. of metallic components by shot peening is produced by increasing dislocation densities, cold working and generation of compressive residual stresses [60]. Controlled shot peening is the cold working of a surface with particles, impinging at predetermined velocity under controlled conditions. In shot peening the surface yields, but it is restrained by the substrate with the result that residual compressive stress is induced as shown in Fig. 2.7 [61].

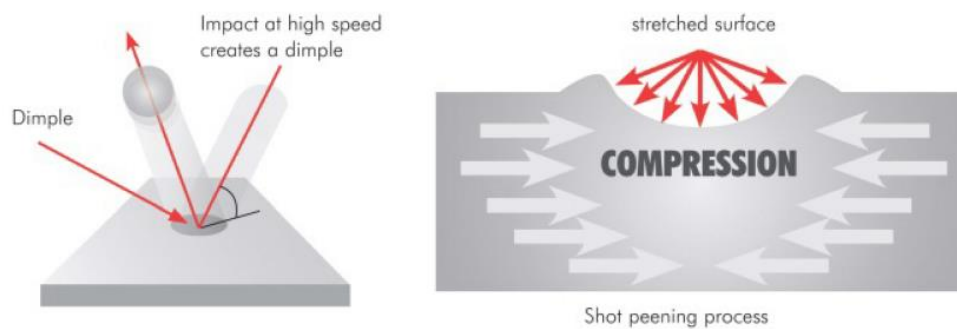


Fig 2.7 Shot peening dimple and residual compression stress generation.

There are many studies carried out on shot peening process. Miao et al. [62] experimentally studied the quantitative relationships between the saturation, surface coverage, and roughness with respect to peening time based on aluminum Al2024 test strips. He found that compressive residual stresses have a beneficial effect on the improvement of the fatigue life of the peened component. However, surface roughness has a detrimental effect on the fatigue life of the peened component. Chang et al. [63] studied the effect of shot peening on wear properties and the die life using shot peening treated AISI H13 steel. They observed an improvement in wear resistance and microstructure of AISI H13 steel due to shot peening. Furthermore, the study found that due to optimal shot peening treatment increased the die life of for cold forging by over three times and hot forging molds by two times. Farrahi et al. [64] studied the effect of various

surface treatments on AISI D3 cold work tool steel and conveyed 14% improvement in fatigue life by using shot peening. Harada et al. [65] researched on micro shot peening of high speed tool steel and claimed a significant increase in fatigue performance. They also examined the effect of processing temperature used during peening and reported enhanced peening effect at higher temperatures. Matsumoto et al. [66] investigated lubrication performance of the shot peened and conventional mechanical polished dies by cold ring compression test of titanium workpiece and found that the shot peened die with mirror finish was effective to confine larger amount of lubricant within micro valleys of surface up to high reduction in height in the ring compression test. Akyildiz et al. [67] have investigated the effect of shot peening parameters on the fatigue strength of steel manufactured by powder metallurgy. They found that the fatigue behavior of this material improved by surface peening process and the best fatigue performance obtained with the specimens that were shot peened at 20 Almen intensity and 100% saturation.

Abrasive blasting is the operation of forcibly propelling a stream of abrasive material against a surface under high pressure to smooth a rough surface, roughen a smooth surface, shape a surface, or remove surface contaminants. A pressurized fluid, typically air, or a centrifugal wheel is used to propel the blasting material to the treating surface. The versatility of abrasive blasting is its ability to perform different processes on parts depending on several variables, such as, choice of abrasive, size and shape of the nozzle and amount of pressure applied which affect the end result. Micro-abrasive blasting (micro blasting) is used in forging tool manufacturing in different stages of the process. There are many studies carried out on the use of micro blasting on the EDM (Electrical discharged machined) surface which is a common manufacturing process use in forging tool manufacturing. Hung et al. [68] have found out that with proper process setup, the abrasive blasting can remove damaged EDM surface layers and introduce a new surface layer with desirable compressive residual stresses. Furthermore, Lee and Zhang [69] also investigated the applications of the blasting process to modify EDM surface layers. Qu et al. [70] studied on micro-blasting of EDMed WC–Co surfaces using fine SiC abrasive and found out that larger size abrasives and higher air pressure produce higher erosion wear rate and reduce the EDM surface roughness more effectively in very short times. Micro blasting process is used after coating to clean, smooth the surface and reduce sharp cutting edges. Studies have shown that micro-blasting treatment of PVD coatings deposited on hard metal substrates improves its residual stress with regard to fatigue strength and cutting performance of the coated tool [71]. Furthermore, there are reports that the use of micro blasting on PVD/CVD multilayers coated surface introduces compressive residual stress [72, 73].

Coatings are a surface treatment used in many metal forming applications, to improve the lifetime and performance of products or tools, by reducing wear and friction by adding hardness to the surface or decreasing interaction forces. Coatings are improving the surface properties of a material without influencing the bulk material properties. Bromark et al. [74] found that multilayered Ti/TiN coatings show promise for combined wear and corrosion protection and that they also offer a means to modify the properties of tribological coatings which then can be used to control the coating's residual stress state. Kocanda et al. [75] studied the effect of low cycle fatigue on TiN coated high-speed steel and high chromium (12.6%) high carbon cold work tool steel. A study by Podgornik et al. [76] found that increasing smoothness of the substrate, the coated surface can withstand a higher critical load and thus polishing of a surface prior to deposition of a coating will increase the critical load for material transfer by reducing friction. Residual stresses are created in coatings as an effect of the manufacturing process and PVD coatings on steel are usually generated compressive residual stresses that contribute to the occurrence of plastic deformation and micro-cracking which in turn affects the tribological response of the coated part [77]. Gahlin et al. [78] found that use of low-temperature TiN coating (deposited at 200°C) gives a significant increase in hardness and residual compressive stress as compared to standard temperature coating (deposited at 400°C).

Wonder Process Craft/ Wide Peening Cleaning (WPC) treatment is a shot peening method that improves the mechanical property of metal products. It was jointly developed by Fuji Manufacturing Co., Ltd. and Fuji Kihan Co., Ltd. (Japan Patent No. 1594395). The difference between conventional shot peening and WPC is conventional shot peening sprays ferrous media 600 to 800 µm in diameter at a velocity of 70 to 80 m/s, while WPC sprays a much harder and finer media of 40 to 200 µm in diameter at a velocity of 200 m/s. The use of ultra-fine particles made it possible to apply this method to precision parts, and this technology has been implemented in widespread areas, that include cutting tools, mold tools and machine parts [79]. During the WPC process, quick heating and cooling are repeated. Therefore, heat-treatment and forging effect with a small-dimpled surface is created. Furthermore, compressive stresses are created at the impact point on the surface when ultrafine particles are projected at high velocities. At the same time, a micro thermal reaction takes place which efficiently seals minor surface cracks and allows a condensed surface to establish with improved density due to compaction [80]. The advantages of the WPC surface treatment included, increased surface life, improved sliding performance, increased impact resistance, increased surface hardness, increased adhesion on films, prevention of low-temperature brittleness and prevention of various forms of corrosion

[81]. Yonekura et al. [82] carried out a rotational bending fatigue tests on SCM 420 H steel modified by a combination of WPC treatment and carburizing, with special attention focused on the effect of surface residual stress on fatigue properties and found out that the notched specimens modified by the combined process showed significantly higher fatigue life. Yamada et al. [83] investigated the IH (induction heating) and WPC on rolling contact fatigue life of 13Cr-2Ni-2Mo stainless steel and concluded that residual stress introduced by WPC near the surface improve life fatigue. The studies carried out on the WPC process are very limited and there is very little literature in English related to this process.

2.7 Fatigue

The fatigue described as the progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fracture after a sufficient number of fluctuations [84]. Metals are the most widely used materials in engineering structures, and one of the most common failure modes of the metal structure is fatigue failure [85]. In fact, it is generally considered that over 80% of all service failures can be traced to mechanical fatigue, whether in association with cyclic plasticity, sliding or physical contact (fretting and rolling contact fatigue), environmental damage (corrosion fatigue) or elevated temperature (creep fatigue) [86].

Fatigue life (N_f) describe as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs [87]. There are three methods to determine the fatigue life of a material: the stress-life method, the strain-life method, and the linear-elastic fracture mechanics method. High cycle fatigue (HCF) where the fatigue life is about 10^4 to 10^7 cycles, can be described by stress-based parameters and Low cycle fatigue (LCF) where typically causes failure in less than 10^4 cycles, can be described by strain-based parameters. Recently, the fatigue behavior of the material at very high cycle fatigue (VHCF) where fatigue limit is beyond 10^7 cycles gain the interest of researchers because the fatigue failure of high strength steels occurs in this region [88]. The S-N curve which is also known as a Wohler curve is a graph of a cyclic stress amplitude (S) against the logarithmic scale of cycles to failure (N) which characterized the fatigue behavior of the material.

Fatigue failure is consists of three stages. The first stage is initial fatigue damage leading to crack nucleation or crack initiation. Then the progressive cyclic growth of a crack (crack propagation) until the remaining un-cracked cross section of the part becomes too weak to

sustain the load imposed. This will be followed by a sudden fracture of the remaining cross section [89]. Initiation of a fatigue crack at a smooth surface under ambient conditions may consume nearly 90% of applied cycles while crack propagation may require only remaining 10% cycles [90]. Even though, the fatigue failure is generally divided into three, different researches have studied this process by dividing furthermore. As an example, Schijve [91] divided the process in to four phases: crack nucleation, micro crack growth, micro crack growth, and failure. Additionally, De-Guang et al. [92] divided the process into five phases: early cyclic formation and damage, micro crack nucleation, short crack propagation, macro crack propagation and final fracture.

In the production of high-volume cold forged parts with net-shaped complex surfaces, fatigue cracking of the active tool elements is the leading cause of failure [93]. Generally, the service life of forging tool failure by fatigue is much shorter than the tool fails by wear. Figure 2.15 shows the general failure modes of a forward extrusion forging die. Fatigue cracks initiate at the transition radius to the extrusion shoulder and propagate in the radial direction. Longitudinal cracks usually result from overloading and occur during the first few loading cycles of a tool. This type of failure can be easily avoided by proper design of tools and selection of tool materials.

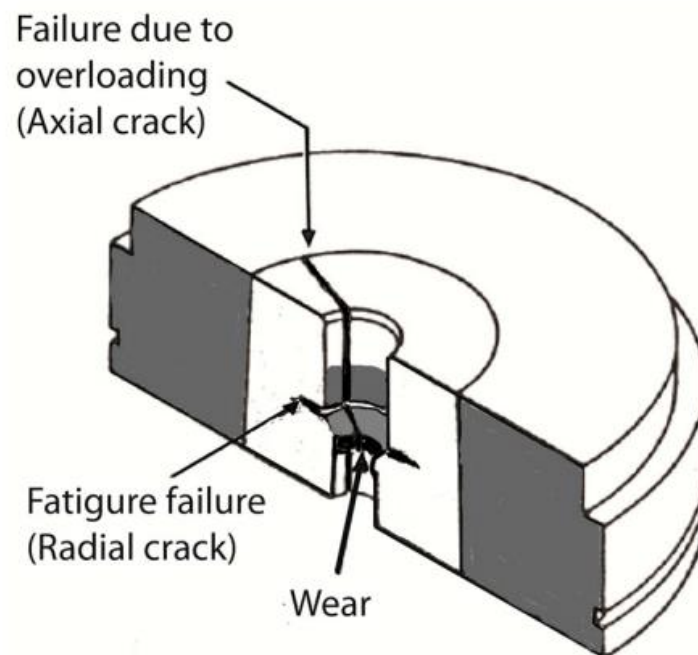


Fig. 2.15 Schematic of failure in forward extrusion forging die.[94]

Researchers have conducted their studies to identify the cause of fatigue failure, predict the fatigue life and improve the fatigue life of forging tools from a different perspective. Wang et al. [95] conducted research to propose an optimal shrink fitting ratio for two-layer compound forging dies. They stated that the method they proposed has the capability of improving fatigue life from 10^4 to 10^5 cycles or more. Saroosh et al. [96] studied the method to predict the high cycle fatigue life of cold forging tools based on work piece material properties. They derived a formula to predict the tool life based on Morrow's approach. Critical process parameters and die design features that affect the fatigue life of forging tools were studied by Akhar and Arif [97] using finite element simulation and fatigue theory. They considered temperature and strain rate as process parameters and bearing length and fillet radius of the die as geometric features and established a correlation between the tool life. Furthermore, Abdullah et al. [98] investigated the effect of corner radii and part orientation on the fatigue life of closed forging die. Lee and Chen [99] conducted research to obtain a relationship between the hardness and the die fatigue life. They proposed a theoretical model to predict the fatigue life of tool based on tool material hardness. Tong et al. [100] have used the S-N approach and finite element analysis for the estimation of forging die fatigue life and validated it by some industrial case studies.

There were many studies carried out on mechanical properties of tool material, their usage in forging tools and improving the mechanical properties by various means to achieve higher tool life. But, there is a lack of a comprehensive study on the behaviour of parameters affecting tool life during forging operation. The researches have proved that the parameters such as residual stress, surface roughness, geometry, etc affect the fatigue behaviour of steel, which is one of the main methods of tool failure. Therefore, the study of the variation of these parameters during forging shows a great importance to predict the tool life and to take counter measures to tool failure. Many studies have carried out on improving the fatigue life of tool steel. They have suggested new methods of achieving higher fatigue life by altering the parameters controlling the fatigue behaviour. Most of these researches were focused on altering a single parameter to improve the fatigue life. There are very few studies carried out on combining different tool life improvement methods to achieve improved tool life. Therefore, there is a necessity to conduct research on introducing methods that can combine the positive effects of different tool life improvement methods.

Referances

- [1] DIN 8580: 2003-09: Fertigungsverfahren-Begriffe, Einteilung. Beuth Verlag, Berlin, (2003).
- [2] S. H. Huang, H. Xing, G. Wang: Int. J. Adv. Manuf. Technol., 18 (2001) 89-97.
- [3] M. Milutinovic, D. Vilotic, D. Movrin: J. Tech. Plasticity., 33 (2008) 73-88.
- [4] G. H. Farrahi, H. Ghadbeigi: J. Mater. Process. Technol., 174 (2006) 318-324.
- [5] A. B. Abdullah, Z. Samad: J. Appl. Sci., 7(6) (2007) 868-876.
- [6] M. Bambach: J. Mach. Eng., 16(2) (2016) 5-17.
- [7] T. Qin: J. Master. Proc. Technol., 177(2006) 8-18.
- [8] D. Del Pozo, L.N. López de Lacalle, J.M. López, A. Hernandez: Int. J. Adv. Manuf. Technol., 37 (2008) 649-656.
- [9] A. Rosochowski: J. Mater. Process. Technol., 115 (2001) 187–191.
- [10] Y. Tsuchiya: R&D Review of Toyota CRDL, 34(4) (1999) 1-10.
- [11] T. Altan, G. Ngaile, M. Shirgaokar: Proceedings of the international conference on “New Developments Bulk Forming 2003”, Stuttgart, Germany (2003) 1-20.
- [12] V. Vazquez, T. Altan: J. Mater. Process. Technol., 98 (2000) 212-223.
- [13] U. Engel, J. Groenbaek, C. Hinsel, T. Kroiß, M. Meidert, R. Neher: UTFScience, 3 (2011) 1-24.
- [14] S. Marsoner, R. Ebner, M. Panzenböck, W. Liebfahrt, F. Jeglitsch: Int. Fatigue. Congr., (2002) 523-532.
- [15] J. Blaha, C. Krempaszky, E. Werner: Proc. 6th Int. Tool Conf. Karlstad, (2002) 245-52.
- [16] K. Kitamura, M. Kobayshi, K. Hayashi: J. Jpn. Soc. Powder Powder Metall., 48(7) (2001) 621-628.
- [17] H. Berns, A. Melander, D. Weichert, N. Asnafi, C. Broeckmann, A. Groß. Weegec: Comp. Mater. Sci., 11(3) (1998) 166-180.
- [18] S. Yurtdas, U. Ince, C. Kilicaslan, H. Yildiz: Eng. Struct. Mat., 3(1) (2017) 65-75.
- [19] P. J. Withers: Strain, 37(1) (2001) 9-33.
- [20] K. H. Kloos: Z. Werkstofftech., 10 (1979) 293-302.
- [21] C. O. Ruud: NDT International, 15 (1) (1982) 15-23.
- [22] M.Y. Toumi, A. Benmarouane, H. Bonneefoy, T. Buslaps, A. Lodini, V. Honkimaki: Mater. Sci. Forum, 706-709 (2012) 1696-1701.
- [23] K. Lange, M. Kammerer, K. Pöhlandt, J. Schöck: Fließpressen (2008).
- [24] A. Czan, J. Holubjak, I. Daniš, J. Martinček, M. Mikloš, R. Čep, M. Hatala, Š. Malotova:

MATEC Web Conf. 157 (2018) 01005.

[25] M. Merklein, K. Andreas, U. Engel, *Procedia. Eng.*, 19 (2011) 252- 257.

[26] E. S. Gadelmawla, M. M. Koura, T. M. A. Maksoud, I. M. Elewa, H. H. Soliman: *J. Mater. Process. Tech.*, 123 (2002) 133-145.

[27] J. Marteau, M. Bigerelle, P. E. Mazeran, S. Bouvier: *Tribol. Int.*, 82 (2015) 319-332.

[28] D. T. Ardi, Y. G. Li, K. H. K. Chan, M. R. Bache: *J. Mater. Eng. Perform.*, 23(10) (2014) 3657.

[29] O. Obiukwu, M. Nwafor, B. Okafor, L. Grema: International conference on Mechanical and industrial engineering (ICMIE'15) Harare, Zimbabwe (2018) 1-5.

[30] J. Lai, H. Huang, W. Busing: *Procedia Struct. Integr.*, 2 (2016) 1213-1220.

[31] M. A. Saroosh, H. C. Lee, Y. T. Im, S. W. Choi, D. L. Lee: *J. Mater. Process. Tech.*, 191 (2007) 178-181.

[32] S. A. McKelvey, A. Fatemi: *Int. J. Fatigue.*, 36(1) (2012) 130-145.

[33] T. Souza, M. Pereira, R. De Souza: SAE Technical Paper; 2016-36-0393, 2016.

[34] S. Syahrullail, C. S. N Azwadi, M. R. Abdul Kadir, N. E. A. Shafie: *J. Appl. Sci.*, 11 (2011) 367–372.

[35] C. Caminaga, F. Neves, F. Gentile, S. Button: *J. Mater. Process. Tech.*, 182 (2007) 432-439.

[36] K. H. Jung, H. C. Lee, S. H. Kang, Y. T. Im: *J. Achiev. Mater. Manuf. Eng.*, 31(2) (2008) 327-334.

[37] M. Gariety, G. Ngaile, T. Altan: *Int. J. Mach. Tools Manuf.*, 47 (2007) 673-681.

[38] T. Altan, G. Ngaile, G. Shen: *Cold and Hot Forging: Fundamentals and Applications*, ASM International, Materials Park, Ohio (2005).

[40] J. Donofrio: *Met. Finish.*, 98(6) (2000) 57-73.

[41] J. Nyamangara: *Agric. Ecosyst. Environ.*, 69(2) (1998) 135-141.

[42] C. J. Baldy: *Met. Finish.*, 94(11) (1996) 23-24.

[43] N. Bay: *Proceed. 46th International Cold Forging Group (ICFG) Plenary Meeting*, (2013).

[44] P. T. Olesen, T. Steenberg, E. Christensen, N. J. Bjerrum: *J. Mater. Sci.*, 33 (1998) 3059-3063.

[45] N. Kobatashi, A. Moriyama, M. Yoshida: *Nihon Parkerizing- Technical report No. 17*, (2005).

[46] P. T. Tang, M. Arentoft, N. Bay, M. Borrild, I. Mizushima, J. D. Jensen, N. A. Paldan: EU Patent 07388045, U.S. Patent 60/929.299.

[47] E. Ceron, N. Bay, M. Arentoft, P.T. Tang: *Steel Res. Int., Special Edition* (2011) 240-244.

- [48] H. Utsunomiya, S. Takagishi, A. Ito, R. Matsumoto: CIRP Annals- Manuf. Tech., 62 (2013) 235-238.
- [49] J. Schoppe: Proceed. New Developments in Forging Technology. (2013) 327-334.
- [50] M. Yoshida, Y. Imai, H. Yamaguchi, S. Nagata: Nihon Parkerizing-Technical Report No. 15, (2003).
- [51] P. Groche, M. Koehler: Final report of AIF-project 14511 (In German), (2008).
- [52] J. Holz: Personal communication with Zvez Chemie, (2013).
- [53] T. Nakamura, Y. Sumioka, Y. Sagisaka, I. Ishibashi, M. Sekizawa: Proceed. 59th Japanese Joint Conference for the Technology of Plasticity, (2008) 579-580.
- [54] T. Nakamura, Y. Sumioka, Y. Sagisaka, I. Ishibashi, M. Sekizawa: Proceed. 59th Japanese Joint Conference for the Technology of Plasticity, (2008) 333-334.
- [55] L. Lazzarotto, L. Dubar, A. Dubois, J. P. Bricout, J. Oudin, P. A. Ravassard: Wear, 215 (1998) 1-9.
- [56] M. Herrmann, C. Schenck, B. Kuhfuss: Dry Met. Form., 4 (2018) 18-24.
- [57] S. M. Hafis, M. J. M. Ridzuan, A. Rahayu, Mohamed, R. N. Farahana, S. Syahrullail.: Procedia Eng., 68 (2013) 639-646.
- [58] E. Bernqocchi, A. Ferrero, E. Gqriboldi, A. Korovkin, G. Ponlini: Metall. Sci. Technol., 14 (1) (1996) 3-11.
- [59] K. J. March: Shot Peening Techniques and Applications, Engineering Materials Advisory Services Ltd., United Kingdom (1993).
- [60] V. Bhavar, S. V. Patil, P. Kattire, P. P. Date, R. K. P. Singh: J. Mater. Sci. Chem. Eng., 5 (2017) 81-90.
- [61] Shot Peening Applications, 9th Edition, Metal Improvement Co. Inc., NJ, 2005.
- [62] H. Y. Miao, D. Demers, S. Larose, C. Perron, M. Lévesque: J. Mater. Process. Tech., 210 (2010) 2089-2102.
- [63] S. H. Chang, S. C. Lee, T. P. Tang: Mater. Trans., 49 (3) (2008) 619-623.
- [64] G. H. Farrahi, H. Ghadbeigi: J. Mater. Process. Tech., 174 (2006) 318-324.
- [65] Y. Harada, K. Fukauara, S. Kohamada: J. Mater. Process. Tech., 201 (1) (2008) 319-324.
- [66] R. Matsumoto, N. Kai, Y. Tomita, A. Kajioka, S. Mori, H. Utsunomiya: Procedia Eng., 207 (2017) 1135-1140.
- [67] H. K. Akyildiz, M. K. Kulekci, U. Esme: Fatig. Fract. Eng. Mater. Struct., 38 (10) (2015) 1246-1254.
- [68] N. P. Hung, L. H. Teong, C. M. Yoong: Proceed. 3rd Biennial Joint Conference on

Engineering Systems Design and Analysis-NY, 75 (3) (1996) 47-53.

[69] T. C. Lee, J. H. Zhang: J. Adhes. Sci. Technol., 12 (6) (1998) 585-592.

[70] J. Qu, A. J. Shih, R. O. Scattergood, J. Luo: J. Mater. Process. Tech., 166 (2005) 440-448.

[71] F. Klocke, T. Schroeder, E. Bouzakis, A. Klein: Surf. Coat. Technol., 202(4) (2007) 1194-1198.

[72] H. Westphal, V. Sottke: Patent DE 10123554 A1, 22.12.2002.

[73] S. Ruppi: Patent US 6,015,614, 18.01.2000.

[74] M. Bromark, M. Larsson, P. Hedenqvist, S. Hogmark: Surf. Coat. Technol., 90 (1997) 217-223.

[75] A. Kocanda: Proceed. 7th ICTP Conference on Advanced Technology of Plasticity, Yokohama, Japan, (2002) 793-798.

[76] B. Podgornik, S. Hogmark, O. Sandberg: Surf. Coat. Technol., 184 (2004) 338-348.

[77] P. Hedenqvist, S. Jacobson, S. Hogmark: Surf. Coat. Technol., 97 (1997) 212-217.

[78] R. Gahlin, M. Bromark, P. Hedenqvist, S. Hogmark, G. Hakansson: Surf. Coat. Technol., 76-77 (1995) 174-180.

[79] Fuji Kihan Co., Ltd. WPC metal surface treatment Japan, <http://japan-product.com/ads/fuji-kihan/>, (2014).

[80] WPC Treatment Co., Inc. Metal surface treatment for motor sports Torrance, <http://www.wpctreatment.com/durability.htm>, (2015).

[81] M. U. Abdullah, S. R. Shah, M. U. Bhutta, R. A. Mufti, M. Khurram, M. H. Najeeb, W. Arshad, K. Ogawa: Proceed. Inst. Mech. Eng. Part D: J. Auto. Eng., (2018) 1-11.

[82] D. Yonekura, J. Komotori, M. Shimizu, H. Shimizu: Japan Soc. Mech. Eng. Part A, 68 (3) (2002) 509-514.

[83] T. Yamada, K. Mizobe, K. Kida: Key Eng. Mater., 777 (2018) 366-371.

[84] H. E. Boyer: Atlas of Fatigue Curves, ASM int., Materials Park, Ohio (1985) 518.

[85] W. Cui: J. Mar. Sci. Technol., 7 (2002) 43-56.

[86] R. O. Ritchie: Int. J. Fract., 100 (1999) 55-83.

[87] R. I. Stephens, A. Fatemi, R. R. Stephens, H. O. Fuchs: Metal Fatigue in Engineering, John Wiley & Sons, Australia (2001).

[88] Y. Shimatani, K. Shiozawa, T. Nakada, T. Yoshimoto: Procedia. Eng., 2 (2010) 873-882.

[89] W. Schütz: Eng. Fract. Mech., 54 (1996) 263-300.

[90] S. Bhat, R. Patibandla: Metal Fatigue and Basic Theoretical Models: A Review. In Tech Open, (2011) 203-236.

- [91] J. Schijve: ASTM STP415, (1967) 415–459.
- [92] S. De-Guang, Y. Wei-Xing, W. De-Jun: Int. J Fatigue, 20 (1998) 683-687.
- [93] K. Lange, Umformtechnik: Handbuch für Industrie und Wissenschaft, New York: Springer 1984.
- [94] K. Lange, L. Cser, M. Geiger, J.A.G Kals: CIRP annals, 41(2) (1992) 667-675.
- [95] C. Wang, H. Kam, X. Wang: Procedia. Eng., 207 (2017) 2215-2220.
- [96] M. A. Saroosh, H. C. Lee, Y. T. Im, S. W. Choi, D. L. Lee: J. Mater. Process. Tech., 191 (2007) 178-181.
- [97] S. S. Akhtar, A. F. M. Arif: J. Fail. Anal. Prevent., 10 (2010) 38-49.
- [98] A. B. Abdullah, K. S. Ling, Z. Samad, S. Sahudin: J. Appl. Sci., 7 (19) (2007) 2871-2875.
- [99] Y. C. Lee, F. K. Chen: J. Mater. Process. Tech., 113 (2001) 539-543.
- [100] K. K. Tong, M. S. Yong, M. W. Fu, T. Muramatsu, C. S. Goh, S. X. Zhang: Int. J. Prod. Res., 43(1) (2005) 131–146.

Chapter 3

EFFECT OF LUBRICATION AND FORGING LOAD ON SURFACE ROUGHNESS, RESIDUAL STRESS AND DEFORMATION OF COLD FORGING TOOLS

3.1 Introduction

Cold forging is a metal forming that which uses localized compressive force at room temperature. During the cold forging process, the tool is subjected to extremely high loads and abrasive wear. Thus, the forging tools subjected to changes to its initial condition with the progress of forging. Finally, these condition changes can lead to tool failure.

Any improvement in the service life of tools reduces the tooling costs, and assists to increase labor productivity by decreasing the needs for either the tools' re-grinding or their replacement. Thus, there are many studies carried out on various methods to improve the tool life of forging tools by altering the residual stress and surface properties. However, in many studies researches had altered the surface properties prior to the experiment and studied the effect. However, there was no comprehensive study carried out on the variation of residual stress and surface condition of the forging tool during service. The understanding of the in-service variation of different parameters that affect the tool life will lead to new scopes in tool life improvement methods, such as partial surface treatment, tool design with predicted deformation, advancement in the tribological system, etc. Therefore, utmost importance is observed in researching and understanding on the in-service variation of parameters which affect the tool life.

The present study has the scope to investigate the variations in the surface roughness, residual stress, and deformation of a tool with the number of cold forging cycles under different forging conditions. The experimental method was designed to execute the research in an almost similar condition of an actual cold forging process. Cold forging upsetting process was carried out with specimens made of heat treated SKH51 material as a punch under with lubrication and without lubrication conditions with two different forging loads. The influences of lubrication and forging load on surface roughness, residual stress and specimen deformation were evaluated and the effect of these parameters on tool life was discussed.

3.2 Experimental procedure

3.2.1 Materials, specimen preparation, and lubricant

A molybdenum-based high-speed tool steel JIS SKH51 (AISI M2; DIN 1.3343) was used. Table 3.1 shows the chemical composition of the material. SKH51 is commonly used in cold forging tool manufacturing due to its specific mechanical properties, such as high abrasion resistance and toughness characteristics. SKH51 is a tool steel that can achieve a high hardness

of over 60 HRC and a high compressive strength of over 3000 MPa [1].

Table 3.1 Chemical composition of SKH51 (wt. %).

C	Si	Mn	Cr	Mo	V	W	P,S
0.80-0.88	≤0.45	≤0.40	3.80-4.50	4.70-5.20	1.70-2.10	5.90-6.70	≤0.03

The specimen was made out of a round bar of steel in such a way that the loading direction is similar to the grain flow direction of the steel. Roughly machined specimens were preheated at 550 °C and 850 °C before being austenitized at 1120 °C. This was followed by quenching and tempering three times at 560 °C, to achieve a hardness of 59-61 HRC. The heat-treated specimens were NC lathe machined to get the outer shape. The top and bottom surfaces of the specimens were ground and the working surface was polished while using diamond paste to get a mirror-like surface finish. Figure 3.1 shows the specimen image and initial dimensions before the test. The yellow transparent metal working fluid “Sunform 350”, as manufactured by Nihon Grease Co., Ltd, Japan, was used as the lubricant for the experiment. Table 3.2 shows the properties of the lubricant.

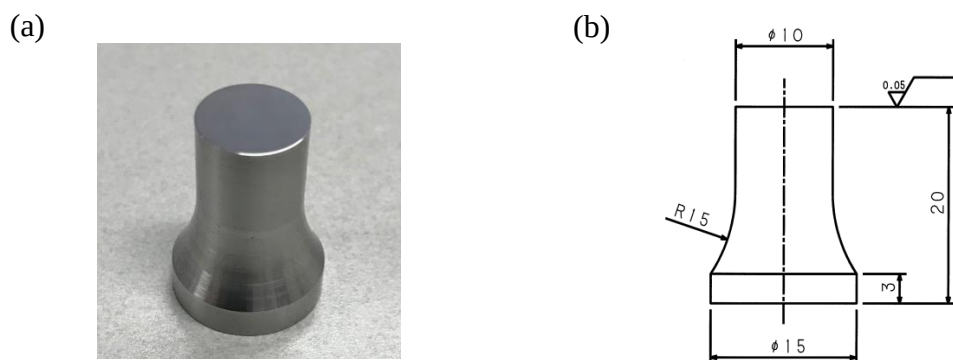


Fig. 3.1 Specimen image and dimension; (a) Image; (b) Dimension

Table 3.2 Properties of lubricant “Sunform 350”.

Parameter	Value
Density (15°C)	891.8kg/m ³
Viscosity (40°C)	77.82 mm ² /s
Flash point (C.O.C)	240°C
Copper corrosion(100°C × 1hr)	1

3.2.2 Experimental setup

Figure 3.2 (a) shows the Shimadzu UH-500KNX universal testing machine (Shimadzu Corporation, Japan). The maximum loads were 150 kN and 180 kN, which corresponded to contact pressures of 1910 MPa and 2290 MPa, respectively. Figure 3.2 (b) shows the zoomed experimental setup. The specimen was glued to the upper head of the universal tester. A low carbon steel SPCC (JIS G3141) sheet with 1.6 mm thickness placed on a spacer with high hardness (65 HRC) was used as the counter face. The zero limit of the stroke was set at 1mm below the point at which the 1 kN load was obtained. The base of the universal tester was moved upward at a speed of 25 mm/min. until the load became the set maximum load, and it stayed there for 1 sec. Thereafter, the base was moved downward until the stroke reached 1 mm from the starting position. The forging process was performed with lubrication and without lubrication as the conditions. The lubrication was periodically applied on the area near the specimen working surface to make sure that the forging operation was done in a lubrication bath for the ‘with lubrication’ condition throughout the experiment. The experiment was repeated for 14000 cycles for each forging condition, with an interval of 1000 cycles to take measurements. “WL” and “WOL” are used to denote the ‘with lubrication’ condition and the ‘without lubrication’ condition, respectively.

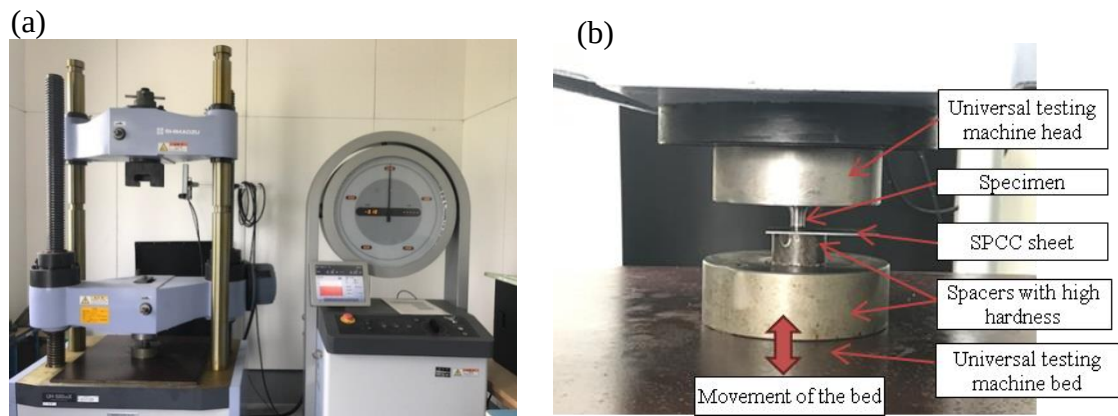


Fig. 3.2 Testing machine and experimental setup; (a) Universal testing machine(UH-500KNX); (b) Experimental setup

3.2.3 Measurements

Figure 3.3 shows the schematic of the dimension change of the specimen due to loading. The initial outer diameter (near the working surface), D , increased by ΔD due to the applied load, while specimen height, H , reduced by ΔH . Furthermore, a deformation at the center with a downward displacement, Z , was observed after loading.

Dimensions (D and H), residual stress (σ), surface roughness (R_a), and downward displacement (Z) were initially measured and after every 1000 cycles of forging. The diameter (D) and height (H) of the specimens were measured while using a digimatic micrometer (Mitutoyo Corporation, Japan) and height gage with a resolution of 1 μm , respectively. The surface roughness (R_a) and residual stress (σ) of the specimen were measured by the surface roughness tester, Surfcom-130A (Tokyo Seimitsu Co., Ltd, Japan) and the portable X-ray residual stress analyzer, Pulstec μ -X360 (Pulstec Industrial Co., Ltd, Japan), respectively. Figure 3.4 (a) and Fig. 3.4 (b) shows the surface roughness measuring direction (measuring length 4 mm) and the residual stress measuring areas, respectively. A contour measuring instrument, Surfcom-1600GH (Tokyo Seimitsu Co., Ltd, Japan) was used to measure the downward displacement (Z) on the working surface and it was measured through the center from edge to edge, as shown in Figure 3.4 (c). The images of specimen surfaces were taken while using an optical microscope, BX-41M (Olympus Corporation, Japan).

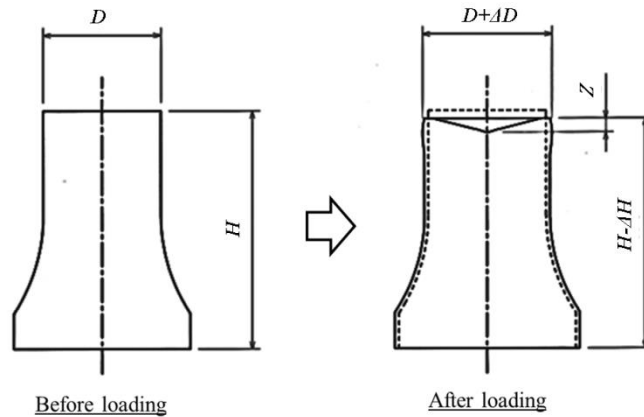


Fig. 3.3 Schematic of the dimension change of the specimen due to loading.

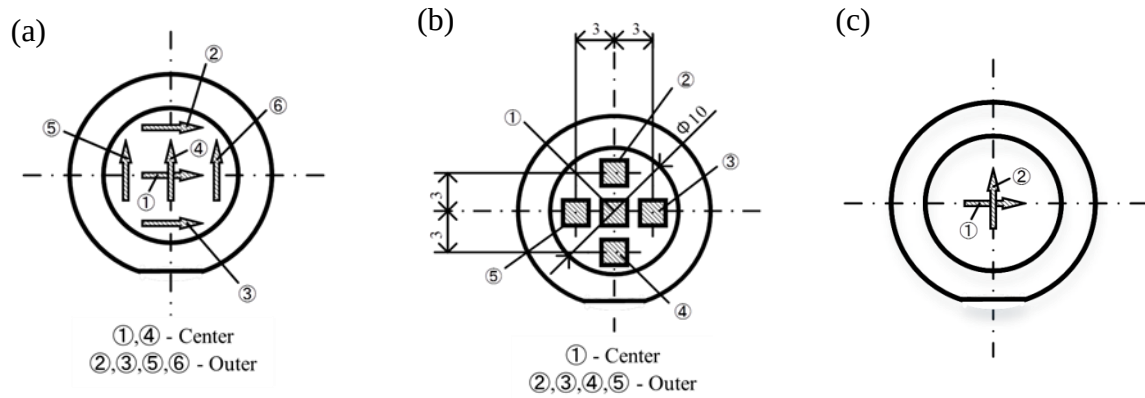


Fig. 3.4 Measuring details; (a) Surface roughness measuring directions; (b) Residual stress measuring areas; (c) Surface deformation measuring directions (From edge to edge through center).

3.3 Results and discussions

3.3.1 Working surface condition and surface roughness

Figure 3.5 shows the surface images of the initial, intermediate, and final working surfaces for all forging conditions. The images show a gradual increase in scratch marks on the surface with the number of forging cycles for all of the forging conditions. The scratch marks were due to the wear of the working surface that was caused by material movement. The shininess of the specimen surfaces on which lubricant was used deteriorated as the number of forging cycles increased. Furthermore, a brownish color substance accumulated on the working surface of specimens that were subjected to forging without lubricant. These were identified as ferrous oxide using an X-ray analytical microscope. Krajewski et al. [2] stated that iron exposed to air or oxygen containing atmosphere always tends to be instantly oxidized, even at room temperature. Moreover, the study of Ghasemi et al. [3] showed that significant quantities of oxides quickly formed on a steel ball during fretting, even with surface temperatures as low as 25–30 °C. It is known that the surface temperature increase is high due to direct metallic contact, when compared to the presence of lubrication between the surfaces. The oxide layer was clearly observed on the working surface of the specimens without lubricant since the temperature increase stimulated the oxidation process. On the other hand, the lubrication blocks the contact between the surface and the atmosphere, preventing the oxidation on the working surface of specimens that were forged with lubrication.

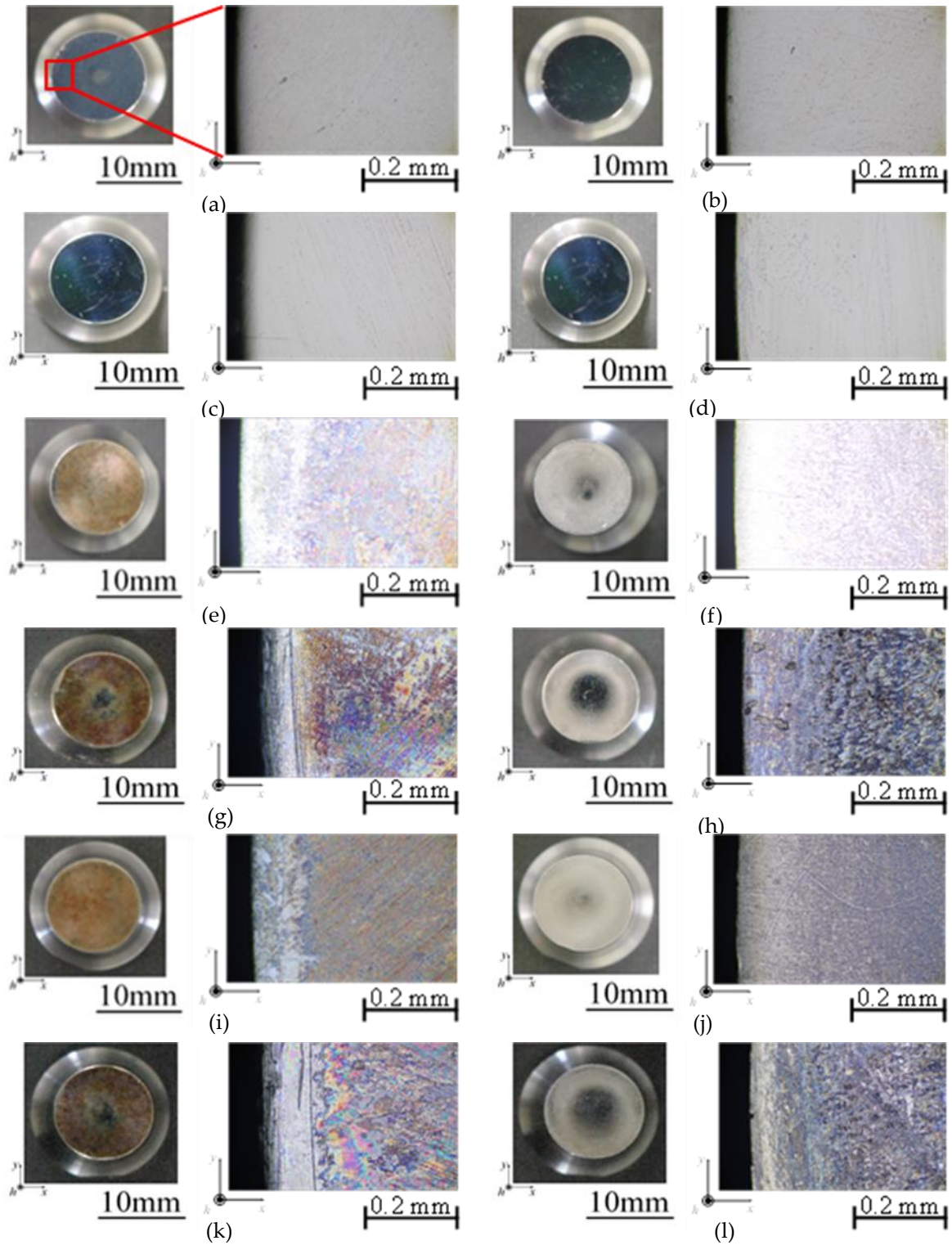


Fig. 3.5 Working surface conditions. (Left-full image, Right- magnified image): (a) 150kN(WOL)-Initial; (b) 150kN(WL)-Initial; (c) 180kN(WOL)-Initial; (d) 180kN(WL)-Initial; (e) 150kN(WOL)-7000 cycles; (f) 150kN(WL)-7000 cycles; (g) 180kN(WOL)-7000 cycles; (h) 180kN(WL)-7000 cycles; (i) 1150kN(WOL)-14000 cycles; (j) 150kN(WL)-14000 cycles; (k) 180kN(WOL)-14000 cycles; (l) 180kN(WL)-14000 cycles. (WL-With Lubrication, WOL-Without Lubrication).

Figure 3.6 shows the average arithmetic surface roughness, R_a at the center and the average value of outer areas by the number of forging cycles, N , for the 150 kN load condition. The surface roughness of the specimen that was forged with lubrication showed a slightly lesser surface roughness increase when compared to the ‘without lubrication’ condition. Regardless of the lubrication condition, the surface roughness at the center rapidly increased at the beginning. Thereafter, it gradually increased until reaching a constant value. On the other hand, the surface roughness of the outer areas gradually increased at the beginning and became constant. A comparatively large difference in surface roughness change is observed between two lubrication conditions at the beginning, and the difference narrowed as the number of cycles increased. There was a large surface roughness difference between the working surface of the specimen (about R_a 0.03) and the counter face (about R_a 0.60) at the beginning of the experiment. Therefore, the surface roughness change is high for the without lubrication condition at the initial stage, due to the direct contact of the fine surface with a rough surface. On the other hand, direct contact was congested with the use of lubricant. Therefore, a low surface roughness increase was observed at the beginning. As the forging process progressed, the difference between the surface roughness of the specimen working surface and counter face decreased. Thus, the surface roughness became almost the same for both lubrication conditions after 14,000 cycles.

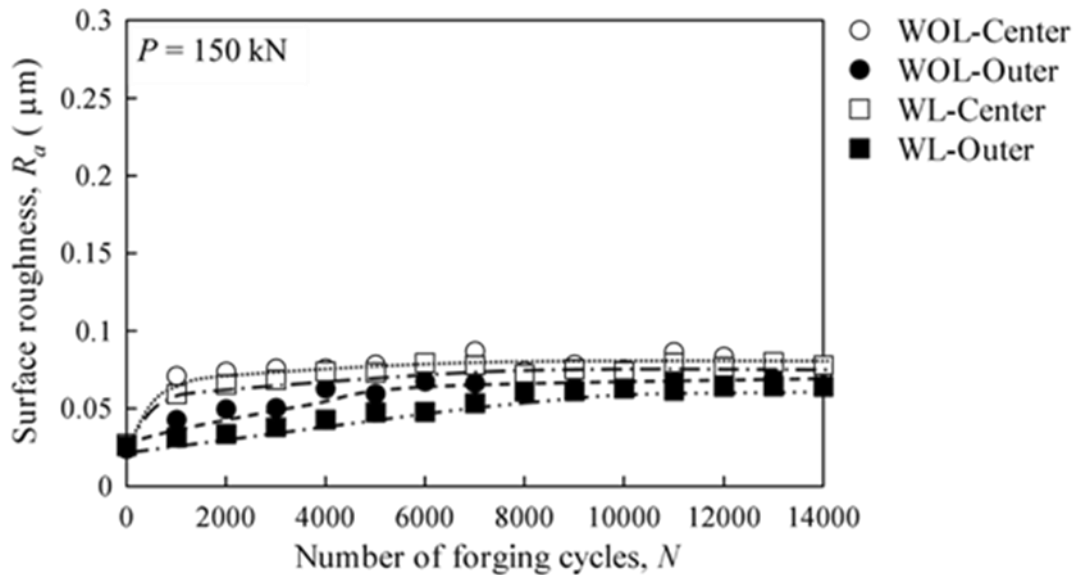


Fig. 3.6 Average arithmetic surface roughness at the center and the average of outer areas by the number of forging cycles, for the 150 kN forging load. (WL-With Lubrication, WOL-Without Lubrication).

Figure 3.7 shows the average arithmetic surface roughness, R_a at the center and the average value of outer areas by the number of forging cycles, N , for the 180 kN load condition. The surface roughness for the 180 kN load condition is very high and the difference between the center and outer areas is significant when comparing with the results of the 150 kN load condition. Similar to the 150 kN load condition, the surface roughness of the specimen that was forged with lubrication showed a slightly lesser surface roughness increase as compared to the ‘without lubrication’ condition. This slight difference may have resulted from the oxidation occurring on the surface under the ‘without lubrication’ condition.

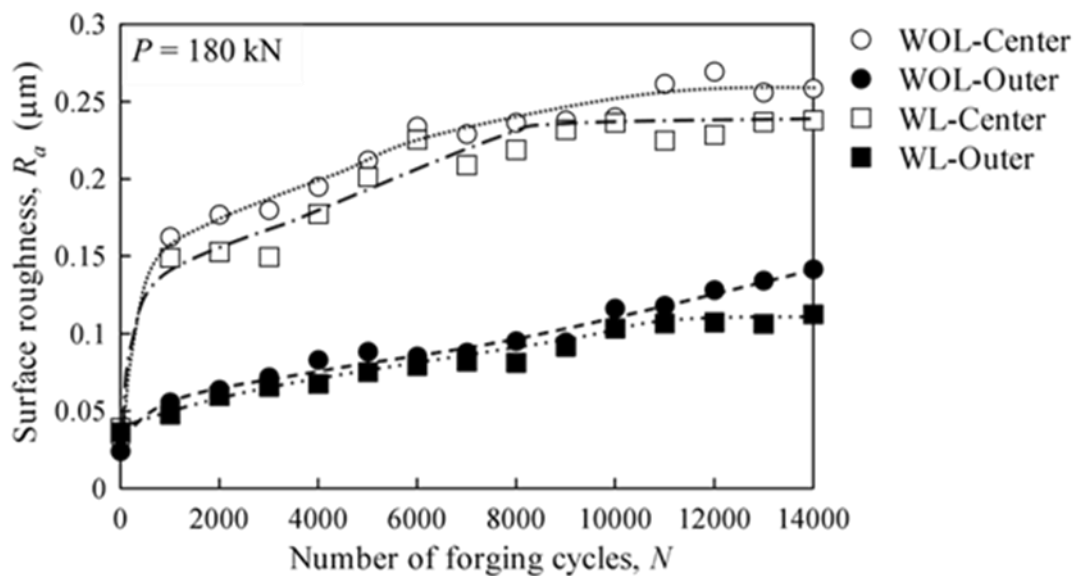


Fig. 3.7 Average arithmetic surface roughness at the center and the average of outer areas by the number of forging cycles, for the 180 kN forging load. (WL-With Lubrication, WOL-Without Lubrication).

There was a relative movement between the working surface of the specimen and the counter face material due to the deformation. The contact areas and forces are responsible for the generated friction, wear and change in surface roughness during the relative motion of the two bodies [4]. The wear on the working surface mainly caused the increase in surface roughness under all the forging conditions. Dry sliding contact between metallic surfaces is often associated with high surface temperatures, which form an oxide layer, resulting in high friction and severe surface damage [5, 6]. Lubrication creates a barrier between the contacting surfaces and it eliminates direct contact between them. Therefore, the wear of the working surface is comparatively low in the presence of lubricant, which results in a low surface roughness increase when compared to the dry forging condition.

3.3.2 Residual stress

Figure 3.8 shows the compressive residual stress, σ at the center and the average of the outer areas by the number of forging cycles, N , for 150 kN load condition. The initial residual stress on the working surface of the specimens was compressive in the radial direction, and it was considered to be generated by machining and polishing performed during specimen preparation. Regardless of the lubrication condition, the residual stress of the center and the outer areas both showed an initial rapid increase, followed by a gradual increase, reaching a constant value thereafter. Furthermore, the ‘without lubrication’ condition showed a slightly higher compressive residual stress than the ‘with lubrication’ condition. Relatively high compressive residual stress was observed at the center when compared to the outer areas for both lubrication conditions.

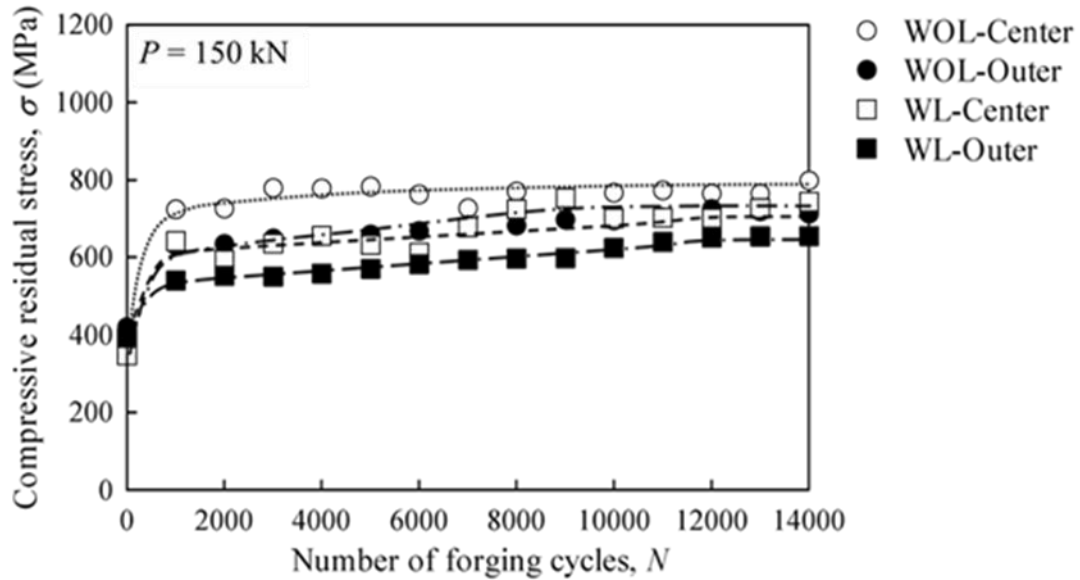


Fig. 3.8 Compressive residual stress at the center and the average of outer areas by the number of forging cycles, for the 150 kN forging load. (WL-With Lubrication, WOL-Without Lubrication).

Figure 3.9 shows the compressive residual stress, σ at the center and the average of outer areas by the number of forging cycles, N , for the 180 kN load condition. The compressive residual stress at the center for both of the lubrication conditions increased at a higher rate and became almost constant at around 7000 cycles. On the other hand, the variation of residual stress in the outer areas did not show a significant increase. At the 150 kN load condition, compressive residual stress increased at both the center and outer areas. However, a large increase in compressive residual stress was found only at the center at the 180 kN load condition.

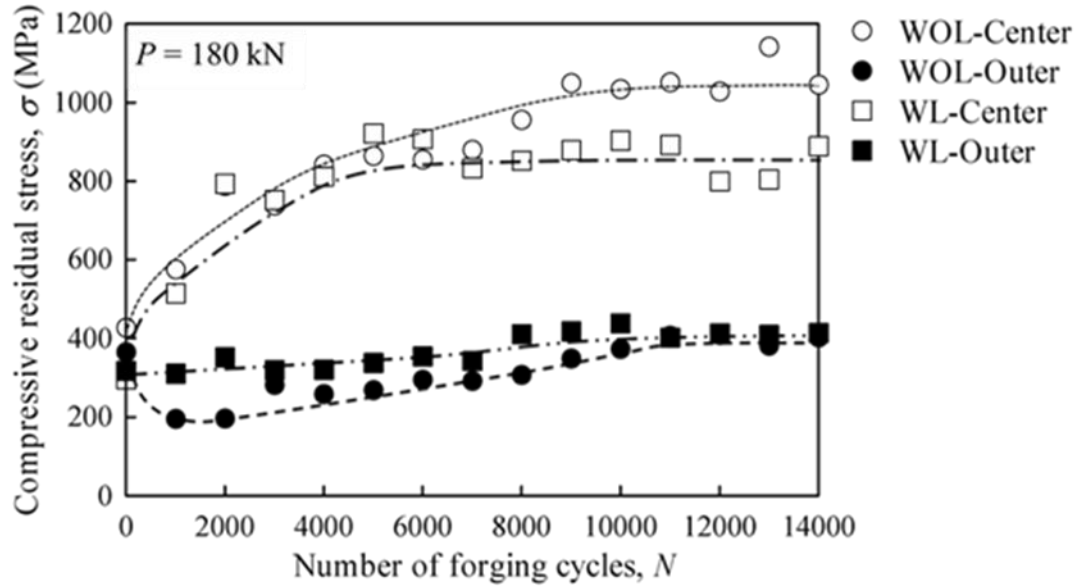


Fig. 3.9 Compressive residual stress at the center and the average of outer areas by the number of forging cycles, for the 180 kN forging load. (WL-With Lubrication, WOL-Without Lubrication).

Jiang et al. [7] studied the effect of machining process and polishing on residual stress. Their study showed that significant compressive stress was present in ground materials, whereas a tensile stress on EDMed surfaces. Moreover, the compressive stress in the ground materials was strongly enhanced when compared to that of polished materials. The specimen preparation process consists of surface grinding, and polishing. Thus, the initial residual stress on the working surface of the specimens was compressive in the radial direction. Plastic deformation is one of the mechanisms that generate residual stress. Plastic deformation occurs and some residual stresses will remain after unloading when the stress exceeds the elastic limit of the material during loading [8, 9]. Compressive residual stresses are generated when the surface is plastically deformed due to a compressive force and they are trying to return to the original position. The larger compressive residual stress that was observed for 180 kN reveals that a larger plastic deformation occurred under this condition.

3.3.3 Deformation of the specimens

Figure 3.10 shows the cross-section images of the specimens after 14,000 forging cycles. Even though the downward displacement at the center of the specimens that were subjected to the 150 kN load was not clearly visible at the current magnification, the displacement of the specimens subjected to 180 kN was clearly observed. According to the pressure distribution equation that Timoshenko and Goodier gave [10], for a circular sectioned punch that was subjected to load

under the frictionless condition, the highest pressure/stress appears at the center of the punch. Higher plastic deformation occurs at the center when the stress at the center largely exceeds the elastic limit of the material.

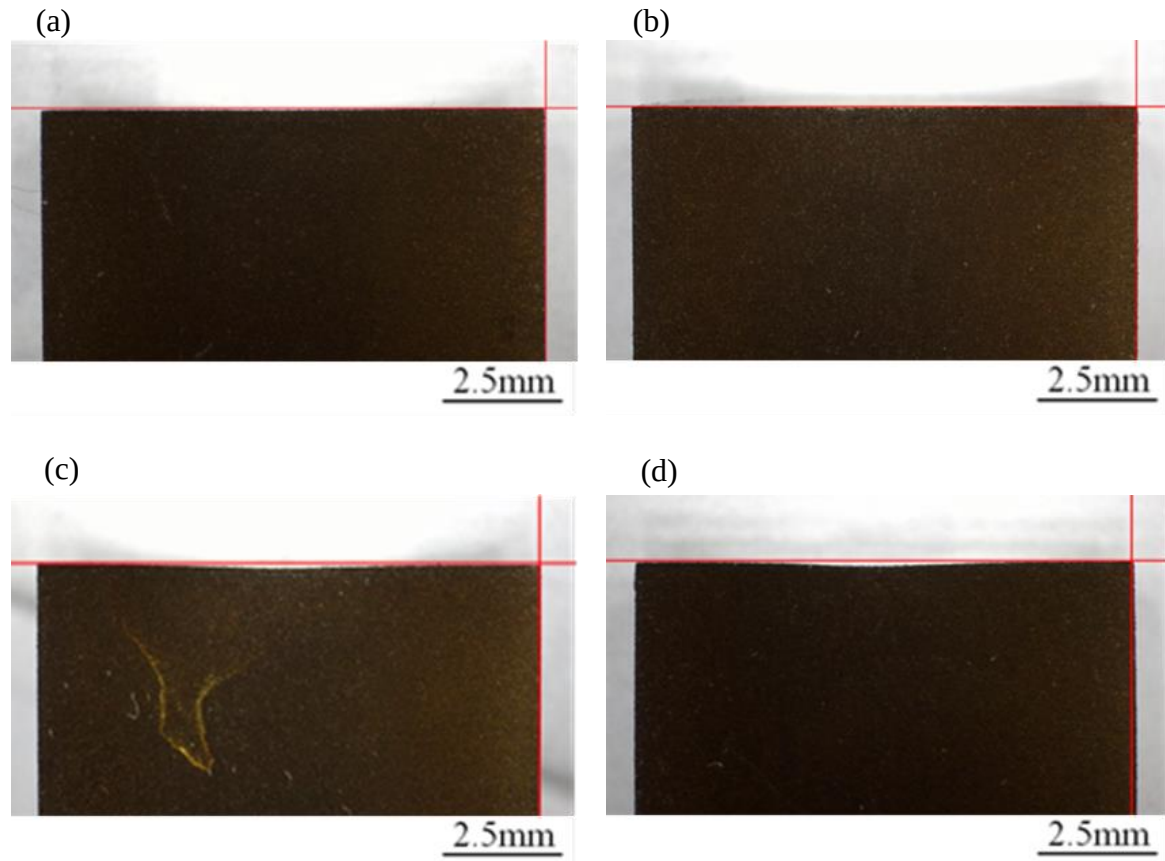


Fig. 3.10 Cross section image of the specimen after 14000 forging cycles (a) 150-WL; (b) 150-WOL; (c) 180-WL; (d) 180-WOL. (150/180-Forging load (kN), WL-With Lubrication, WOL- Without Lubrication).

Figure 3.11 shows the variation in the downward displacement, Z , by the number of forging cycles, N . A larger displacement was observed under the 180 kN condition. The downward displacement with lubrication had close resemblance to that of ‘without lubrication’, in the case of a forging load of 150 kN. However, in the case of a forging load of 180 kN, the center deformation with lubrication was larger than that of the ‘without lubrication’ condition. The lubrication encouraged the plastic deformation of the specimen. Regardless of lubrication and load conditions, the downward displacement rapidly increases at the beginning, followed by a gradual increase and then a constant value. Work hardening occurs on surfaces that are subjected to cyclic loading, which increases the strength of the material and increases the elastic limit. Thus, the propagation of deformation of the specimen was terminated after a certain number of forging cycles.

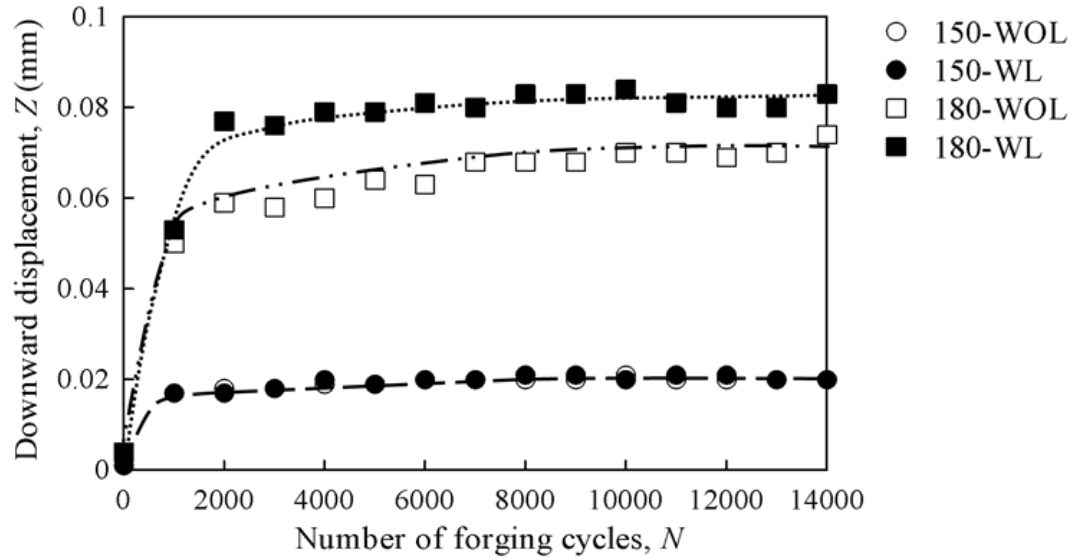


Fig. 3.11 Variation in the downward displacement with number of forging cycles. (150/180-Forging load (kN), WL-With Lubrication, WOL- Without Lubrication).

Figure 3.12 shows the variation in specimen average height reduction, ΔH , by the number of forging cycles, N . A large height reduction was observed on the specimen that was subjected to the 180 kN load when compared to specimen subjected to the 150 kN load. Regardless of forging load or lubrication conditions, a large height reduction was initially observed. This was followed by a further decrease with a slower rate, and finally by a constant. Z and ΔH show the same tendency against the number of forging cycles.

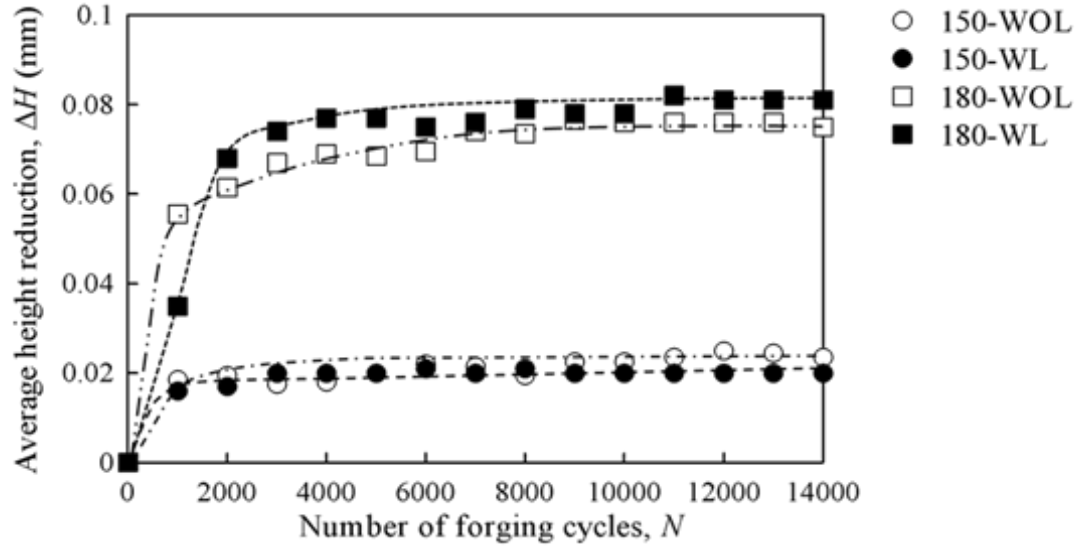


Fig. 3.12 Variation in the specimen average height reduction with number of forging cycles. (150/180-Forging load (kN), WL-With Lubrication, WOL- Without Lubrication) Lubrication).

Figure 3.13 shows the change in the variation of the outer diameter (near the working surface), ΔD , by the number of forging cycles, N . A large change in diameter was observed for the 180 kN load condition when compared to the 150 kN load condition. The diameter changes under the ‘with’ and ‘without’ lubrication conditions are almost the same for the 150 kN forging load. Furthermore, when the forging load was 150 kN, the diameter of the specimens gradually increased until 11,000 cycles, followed by no change. In contrast, when the load increased to 180 kN, the diameter of the specimen continued to increase until 14,000 cycles. Furthermore, an effect of lubrication on diameter change was observed under the 180 kN load condition. The diameter increasing tendency was almost the same as the downward displacement and the average height change. The difference was the effect of lubrication at the 180 kN forging load. The presence of lubrication makes the radial deformation easier. Therefore, the material in the surface easily moves outward in the radial direction, as the vertical deformation occurs near the surface. On the other hand, under the ‘without lubrication’ condition, the radial displacement at the surface was restricted by friction. The cross-section image of the specimen that was subjected to the 180 kN load under the ‘without lubrication’ condition illustrated in Figure 3.10 clearly shows bulging on the outer surface. Thus, the maximum diameter was observed not at the surface, but about 2 mm to 4 mm below the working surface. Bulging occurs by plastic deformation near the surface of the specimen, and the degree of bulging depends on friction and it has a positive relationship [11]. The bulging effect is high in the ‘without lubrication’ condition when compared to the ‘with lubrication’ condition due to high friction between the counter face and the specimen working surface. The diameter close to the working surface of the specimen without lubrication showed a higher value when compared to the ‘with lubrication’ condition due

to the larger bulging.

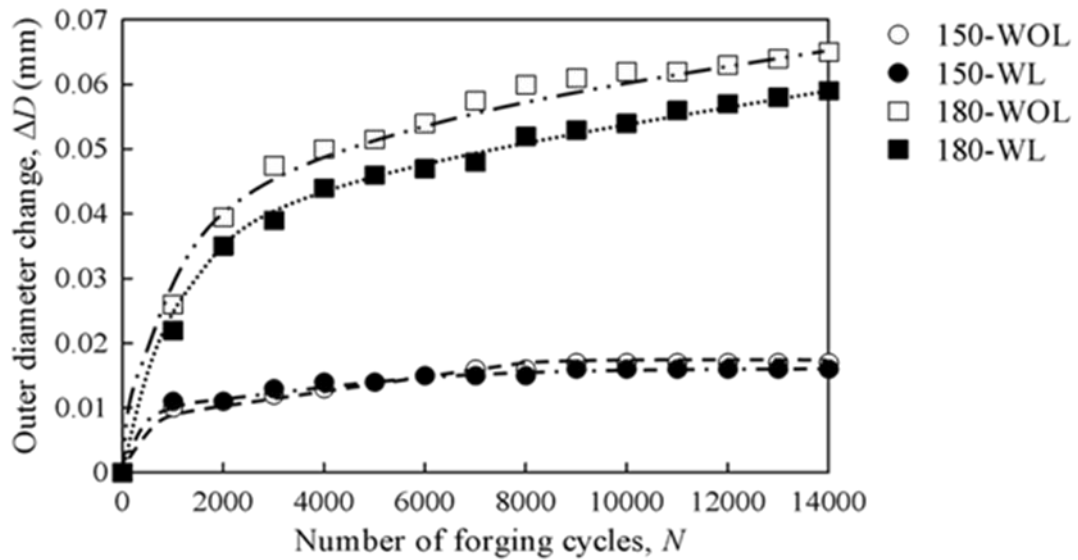


Fig. 3.13 Variation in the specimen outer diameter change (near the working surface) with number of forging cycles. (150/180-Forging load (kN), WL-With Lubrication, WOL- Without Lubrication).

3.3.4 Interrelation among evaluated parameters

The relationship between total center displacement, $Z+\Delta H$ and downward displacement, Z is shown in Fig. 3.14. A linear relationship with a slope of 2 was identified between the two parameters regardless of load or lubrication condition. Even though the vertical deformation varies with the load, it was not affected by lubrication. It was identified that the downward displacement occurred with the same rate against the average height change throughout the experiment.

Figure 3.15 shows the relationship between outer diameter change, ΔD and total center displacement, $Z+\Delta H$. A linear relationship was observed between two parameters at low deformation stage for both lubrication conditions. As the deformation progresses, the effect of lubrication on the relationship between the parameters can be observed. At higher loads, radial deformation showed a larger variation than to the vertical deformation. The vertical shifting of the plots means the difference of deformation shape, namely, uniform radial deformation near the surface or bulging at 2 to 4 mm below the working surface. A large ΔD value is obtained at the same value of $Z + \Delta H$ since the bulging is a more localized deformation restricted by friction on the surface.

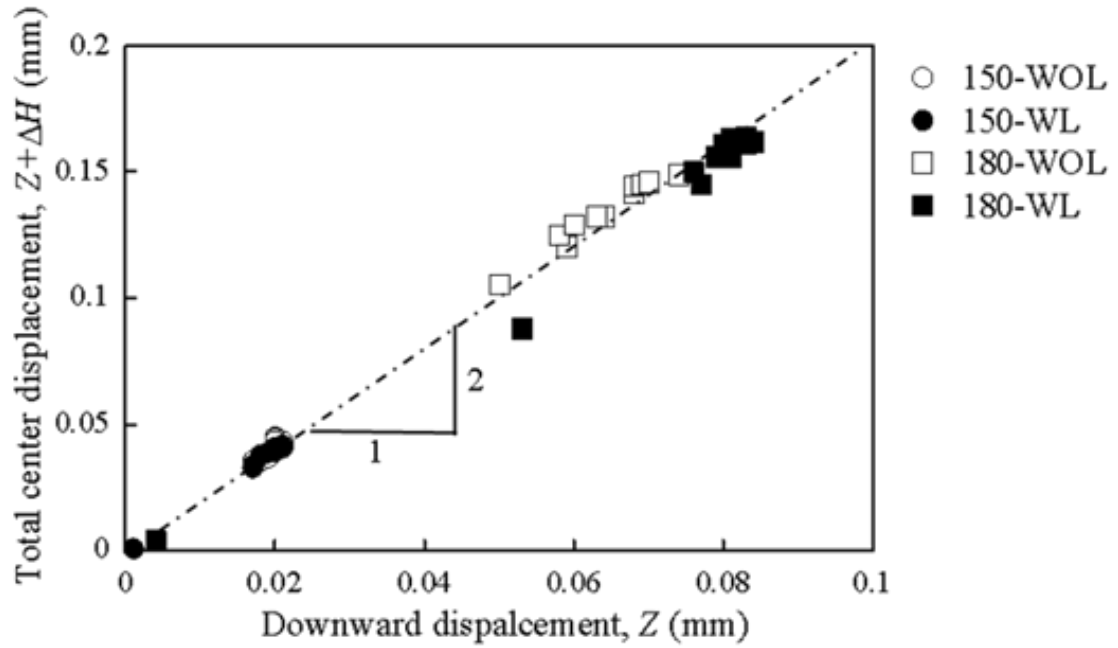


Fig. 3.14 Relationship between the total center displacement and downward displacement. (150/180-Forging load (kN), WL-With Lubrication, WOL-Without Lubrication).

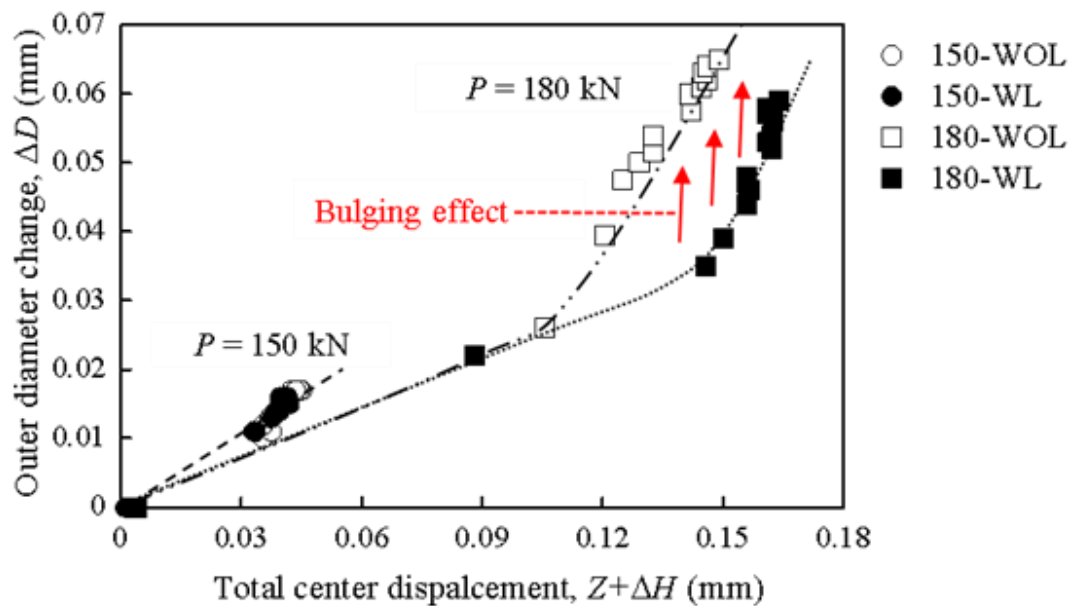


Fig. 3.15 Relationship between the outer diameter change (near the working surface) and total center displacement. (150/180-Forging load (kN), WL-With Lubrication, WOL- Without Lubrication).

The relationship between compressive residual stress change at the center, $\Delta\sigma$ and total center displacement, $Z+\Delta H$ is shown in Fig. 3.16. A positive relationship was observed between parameters. Even though the effect of forging load was clearly observed, the effect of lubrication was not identified.

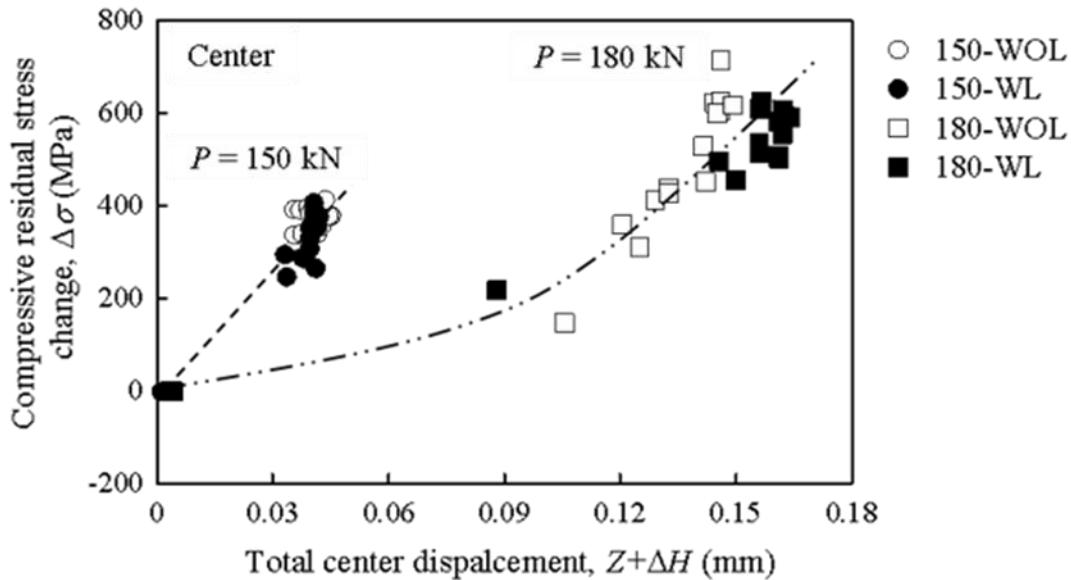


Fig. 3.16 Relationship between the compressive residual stress change and total center displacement. (150/180-Forging load (kN), WL-With Lubrication, WOL-Without Lubrication).

Figure 3.17 illustrates the relationship between surface roughness change at the center, ΔR_a and total center displacement, $Z+\Delta H$. A Positive relationship was observed for all forging conditions. At lower loads effect of lubrication was not observed. As the load increases the specimen with lubrication showed less surface roughness change for the similar deformation of without lubrication specimen. It is found from Fig. 3.11, Fig. 3.12 and Fig. 3.14 that the lubrication makes the specimen deformation easier. Therefore, the radial sliding and deformation on the surface under with lubrication condition are considered to be larger than under without lubrication condition. On the contrary, the surface oxidation occurred intensely without lubrication and the oxide increased the friction on the surface and its wear and abrasion resulting in increased surface roughness. The different curves for 180 kN load condition may have caused by oxidation.

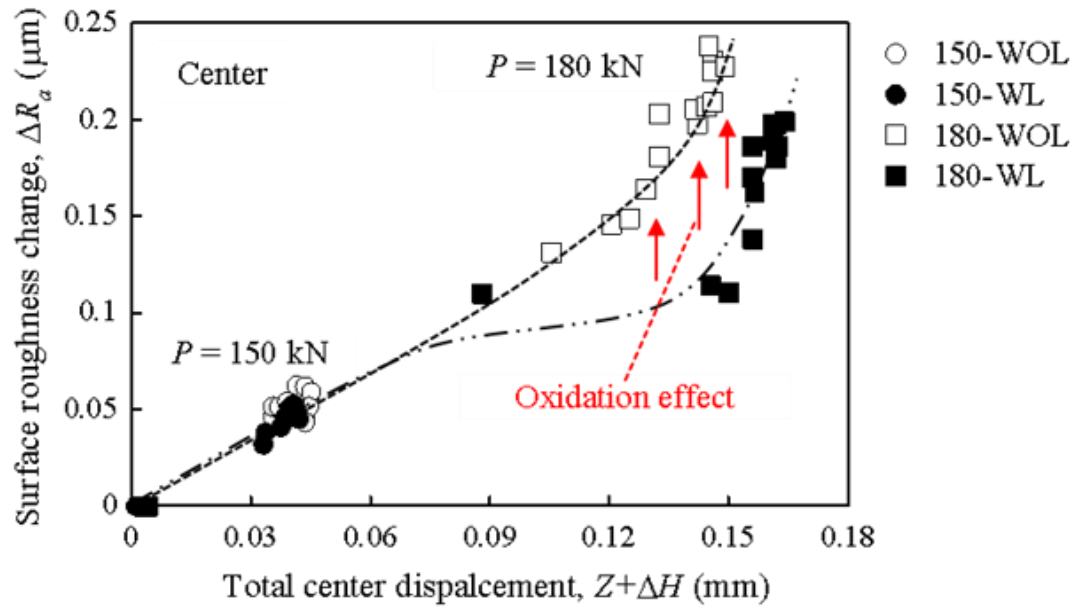


Fig. 3.17 Relationship between the surface roughness change and total center displacement. (150/180-Forging load (kN), WL-With Lubrication, WOL-Without Lubrication).

Figure 3.18 shows the schematic of specimen deformation during the experiment. During loading, the material on the specimen surface moves outward (radial displacement), and the height of the specimen is reduced due to deformation that is caused by the applied load. Radial deformation occurs and the surface extended outward uniformly when the lubrication is present and works properly. On the other hand, the ‘without lubrication’ condition caused high friction and restricted the radial deformation on the surface, resulting in barrel-shaped deformation near the working surface. The deformed surfaces try to return to the original position as the specimen releases the contact with the counter face. A downward displacement at the center occurs and compressive residual stress is generated on the working surface since the material cannot move to the original position due to the plastic deformation and high-contact pressure at the center. Higher compressive residual stress and surface roughness were observed at the center for all forging conditions due to the downward deformation at the center of the specimens.

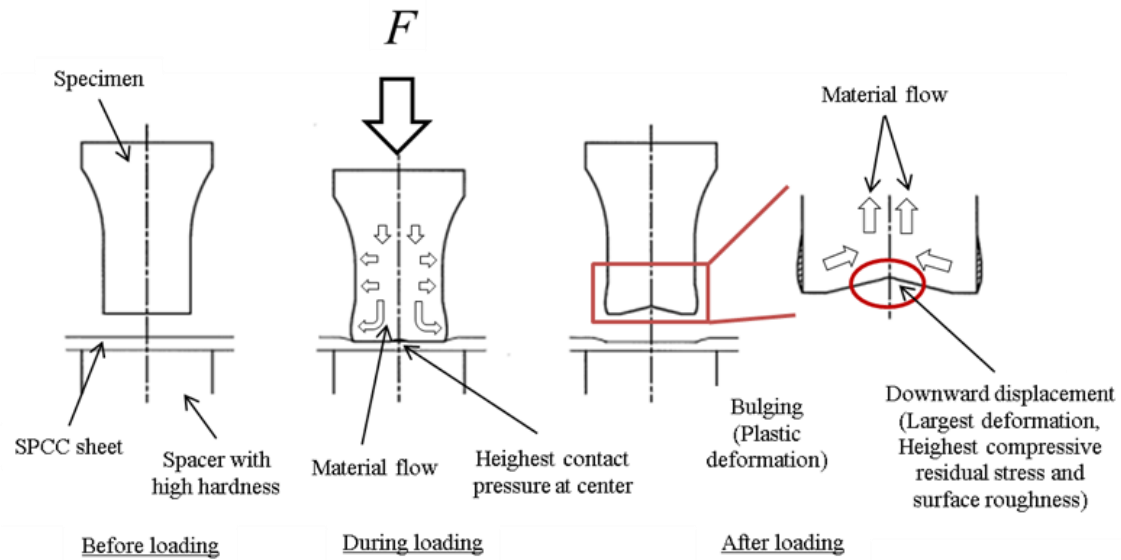


Fig. 3.18 Schematic of the specimen deformation during experiment.

The summary of the results was present in Table 3.3. An increase in the forging load resulted in a large positive effect on surface roughness, compressive residual stress, downward displacement, average height change, and outer diameter change. On the other hand, lubrication does not show a large effect on the above parameters. The presence of lubrication during forging showed a small negative effect on surface roughness, compressive residual stress, and outer diameter change, while showing a small positive effect on average height change and downward displacement. Analysis of the overall results shows that the effect of the magnitude of the forging load on the discussed parameters is large when compared to the effect of the lubrication condition.

Table 3.3 Summary of the results

Parameter	R_a	σ	Z	ΔH	ΔD
Increase in load	↑↑	↑↑	↑↑	↑↑	↑↑
Presence of lubrication	↓	↓	↑	↑	↓

↑↑: Large positive effect; ↑: Small positive effect; ↓: Small negative effect

(R_a : Surface roughness; σ : Compressive residual stress; Z : Downward displacement; ΔH : Average height change; ΔD : Outer diameter change)

Fatigue, wear, and overload are the three leading causes of forging tool failure. The failure due to fatigue and wear occurs as a result of continuous use of the tool. The initiation of

the failure most probably starts from the point with the largest deformation or abrasion. Table 3.4 shows the effects of increases in the analyzed parameters on forging tool life and forged part accuracy. Generally, surface roughness, R_a , increase has a negative effect on tool life, because the rough surface stimulates the initiation of cracks on the surface and increases the wear rate. Moreover, oxidation on the working surface of the tool, which is a reason for surface roughness, R_a , increase, considerably reduces the tool life [12]. Therefore, forging at higher loads without lubrication, which increases the surface roughness, R_a , will lead to a reduction in tool life when compared to forging at a moderate load with lubrication. It is known that compressive residual stress, σ , positively affects fatigue life, fracture strength, and stress corrosion. Fatigue is one of the main causes of forging tool failure. Therefore, an increase in compressive residual stress, σ , during forging will have a favorable effect on tool life. Deformation on the forging tool, which is represented by parameters Z , ΔD , and ΔH , reduces the tool life by creating a favorable environment for crack initiation. Furthermore, large deformation on tools causes defects on the forged product; thus, tools need to be removed from production before failure occurs by fracture or wear. Surface roughness, R_a , increase has a negative effect, even though compressive residual stress, σ , increase in the forging tool during operation causes no effect on product accuracy, because cold forging is mainly used for the production of net or near- net shape products, which required useable surface after forging. Deformation (Z , ΔD , and ΔH) in the tool will generally negatively affect the accuracy of the forged product. When considering the above facts, designing the forging process in such a way that the forging tools are operated with moderate forging loads under with lubrication conditions will accuracy increase the tool life of the forging tool and product, when compared to forging tools operated with high loads under no lubrication conditions.

Table 3.4 Effect of increase in analyzed parameters on forging tool life and forged part accuracy

Parameter	R_a	σ	Z	ΔH	ΔD
Tool life	↓	↑	↓	↓	↓
Forged part accuracy	↓	—	↓	↓	↓

↑ : Positive effect; ↓ : Negative effect; —: No effect

(R_a : Surface roughness; σ : Compressive residual stress; Z : Downward displacement; ΔH : Average height change; ΔD : Outer diameter change)

3.4 Summary

A cold forging upsetting process was carried out with specimens that were made of heat-treated SKH51 (59–61 HRC) material as the punch, under ‘with lubrication’ and ‘without lubrication’ conditions, with two different forging loads. The influences of lubrication and forging load on surface roughness, residual stress, and specimen deformation were studied. The main findings can be listed, as below:

- The forging conditions greatly influence changes in surface compressive residual stress, surface roughness, and deformation of the forging tools during operation. There is a positive relationship between the forging load and all of the above parameters (surface compressive residual stress, surface roughness, and tool deformation).
- The presence of lubricant during the forging process reduces the increase in surface compressive residual stress and surface roughness of the tool. A uniform distribution of compressive residual stress or surface roughness is not present on the working surface of the tool, for a higher forging load.
- The use of lubricant in forging changes the deformation behavior of the tools and surface condition deterioration. The downward displacement at the center has a positive linear relationship with average height reduction. The presence of lubrication changes the deformation behavior at higher loads.
- The surface roughness change depends on both the forging load and lubrication conditions, but compressive residual stress change largely depends only on forging load.
- The use of lubricant and a moderate forging load will lead to an increase in the tool life, when compared to forging without lubrication (dry forging) at high forging loads. Furthermore, the results of this study can be used in forging tool design and decisions regarding surface treatment conditions, in order to improve the tool life and product quality.

3.5 References

- [1] T. W. Ku, B. S. Kang: *Int. J. Adv. Manuf. Technol.*, 74 (2014) 1337-1354.
- [2] M. Krajewski, K. Brzozka, W. S. Lin, H. M. Lin, M. Tokarczyk, J. Borysiuk, G. Kowalskia, D. Wasik: *Phys. Chem. Chem. Phys.*, 18 (2016) 3900-3909.
- [3] H.M. Ghasemi, M.J. Furey, C. Kajdas: *Wear*, 162-164 Part A (1993) 357-369.
- [4] E. Labašová: *Am. Int. J. Contemp. Res.*, 3-4 (2013) 1-5.
- [5] T. Herai, M. Ejima, K. Yoshida, K. Miyauchi, H. Ike: *Sci. Pap. Inst. Phys. Chem. Res. (Japan)*, 72 (1978) 1- 13.
- [6] K. Osakada, R. Matsumoto: *CIRP Ann. Manuf. Technol.*, 49-1 (2000) 161-164.
- [7] D. Jianga, G. Annéa, J. Vleugelsa, K. Vanmeensela, W. Eeraertsb, W. Liub, B. Lauwersb, O. V Biesta: In *Proceedings of the 16th International Plansee Seminar*, Reutte, Austria, Vol. 2 (2005) 1075-1085.
- [8] J. A. Williams, R. S. Dwyer-Joyce: *Modern Tribology handbook (Principles of Tribology)*, Springer-Verlag Berlin Heidelberg. Vol.1 (2000).
- [9] M. Natori, S.M. Song, K. Sugimoto: *J. Soc. Mater. Sci.*, 63 (2014) 662-668.
- [10] S. P. Timoshenko, J. N Goodier: *Theory of Elasticity*, McGraw-Hill, New York (1951).
- [11] S. Malayappan, R. Narayanasamy: *Int. J. Adv. Manuf. Technol.*, 23 (2004) 636–643.
- [12] O. Barrau, C. Boher, C. Vergne, F. Rezai-Aria, R. Gras: *Proc. 6th Int. Tool Conf. Karlstad*, (2002) 81-94.

Chapter 4

EFFECT OF FORGING CONTACT PRESSURE APPLIED TO TOOL SURFACE ON FATIGUE LIFE OF HIGH SPEED TOOL STEEL

4.1 Introduction

The lifetime of tools for cold forging process is limited by wear and fatigue. Certain factors like surface topography and residual stress are important in controlling fatigue behavior. Figure 4.1 shows the basic configuration of a closed die cavity forging which consists of a die, punch and counter punch. Based on the forging load, the internal pressure of the die container increases, resulting a radial force on die internal surface which creates a contact pressure on the tool surface. It is known that the radial and circumferential stresses generated due to internal pressure in the die are always compressive and tensile respectively [1]. Furthermore, the working surfaces of punch and the counter punch are also subjected to compressive stresses during forging. In continuous forging, there is a cyclic radial force applied on the die surface due to the internal pressure generated in the cavity which creates cyclic contact pressure. Moreover, the punch and counter punch are also subjected to cyclic contact pressure during continuous forging.

Chapter 3 discussed about the parameters (surface roughness, residual stress and deformation) which vary on the forging tool during a cold forging operation. It is important to understand the effect of the variation of these parameters on the fatigue properties of the tool steel, since fatigue is one of the main modes of failure. The parameters are varied due to the contact pressure applied on tool surface and the relative motion between the workpiece material and the tool during the forging process. The contact pressure applied on forging tool varies depending on the load of the forging process.

The objective of this study is to investigate the effect of the cyclic contact pressure applied on tool's surface during forging on the fatigue life of the tool material. Heat treated and polished JIS SKH51 specimens were used in the experiment. Compressive loads with three different magnitudes were applied on the specimen surface to demonstrate the radial force applied during forging. The effect of the magnitude of contact pressure on deformation, residual stress, material hardness and surface condition was evaluated. This was followed by tensile and fatigue tests to evaluate the effect of contact pressure on the tensile strength and fatigue life of the material. Ultimately the results were used to discuss the effect of cyclic contact pressure applied on tool surface on tool life of the cold forging tool in the perspective of fatigue life.

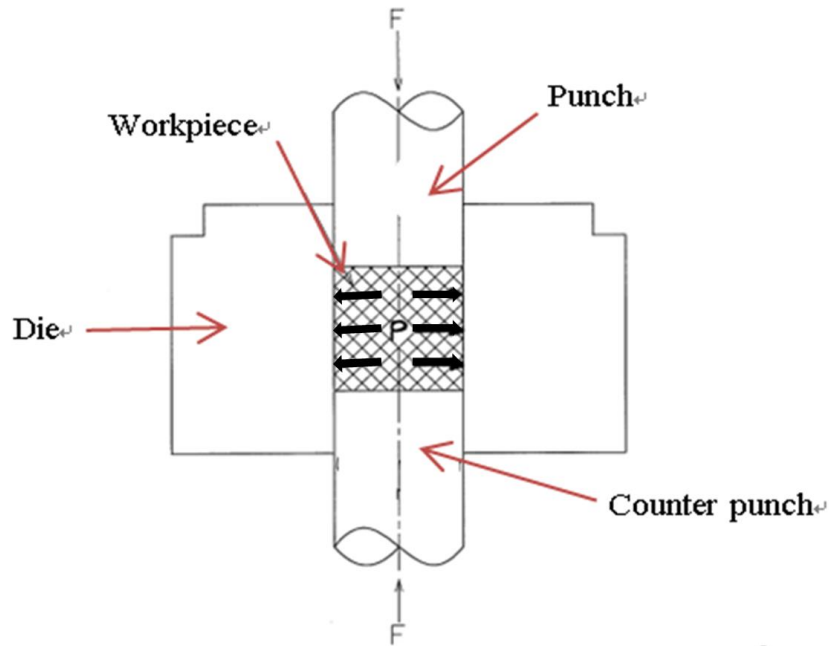


Fig 4.1 Basic configuration of closed die cavity forging.

4.2 Experimental procedure

4.2.1 Testing materials and specimen preparation

High speed tool steel SKH51 (AISI M2; DIN 1.3343) was used. The chemical composition of the material is shown in Table 4.1. The specimen was made out of a round bar of steel in a way that the loading direction is similar to the grain flow direction of the steel. The round bar of steel was machined to get a cube shaped material block. The material block was preheated at 550 °C and 850 °C before austenitized at 1120 °C. Then it was quenched and tempered 3 times at 560 °C, to achieve a hardness of 59-61 HRC. Heat treated material was machined to get the outer shape and thickness of the specimen using wire electrode discharged machining (WEDM) process. This was followed by surface grinding of the sliced specimens. Initially, the rough surface occurred due to grinding was removed by “Iepco” surface treatment equipment using cleaning and peening agents with processing pressure of 0.1 MPa. This was followed by polishing using abrasive polishing machine SMAP (Shot Machine A. one Polish) of Toyo Kenmazai Kogyo Ltd. Diamond media #3000 and #10000 was used respectively to achieve a surface roughness of $R_a = 0.07 \mu\text{m}$ to $0.08 \mu\text{m}$. Initial dimensions of the specimen are shown in Fig. 4.2.

Table 4.1 Chemical composition of SKH51 (wt. %).

C	Si	Mn	Cr	Mo	V	W	P,S
0.80-0.88	≤0.45	≤0.40	3.80-4.50	4.70-5.20	1.70-2.10	5.90-6.70	≤0.03

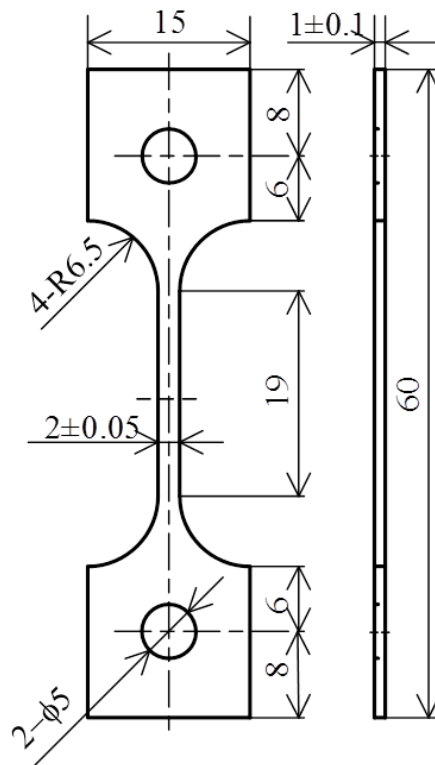


Fig 4.2 Initial dimensions of specimen.

4.2.2 Forging setup

Shimadzu UH-500KNX universal testing machine (Fig. 4.3) was used for forging of specimens. Experimental set up is shown in Fig. 4.4. The specimen was placed on a spacer made of SKH55 (AISI M35) material with a hardness of 65 HRC. The set forging speed was 25 mm/min. The zero limit of the stroke was set at 1 mm below the point that 1 kN load was obtained. The bed of the universal tester was moved upward until the load became set load value and kept at that position for 1 sec. The set load values were 150 kN, 300 kN and 450 kN, which give 750 MPa, 1500 MPa and 2250 MPa of contact pressure on the specimen surface, respectively. Then the base was moved downwards until the stroke reached 1mm from starting position. Each specimen was forged 3000 cycles.

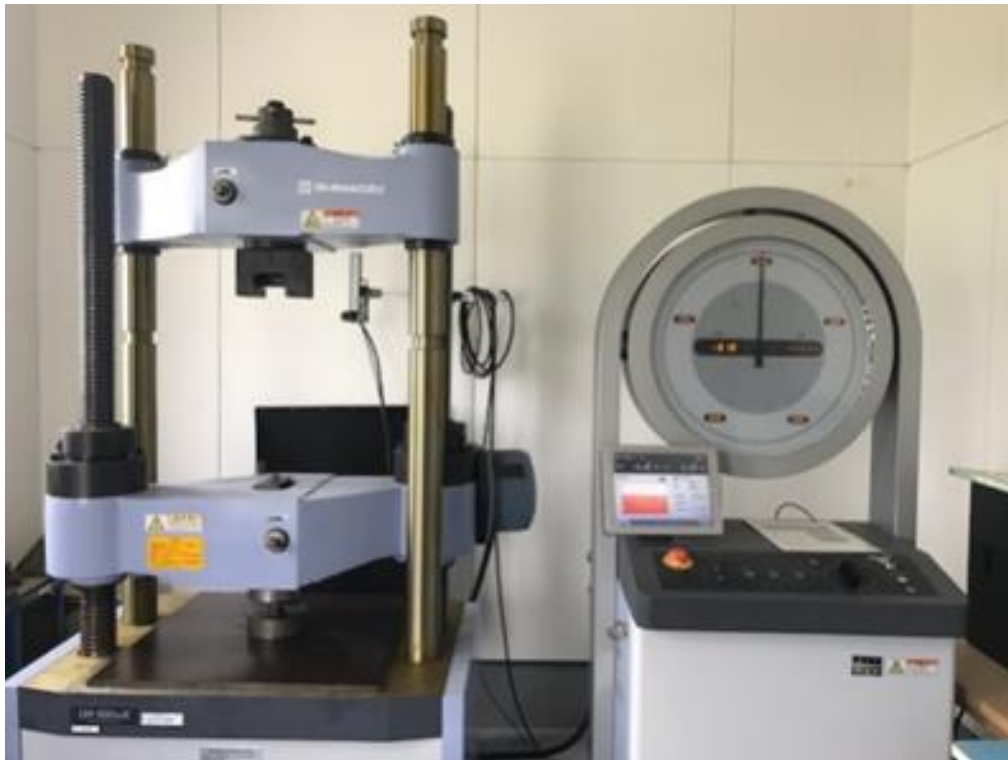


Fig 4.3 Universal testing machine.

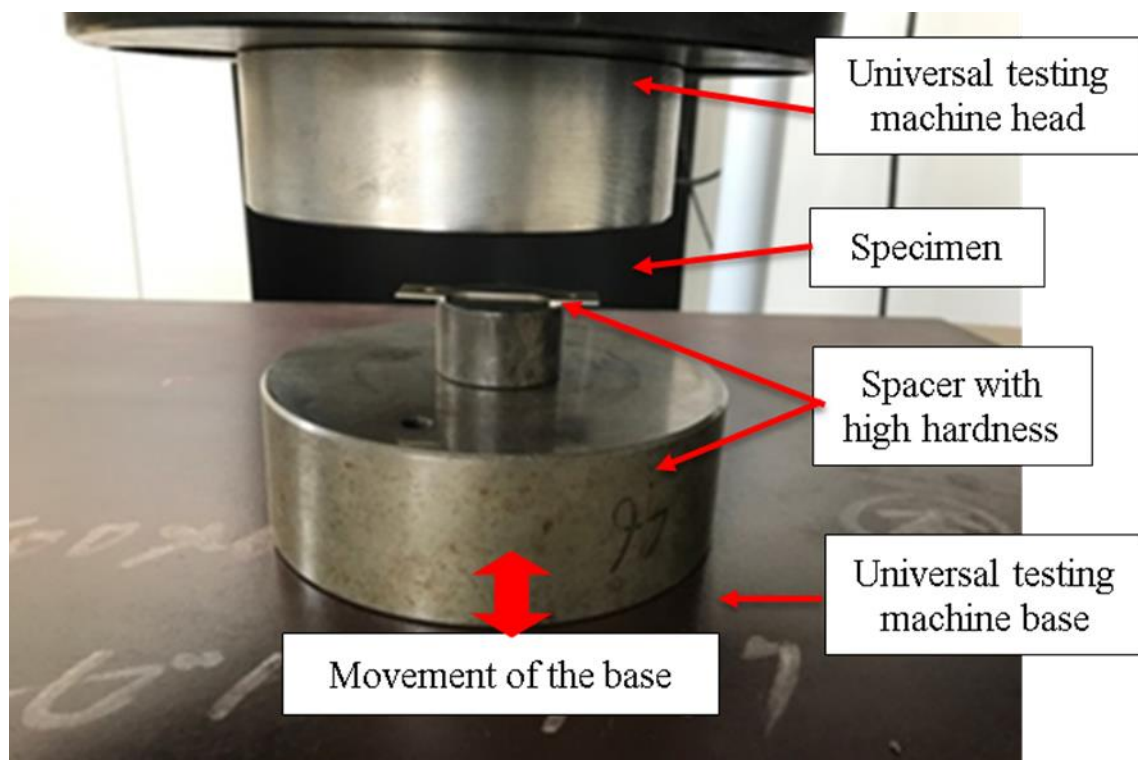


Fig 4.4 Experimental setup for forging of fatigue test specimens.

4.2.3 Tensile and fatigue tests

Shimadzu Autograph (AGS-J series) tensile testing machine (Fig. 4.5) was used for the tensile test. The tensile test was carried out at room temperature with the crosshead speed of 0.5 mm/min for both forged and unforged specimens. Hydraulic servo type fatigue testing machine (SHIMADZU; EHF-EB50KN-10L) (Fig. 4.6) was used for axial fatigue test. Fatigue test for both forged and unforged specimens was done at room temperature with the maximum stress of 1680 MPa, 1440 MPa, 1200 MPa, and 960 MPa. Minimum stress was set as 48 MPa for all test conditions. The test was performed with a loading of repeated stress cycle in a sine waveform at a 1 Hz frequency.



Fig. 4.5 Shimadzu Autograph (AGS-J series) tensile testing machine

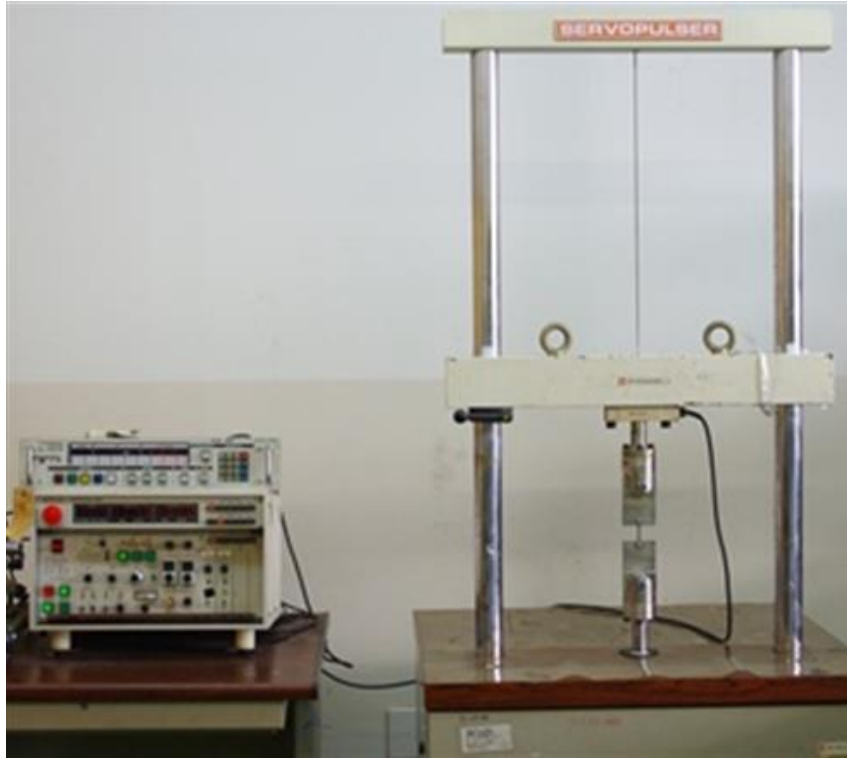


Fig. 4.6 SHIMADZU-EHF-EB50KN-10L Hydraulic servo type fatigue testing machine

4.2.4 Measurements

Dimensions, surface roughness, residual stress and hardness of specimens before and after forging were measured. Dimensions of the specimens were measured using a digimatic micrometer with a resolution of 0.001 mm. The surface roughness of both sides of the specimen was measured using surface roughness tester (Tokyo Seimitsu; Surfcom-130A). The residual stress of the specimen surface was measured using the X-ray residual stress analyzer (Pulstec; μ -X360). The hardness of the specimens was measured using Vickers hardness tester (Shimadzu; HMV-G20) with a testing force of 980.7 mN. Specimen surfaces before and after forging, and fracture surfaces after fatigue test were observed by the optical microscope (Olympus; BX-41M) and scanning electron microscope (Hitachi; S-3500N).

4.3 Results and discussion

4.3.1 Forging test

Fig. 4.7 shows the full specimen image, optical microscope image and SEM observation of the surface near the center of forged and unforged specimens. Specimen images show that the shininess of the surface was reduced and a brownish color substance was accumulated on the areas where the load was applied. It can be considered as ferrous oxide debris generated due to the tribological contact during forging. According to the optical micrographs, surface appearance deteriorates as the contact pressure increases. According to the SEM observation, the groove like surface texture observed in the unforged surface was disappeared as the contact pressure increased. The groove marks are the remaining tool marks of the surface grinding operation which was not removed during the polishing process. Due to the applied pressure, the peaks of the surface were plastically deformed and the peak height was reduced to make a flat surface. The carbide of the material can be clearly identified in white spots. The light ash color in the SEM image of the specimen subjected to 2250 MPa contact pressure is considered to be the oxide layer.

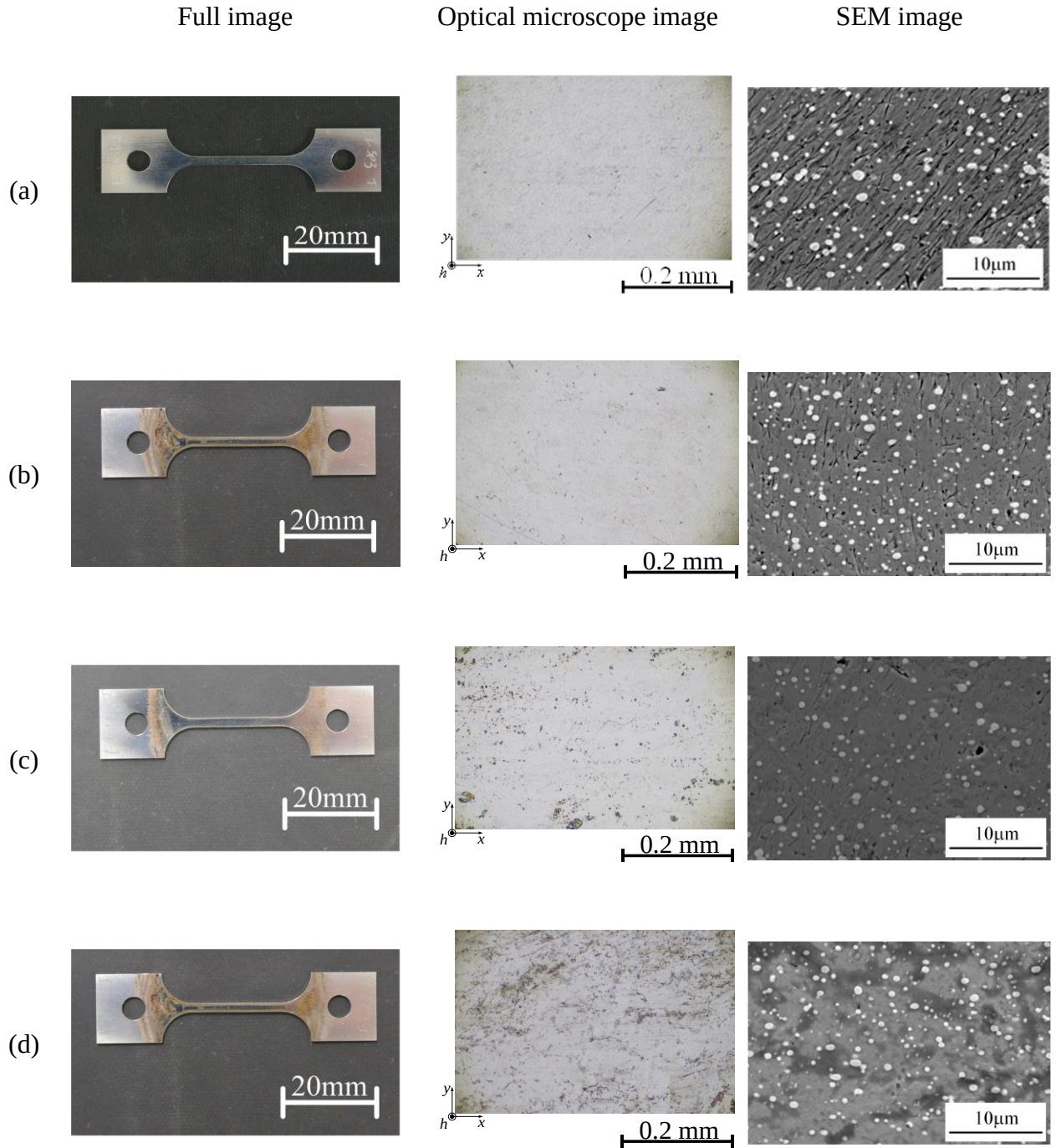


Fig. 4.7 Full image, Optical microscope image and SEM image of specimens

(a) Unforged; (b) Forged-150 kN (Contact pressure-750 MPa);(c) Forged-300 kN (Contact pressure-1500 MPa) ; (d) Forged-450 kN (Contact pressure-2250 MPa).

The specimen thickness reduced while the width increased due to forging. Fig. 4.8 shows the variation in average dimension due to forging. The average change in thickness reduction and width increase has a positive relationship with contact pressure applied on the specimen surface. At 750 MPa contact pressure, the dimensional change for both thickness and width did not show a significant difference. Due to the shape of the specimen and the forging set up arrangement, the width direction has the highest degree of freedom for material movement. Therefore, as the contact pressure increases, the change in width surpassed the change in thickness. The results show that the change in both the thickness and width nearly doubled when the contact pressure was doubled. On the other hand, as the contact pressure increased by a factor of 3, the thickness and parallel path width showed a higher plastic deformation. When consider this in actual forging condition, higher dimensional change in the forging tool can lead to defective forged parts in the perspective of dimensional accuracy.

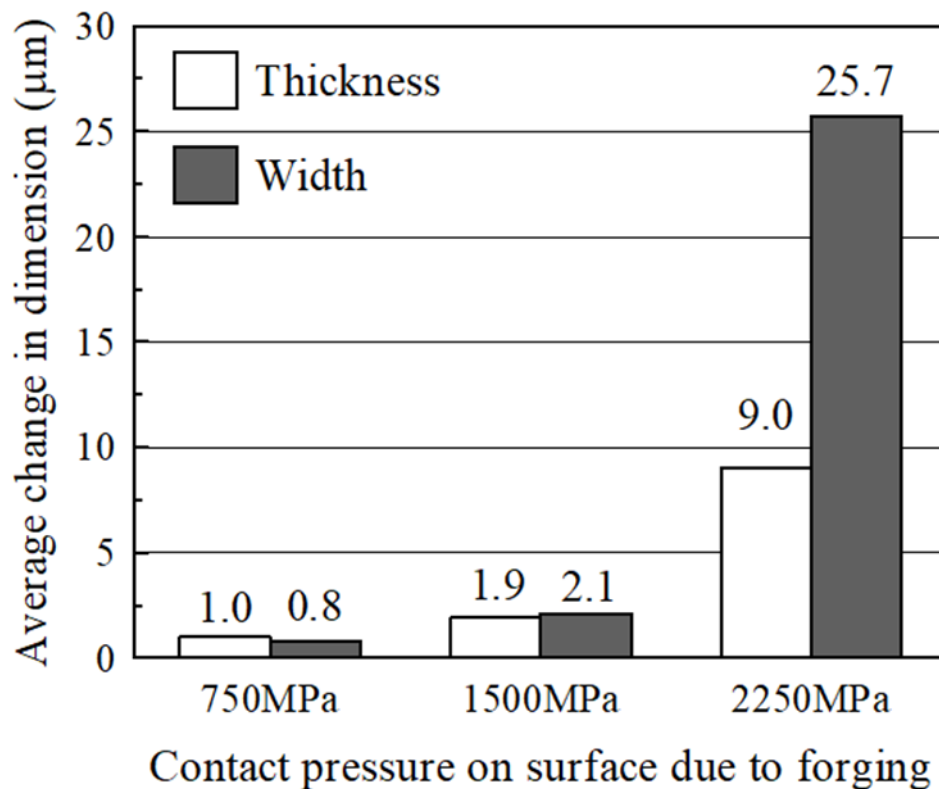


Fig. 4.8 Variation of dimension with contact pressure

The results of residual stress measurement on the longitudinal direction of the specimen surface before and after forging showed an increase in compressive residual stress on the specimen due to forging. The relationship between contact pressure on the surface and the

average change in compressive residual stress due to forging is shown in Fig. 4.9. The compressive residual stress and contact pressure applied on specimen surface shows a positive relationship. According to the results, as contact pressure doubled the compressive residual stress nearly doubled. On the other hand, as the contact pressure increased by a factor of 3, the compressive residual stress was increased by a factor of 4.5. Natori et al. [2] stated that plastic strain due to severe plastic deformation and expansion strain due to strain induction transformation of metastable retained austenite are primarily related with higher compressive residual stress. The increase in dimensional change and compressive residual stress change is nearly similar to the increase of contact pressure. As the plastic deformation was large at the contact pressure 2250 MPa, the compressive residual stress also showed a higher change.

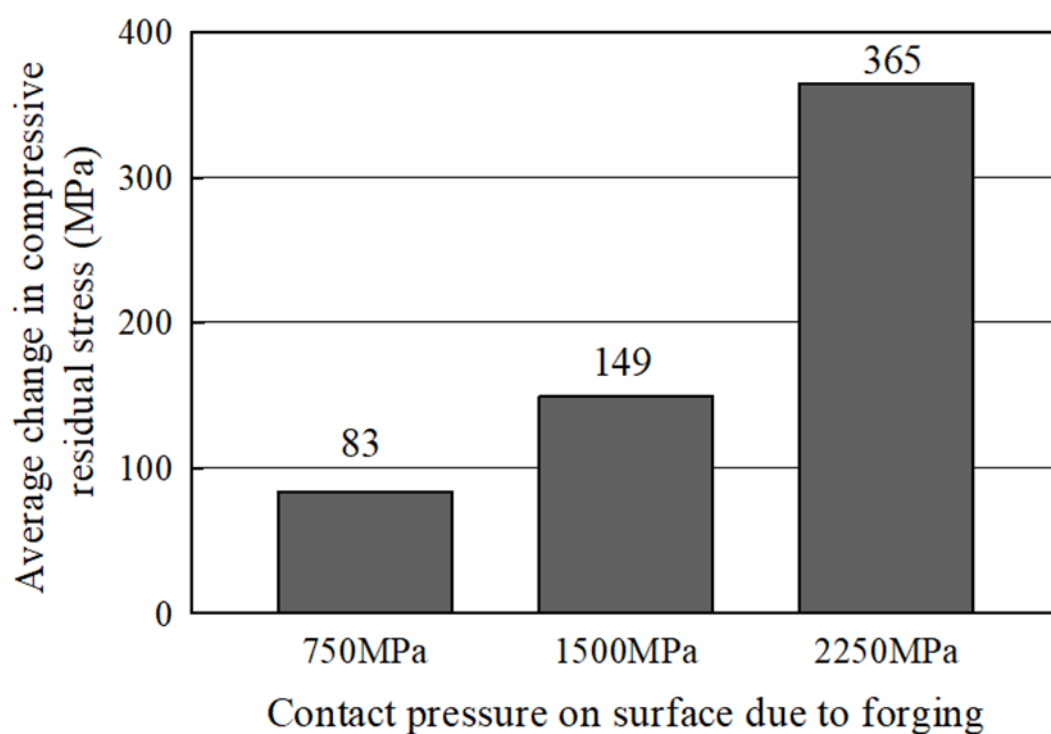


Fig. 4.9 Variation in compressive residual stress with contact pressure

Three specimens were forged with 150 kN, 300 kN, and 450 kN to study the hardness change in the material due to forging. The change in hardness in respect to contact pressure is shown in Fig. 4.9. The results illustrate a hardness increase in specimen surface due to forging. It is caused by the work hardening of specimen surface due to plastic deformation during forging. Due to the hardness increase, the material surface becomes brittle. This brittleness is due to the inability of the material to support incremental loading due to the jamming process without

plastic arrangement [3].

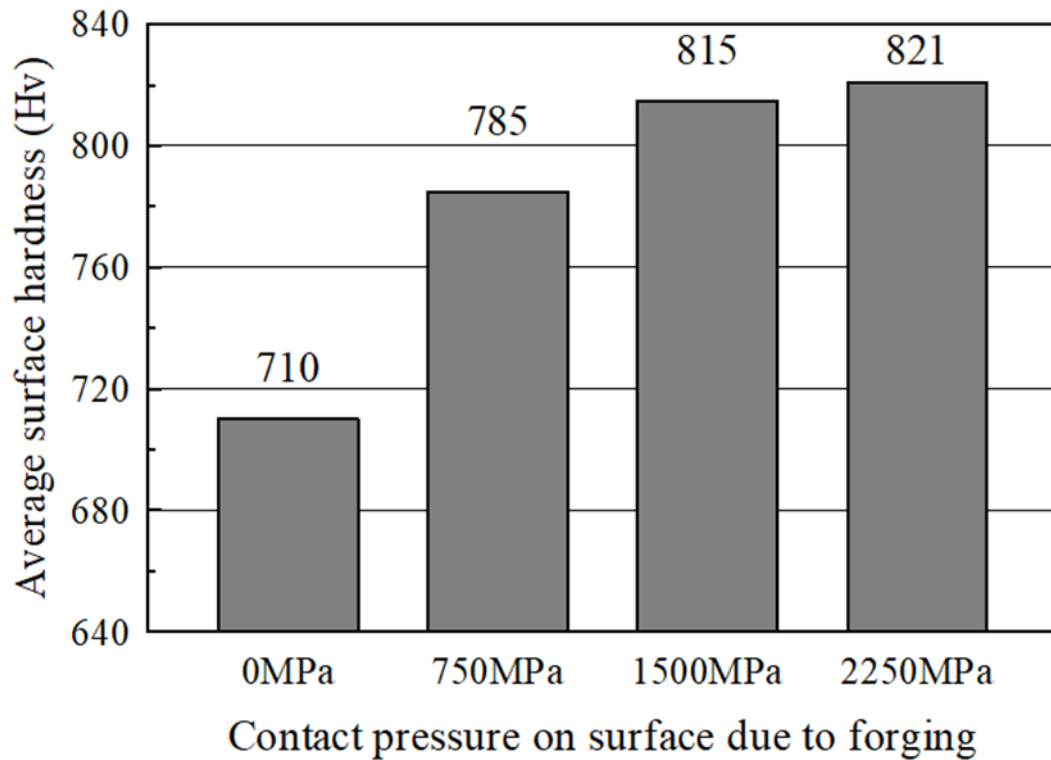


Fig. 4.10 Variation in average surface hardness with contact pressure (0 MPa= before forging)

Figure 4.10 shows the effect of forging on the surface roughness of the specimen. The surface roughness of the specimens forged with the contact pressure of 750 MPa and 1500 MPa did not show a significant difference with initial roughness value. On the other hand, the specimens forged with higher contact pressure (2250 MPa) showed a slight decrease in surface roughness. This may cause by the deformation of the uneven surface to a flat surface due to the pressure applied on the surface.

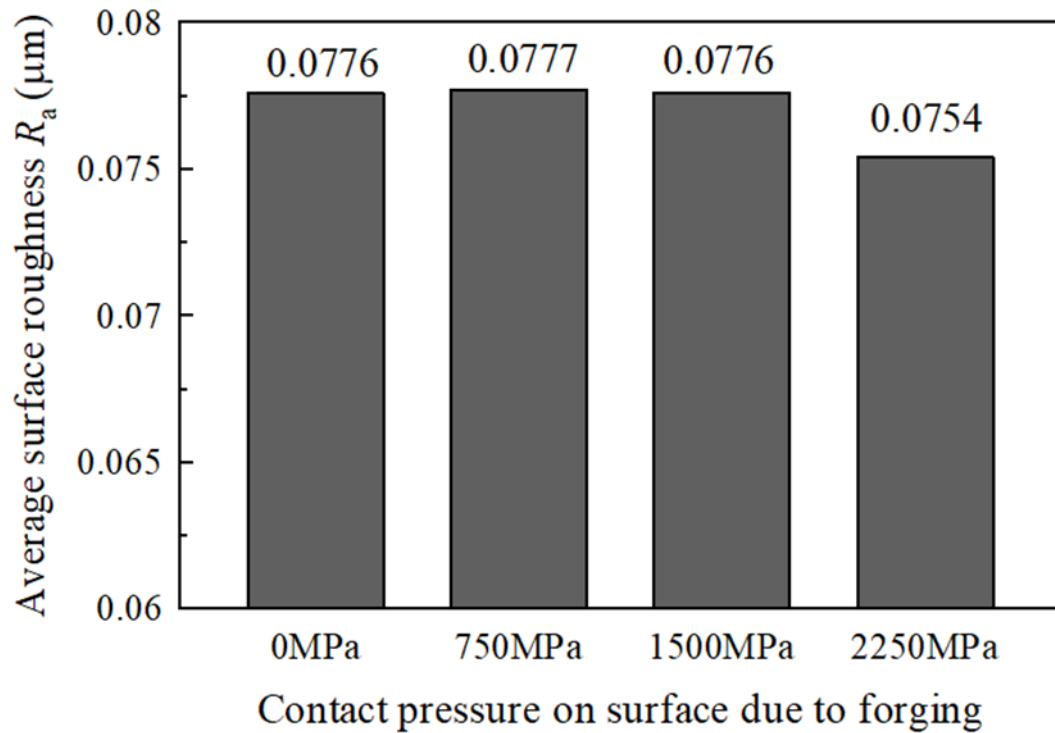


Fig. 4.11 Variation in average surface roughness with contact pressure (0 MPa= before forging)

4.3.2 Tensile test

Results for forged and unforged specimens are listed in Table 4.2 and nominal stress-strain curves are shown in Fig. 4.11. The tensile strength and strain at fracture of the specimen subjected to 750 MPa slightly increased while the specimen forged with 1500 MPa showed an approximately similar value compared to the unforged specimen. On the other hand, the tensile strength of the specimen forged with 2250 MPa slightly decreased in tensile strength and strain at fracture. In general, yield strength and tensile strength of steel show a positive correlation with hardness value [4, 5]. Shaid and Hashim [6] stated that the rough surfaced steel specimens show a lower tensile strength in comparison to polished specimens. Since there was no significant surface roughness variation in current specimens the results was not effected by surface roughness. It is known that compressive residual stress improves the mechanical properties. Therefore, the slight increase in tensile strength and fracture strain of specimen subjected to 750 MPa was affected by the increase in surface hardness and compressive residual stress with compared to the unforged specimen. Since the variation is minimal, it can be concluding that the contact pressure applied on tool steel is not affecting the tensile strength of the material.

Table 4.2 Results of tensile test for forged and unforged specimens.

Specimen	Tensile strength (MPa)	Fracture strain
Unforged (Contact pressure-0 MPa)	2302	0.154
Forged-150 KN (Contact pressure-750 MPa)	2432	0.179
Forged-300 KN (Contact pressure-1500 MPa)	2318	0.160
Forged-450 KN (Contact pressure-2250 MPa)	2150	0.143

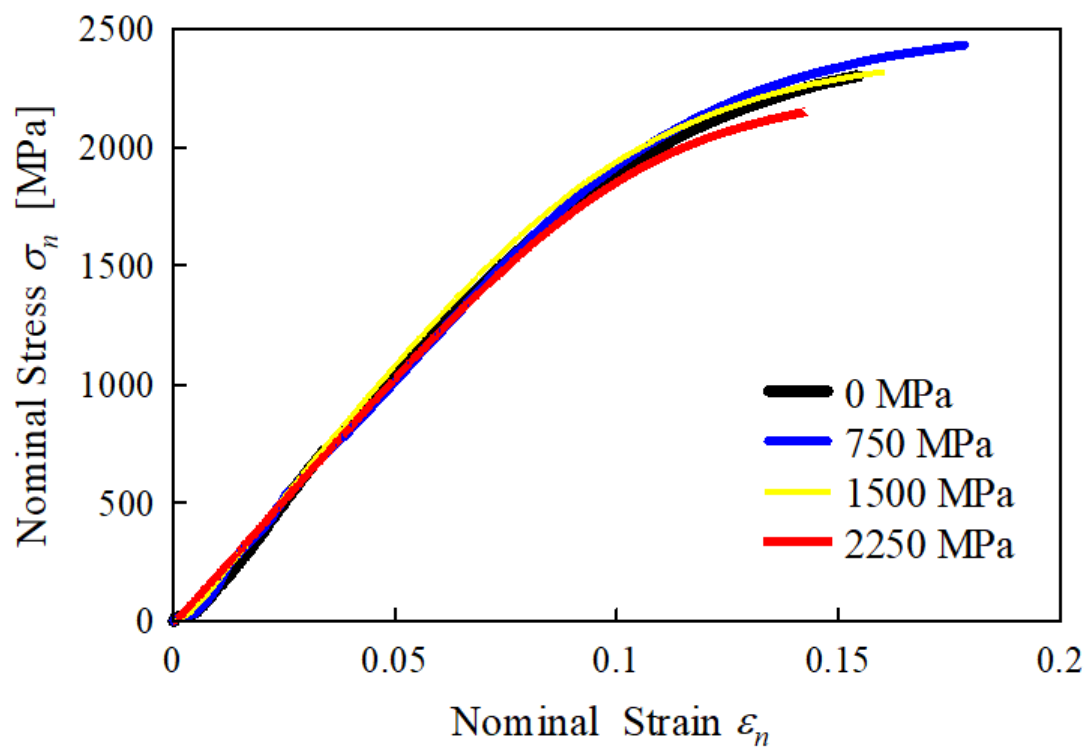


Fig. 4.12 Nominal stress- strain curve for forged and unforged SKH51 specimens (0 MPa= Unforged specimen).

4.3.3 Fatigue test

Figure 4.12 shows the S-N curves for forged and unforged specimens. There was a slight increase in fatigue life of specimens forged with contact pressure 750 MPa and 1500 MPa with compared to unforged specimens at the stress amplitude of 816 MPa. On the other hand, as the stress amplitude decreases to 696 MPa, the fatigue life for specimen subjected to contact pressure of 750 MPa slightly increased while specimens subjected to 1500 MPa and 2250 MPa decreased in fatigue life with compared to unforged specimens. Furthermore, as the stress amplitude decreased to 576 MPa, the specimens subjected to contact pressure 750 MPa and 1500 MPa improve with compared to the unforged specimens, although the specimens subjected to 2250 MPa contact pressure decreased in fatigue life. As the stress amplitude lowered to 456 MPa, neither of the specimens was broken. The fatigue life variation between different specimen types was increase as the stress amplitude decreases. As a summary of the results the specimens subjected to low (750 MPa) and medium (1500 MPa) contact pressures showed an improved fatigue life with compared to unforged specimens in all stress amplitude. On the other hand, as the specimens subjected to high contact pressure (2250 MPa), fatigue life decreases irrelevant to stress amplitude.

It is known fact that surface roughness and surface residual stress affect the fatigue life of the material. Previous results show that forging increased the compressive residual stress of the specimens (fig. 4.9). Even though, there is no significant difference in surface roughness, surface texture improvement can be observed by SEM due to forging. Kamaya and Kawakubo [7] stated that the compressive residual stress has a positive effect on the fatigue strength of components due to the reduction of the mean stress value. Furthermore, Ezhov and Sidyachenko [8] reported that plastic pre-deformation by bending to create deep residual compressive stress increased the fatigue strength by about 20% in steel specimens and compressor blades. Obiukwu et al. [9] stated that the surface roughness of specimen has a great effect on fatigue strength because fatigue cracks generally initiate on the specimen surface. Furthermore, he concluded his study stating that the polished surface increased the fatigue life because the rough surfaces create stress concentration centers leading to a decrease in the endurance limit. Due to the increase in surface compressive stress and surface condition improvement during forging an increase of fatigue life is observed with compared to unforged specimens except for the specimen forged with 2250 MPa.

Generally, the compressive residual stress is balanced by tensile residual stresses

generated below the compressive layers. The specimens subjected to 2250 MPa should have higher internal tensile stress with compared to other specimens due to comparatively high surface compressive residual stress. Therefore initiation of internal crack or increases in crack growth rate, once the crack passes the compressive layer may have caused the decrease in fatigue life for the specimens subjected to high contact pressure. Furthermore, according to the study of Kelleher et al. [10], the internal material defect could be an origin of crack initiation. If this is the reason for the failure, it is not related to surface or residual stress condition.

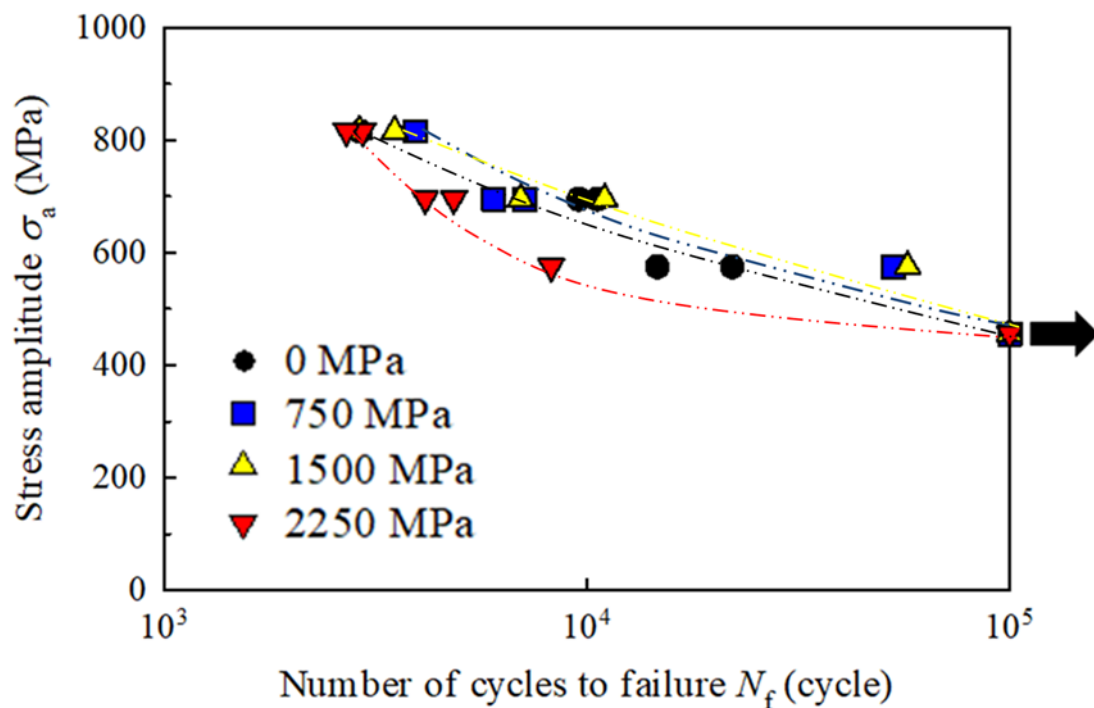


Fig. 4.13 S-N curves for forged and unforged SKH51 specimens (0 MPa= Unforged specimen).

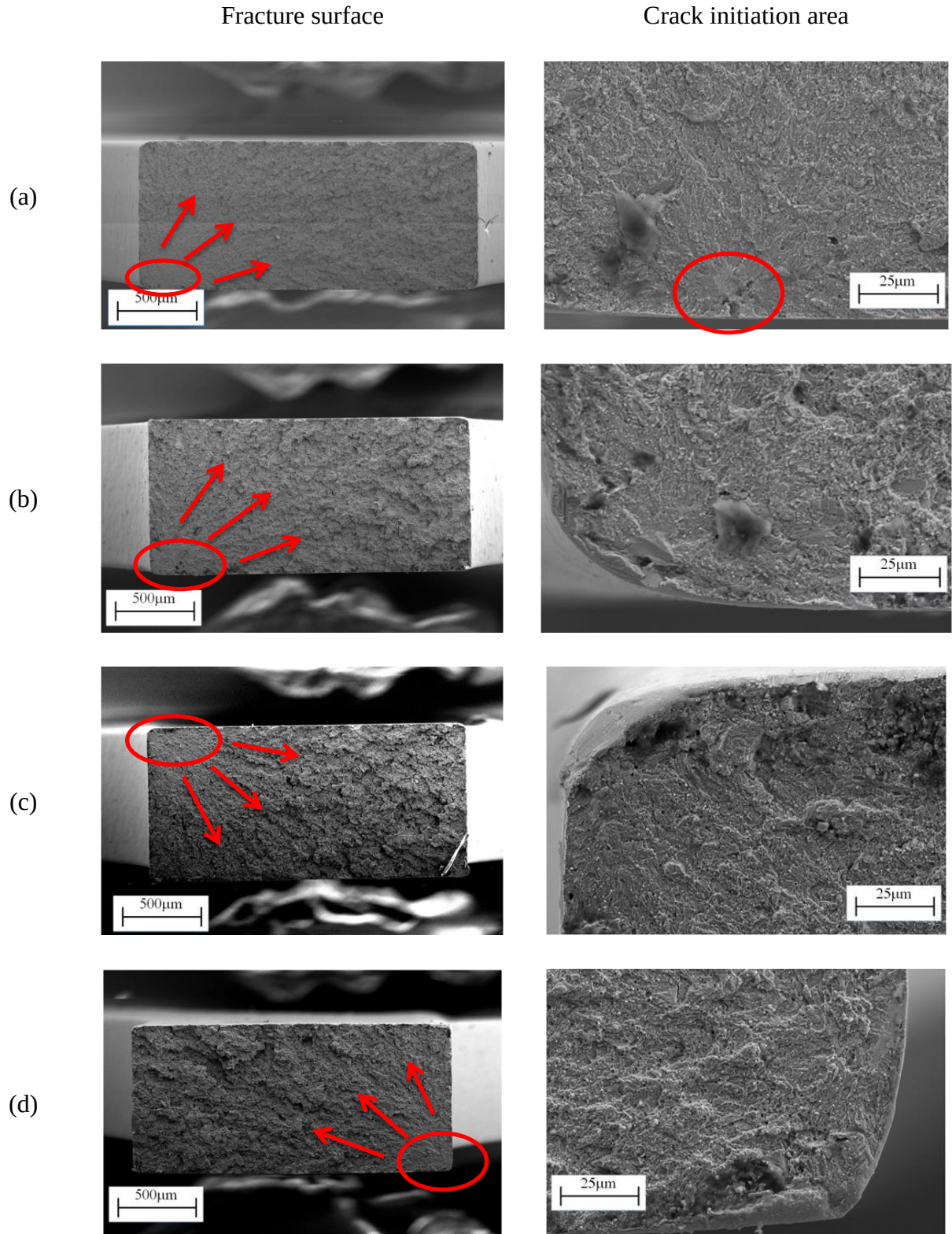


Fig. 4.14 SEM images of fracture surface and crack initiation area for specimens fatigue tested with stress amplitude of 696 MPa. (a) Unforged; (b) Forged-150 kN (Contact pressure-750 MPa); (c) Forged-300 kN (Contact pressure-1500 MPa) ; (d) Forged-450 kN (Contact pressure-2250 MPa).

Fig. 4.13 shows the SEM observation of the fracture surface of the specimen fatigue tested with stress amplitude of 696 MPa. Both crack initiation area (marked by circles) and failure direction (marked by arrows) were clearly observed for all specimens. In all cases, crack was initiated at one of the corners and propagated inwardly. In unforged specimen, the origin was very clear as indicated in Fig. 4.13(a).

As the fatigue life increases, the service life of the forging tool also increases because it is one of the causes for cold forging tool failure. According to the results obtained in the present study, the fatigue life of material increased as the contact pressure increased up to certain level. On the other hand, once it exceeds the certain limit the fatigue life decreases. Therefore it is important to know the optimum contact pressure where the fatigue life is maximized. These tests are useful for tool design and process control to increase the service life of the tool in respect to fatigue failure.

4.4 Summary

Heat treated SKH 51(AISI M2) tool steel specimens were forged with three set loads to achieve three contact pressures values on specimen surface. Influence of the magnitude of the contact pressure on dimension change, surface hardness, surface roughness, and surface residual stress was studied. Forged and unforged specimens were subjected to tensile and axial fatigue tests and fracture surface was examined. The main findings can be listed, as below:

- There is a positive relationship between dimensional change, surface hardness and the surface compressive residual stress with the contact pressure.
- No significant relationship was observed between surface roughness and the contact pressure. The tensile strength of the specimens forged with lower and medium contact pressures increased with compared to unforged specimen while the specimen forged with higher contact pressure decreased.
- Fatigue life improved when the specimen was forged with lower and medium contact pressures. Conversely, the fatigue life decreased as the specimens forged with high contact pressure.
- Assuming that all specimens are homogeneous, the fatigue life of the tool steel varies depending on the contact pressure applied on tools during the forging process.

References

- [1] A.O.A. Ibadode: Precision die design by the die expansion method, Trans tech publications, Switzerland (2009) 1-231.
- [2] M. Natori, S. M. Song, K. Sugimoto: J. Soc. Mater. Sci., Japan, 63 (2014) 662-668.
- [3] M. E. Cates, J. P. Wittmer, J. P. Bouchaud, P. Claudin: Phy. Rev. lett., (1998) 1841-1844.
- [4] A. Cicek, F. Kara, T. Kivak, E. Ekici, I. Uygur: J. Mater. Eng. Perform., 24 (2015) 4431-4439.
- [5] E. J. Pavlina, C. J. Van Tyne: J. Mater. Eng. Perform., 17 (2008) 888-893.
- [6] M. Shaid, S. A. Hashim: Int. J. Adhes. Adhes., 22 (2002) 235-244.
- [7] M. Kamaya, M. Kawakubo: Trans. Jpn. Soc. Mech. Eng., 80 (2014) 1-15.
- [8] V. N. Ezhov, V. M. Sidyachenko: Strength. Mater., 26 (1994) 772-782.
- [9] O. Obiukwu, M. Nwafor, B. Okafor, L. Grema: International Conference on Mechanical and Industrial Engineering (ICMIE'15) Harare, Zimbabwe (2018) 1-5.
- [10] J. Kelleher, M. B. Prime, D. Buttle, P. M. Mummery, P. J. Webster, J. Shackleton, P. J. Withers: J. Neutron. Res., 11 (2003) 187-193.

Chapter 5

EFFECT OF POST-TREATMENT POLISHING ON FATIGUE LIFE OF PRECISION SHOT PEENED AND MICRO-ABRASIVE BLASTED HIGH SPEED TOOL STEEL

5.1 Introduction

Surface treatments are widely used on steel to improve wear resistance, improve mechanical properties, define tribological behavior, corrosion resistance, optical behavior, etc... Surface treatment is done by mechanical, thermal, chemical and electrochemical processes while retaining toughness of the core material. Increasing surface hardness and lowering the friction coefficient by improving tribological behavior are the main aims of surface treatment in forging tool manufacturing. Such treatments should imply a correct balance between hardness and toughness to achieve suitable strength with limited crack susceptibility. Mechanical surface treatment and surface coating are the most common surface treatments used in cold forging tools. Polishing is the process to reduce the roughness of the surface with minimum material removal. Polishing is a time-consuming and value-adding process in forging tool production to increase the service life.

In the previous chapters, the effect of surface roughness and residual stress on tool life cold forging tools was discussed. This chapter discusses the effect of combining different surface treatment methods on the fatigue life of tool steel. The combination of surface treatment methods assist to reduce the negative effects of each process on fatigue life of the tool steel. On the other hand, combination of processes will increase the favorable condition to improve the fatigue life due to accumulation of positive effects of each process.

Wonder Process Craft/ Wide Peening Cleaning (WPC) treatment and micro-abrasive blasting (MB) are surface modification methods to improve the mechanical properties of the tool steel. WPC treatment is a precision shot peening method that was jointly developed by Fuji Manufacturing Co., Ltd. and Fuji Kihan Co., Ltd. (Japan Patent No. 1594395). WPC treatment and micro-abrasive blasting increase the compressive residual stress which enhances the fatigue life. On the other hand, these treatments will increase the surface roughness of the treated area, which creates a negative effect on fatigue life. Polishing after above surface treatments will reduce the surface roughness and create an environment that improves fatigue life.

The objective of this study is to investigate the effect of post-treatment polishing on fatigue life of WPC treated and MB treated JIS SKH 51 high-speed tool steel with a hardness of 59-61HRC.

5.2 Experimental procedure

5.2.1 Testing materials and specimen preparation

Molybdenum based high-speed tool steel SKH51 (AISI M2; DIN 1.3343) was used. The chemical composition of the material is shown in Table 5.1. The specimen was made out of a round bar of steel in a way that the loading direction is similar to the grain flow direction of the steel. The round bar of steel was machined to get a cube-shaped material block. The material block was preheated at 550 °C and 850 °C before austenitized at 1120 °C. Then it was quenched and tempered three times at 560 °C, to achieve a hardness of 59-61 HRC (675-720 HV). Heat treated material was machined using electrode discharged machining (WEDM) to get the outer shape and thickness of the specimen. This was followed by surface grinding of the sliced specimens using # 600 grinding wheel. The dimension of tensile and fatigue test specimen after surface grinding is shown in Fig. 5.1.

Table 5.1 Chemical composition of SKH51 (wt. %).

C	Si	Mn	Cr	Mo	V	W	P,S
0.80-0.88	≤0.45	≤0.40	3.80-4.50	4.70-5.20	1.70-2.10	5.90-6.70	≤0.03

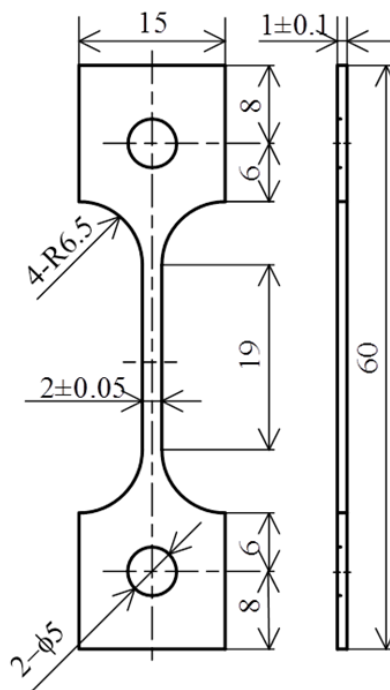


Fig 5.1 Dimensions and shape of specimen after grinding.

5.2.2 Surface treatment and polishing

Tables 5.2 and 5.3 show the surface treatment conditions of Wonder Process Craft/ Wide Peening Cleaning (WPC) treatment (by Fuji WPC Co., Ltd.) and Micro-abrasive blasting (MB) treatments (by Plustron Co. Ltd.), respectively. MB treatment consists of two processes, cleaning and peening. Dimension controlled polishing was performed with buff polisher using diamond media #3000 in the loading direction (Material removal 0.5 μ m to 1 μ m). Six types of specimens were made using different combinations of surface modification methods. Specimen code and preparation method are shown in Table 5.4.

Table 5.2 WPC surface treatment conditions.

Material	Media		Pressure (MPa)	Distance (mm)	Time (s)	Coverage	Arc height (mm)
	Hardness (HV)	Size (μ m)					
Ceramic	900	45	0.40	70	30	< 200%	0.08

Table 5.3 Micro-abrasive blasting surface treatment conditions.

Process	Media			Pressure (MPa)	Distance (mm)	Time (s)
	Material	Hardness (HV)	Size (μ m)			
Cleaning	Natural ore (MS300A)	3000	30-50	0.05	30	70
Peening	Zirconia (MS/Z500B)	1300	30-70	0.40	30	60

Table 5.4 Specimen code and preparation method.

Code	Preparation method
G	Ground
GP	Ground + Polished
GW	Ground + WPC treated
GWP	Ground + WPC treated + Polished
GM	Ground + MB treated
GMP	Ground + MB treated + Polished

5.2.3 Tensile and fatigue tests

Three specimens each from 6 types of surface conditions were subjected to tensile tests using Shimadzu Autograph (AGS-J series) (Fig. 5.2) tensile testing machine at room temperature with the crosshead speed of 0.5 mm/min. Axial fatigue test for three specimens each of every surface condition was done using hydraulic servo type fatigue testing machine (SHIMADZU; EHF-EB50KN-10L) (Fig. 5.3). The fatigue test was done at room temperature with the loading of repeated stress cycle in a sine waveform at a 1 Hz frequency. The maximum and minimum stresses were taken as 50% and 2% of average tensile strength of ground specimen, respectively. (Maximum stress-1150 MPa; Minimum stress-46 MPa) The fatigue cycle limit was set at 300000 cycles.



Fig. 5.2 Shimadzu Autograph (AGS-J series) tensile testing machine.

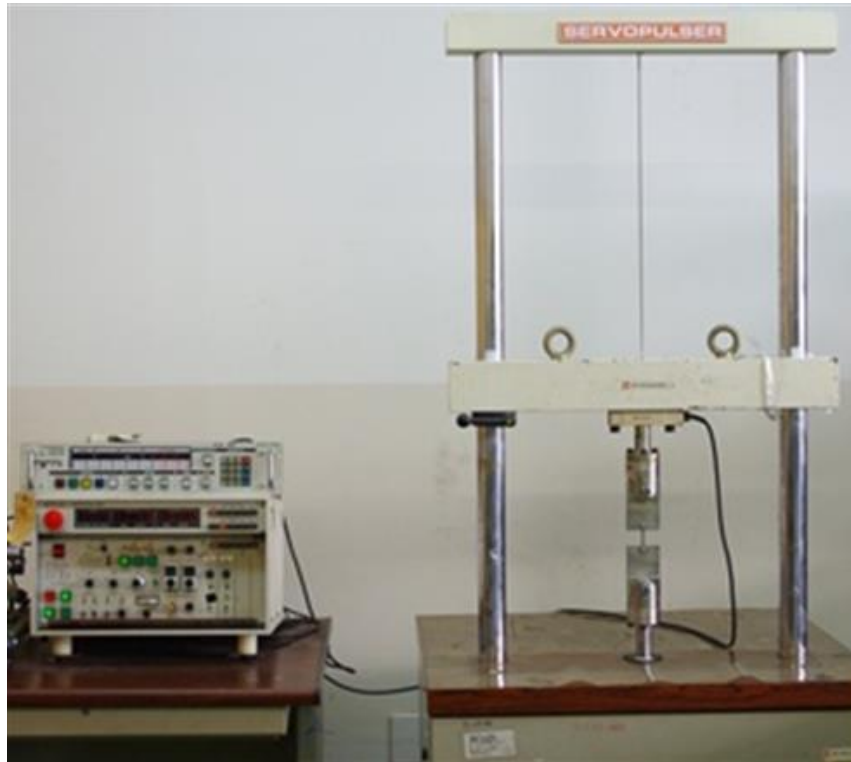


Fig. 5.3 SHIMADZU-EHF-EB50KN-10L Hydraulic servo type fatigue testing machine.

5.2.4 Measurements

Dimensions, surface roughness and residual stress of the specimens were measured after each process. Dimensions of the specimens were measured using digimatic blade micrometer with a resolution of 1 μm . Hardness of the specimen surface was measured using Vickers hardness tester (Shimadzu; HMV-G20) with testing force of 980.7 mN. Surface roughness was measured in front and back side of the specimen in X and Y directions using surface roughness tester (Tokyo Seimitsu; Surfcom-130A). Surface roughness measuring equipment and positions are shown in Fig. 5.4 (a) and Fig. 5.4 (b). The residual stress was measured on front and back sides (five positions in each side) using the X-ray residual stress analyzer (Pulstec; μ -X360). Residual stress measuring equipment and positions are shown in Fig. 5.5 (a) and Fig. 5.5 (b). Furthermore, X-ray residual stress analyzer was used to measure the residual stress of surface treated specimen after electro polishing. Chromium oxide and phosphoric acid were used for electro polishing. Specimen surfaces after each process and fracture surfaces after fatigue test were observed by scanning electron microscope (SEM) (Hitachi; S-3500N).

(a)



(b)

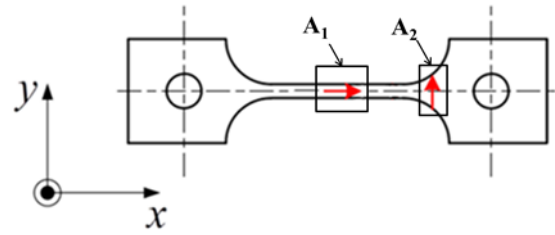
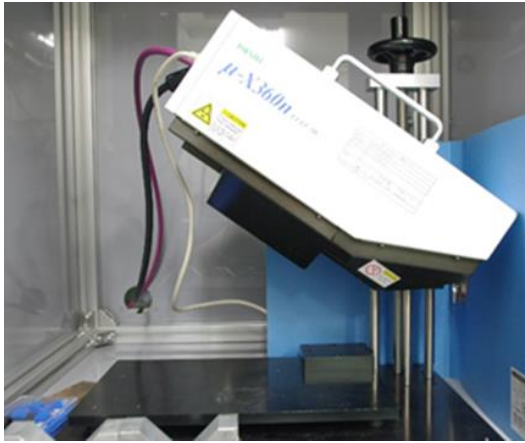


Fig. 5.4 (a) Surface roughness measuring device; (b) Measuring areas and directions.

(a)



(b)

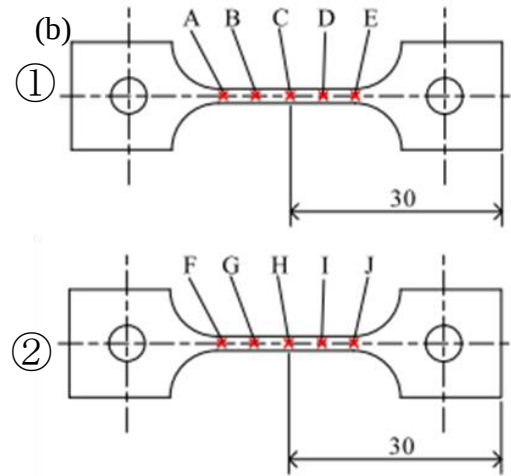


Fig. 5.5 (a) Residual stress measuring device; (b) Measuring positions (①- Front, ②- Back).

5.3 Results and discussion

5.3.1 Specimen surface condition and surface roughness.

Figure 5.6 shows the scanning electron microscope (SEM) observation of the surface near the center of the specimens. The grinding wheel marks were clearly observed in the SEM image of the ground specimen. Due to the removal of material during the polishing process, the grinding wheel marks were disappeared and a smooth surface was observed in the polished specimen. SEM images of WPC and MB treated specimen surface showed a clear difference from the initial ground surface. Surface treatment removed the grinding wheel marks completely from the specimen surface and created a small craters like textured. This was due to the collision of the media used for WPC and MB treatments with very high speed on the surface. The MB

treated surface showed more randomly overlapping craters with no specific texture or preferential direction with compared to WPC treated surface. The crater diameter up to 10 μm was observed in MB treated surface while craters on the WPC treated surface is up to 3 μm . This difference is caused by the difference in hardness and particle size used in WPC and MB treatments. Due to the material removal in the polishing process done after the surface treatment, the rough texture has disappeared to a certain extent and clear surface is observed. The craters with larger depth were remained even after the polishing process because the material removal was controlled (0.5 μm to 1 μm) during polishing.

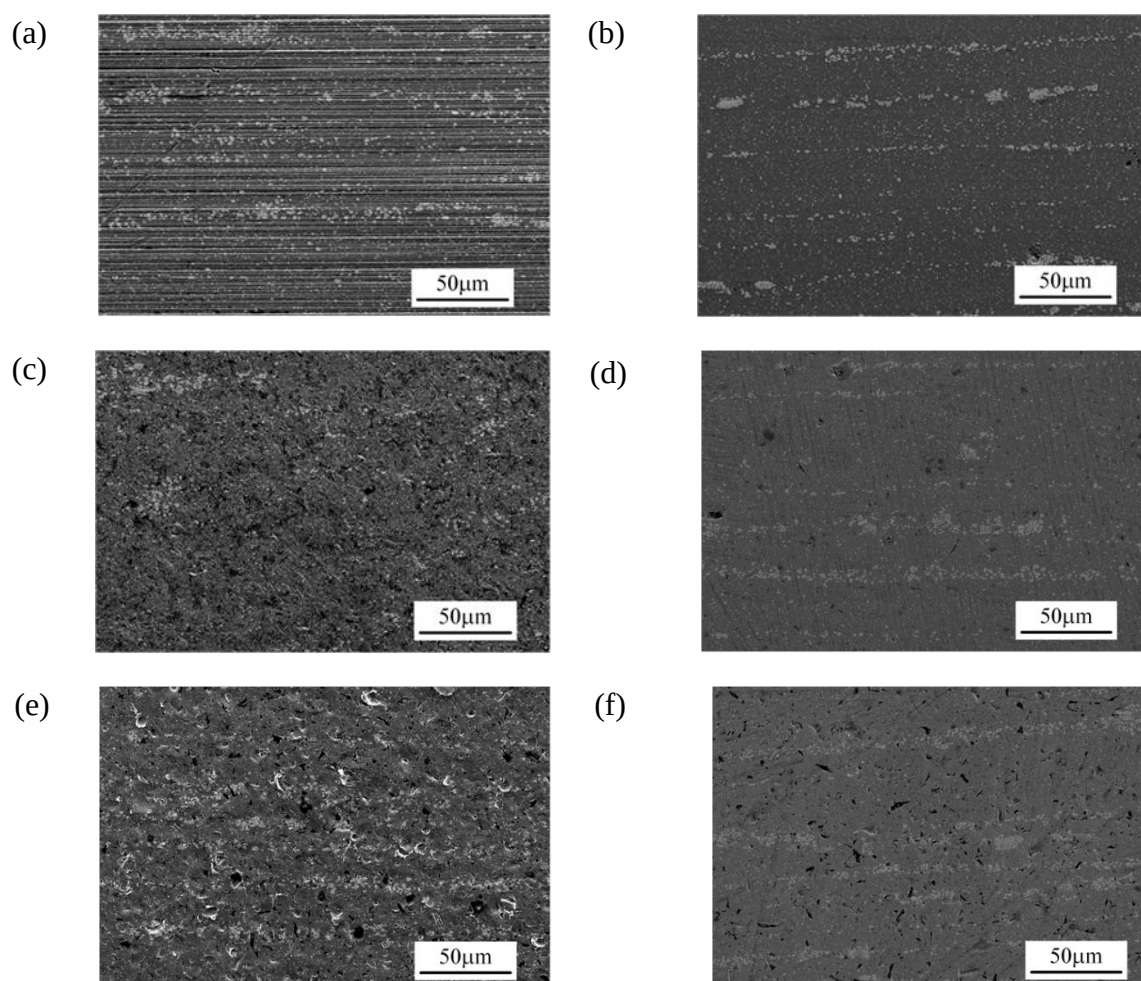


Fig. 5.6 Scanning electron microscope (SEM) image of specimens' surface (a) Ground (G); (b) Ground + Polished (GP); (c) Ground + WPC treated (GW); (d) Ground + WPC treated + Polished (GWP); (e) Ground + MB treated (GM); (f) Ground + MB treated + Polished (GMP).

The thickness and parallel path width of the specimen showed a decrease due to the surface treatment. The dimension reduction due to WPC treatment was 1 μm to 2 μm . In contrast, dimension reduction due to MB treatment was 2 μm to 3 μm . The two processes, cleaning and peening, performed in MB treatment have caused larger reduction in dimension with compared to WPC treatment which has only one process.

Figure 5.7 shows the surface hardness variation on specimen due to surface treatment. 10% hardness increase was observed due to both types of surface treatment. The hardness increase is the results of strain hardening caused by plastic deformation occurred on specimen surface due to the impact of surface treatment media.

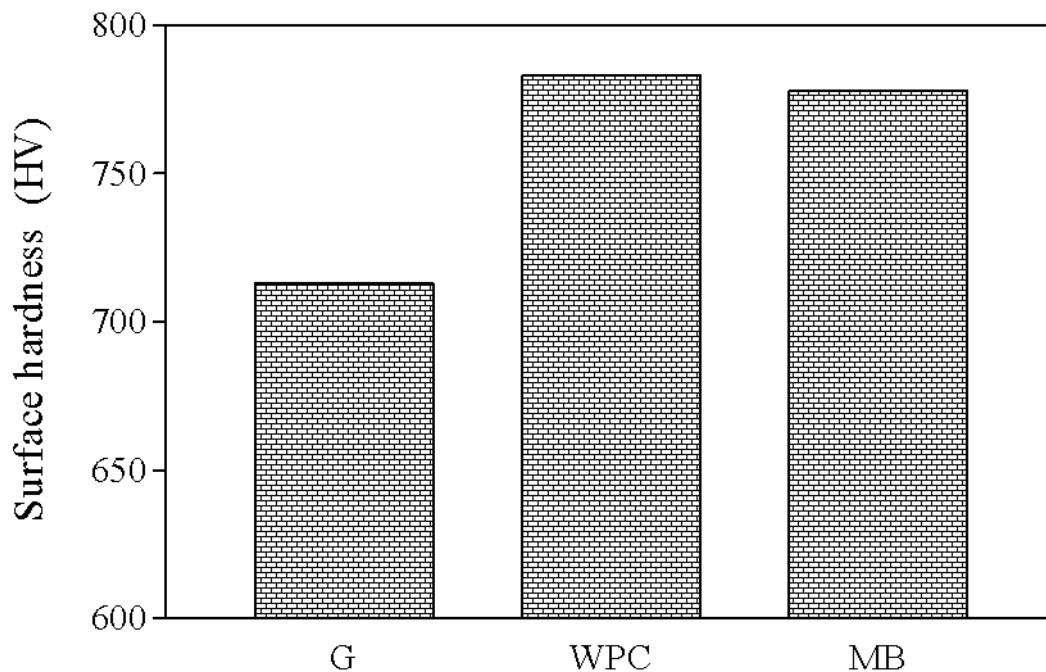


Fig. 5.7 Variation of surface hardness due to surface treatment.

The variation of average arithmetic surface roughness (Ra) due to surface treatment and polishing is shown in Fig. 5.8. Initial surface roughness (after grinding) was between 0.048 μm to 0.054 μm . Surface roughness decreased due to the polishing process. The material removal during the polishing process eliminates the grooves create by grinding process and reduced the surface roughness. On the other hand, the WPC and MB treatments increased the surface roughness of the treated surface. Surface roughness increased by 1.5 times of the initial surface roughness was observed for WPC process. On the other hand, MB treatment doubled the surface roughness at the stated treatment conditions. The study of Adoberg et al. [1] illustrated that initial

surface roughness (R_a) of $0.06\text{ }\mu\text{m}$ can be increased up to $0.70\text{ }\mu\text{m}$ based on the MB treatment condition. Abdullah et al. [2] observed that surface roughness doubled due to WPC treatment. Surface roughness increase was due to the surface texture created during the treatment process. The size of the media used for the WPC treatment is smaller and less in hardness than that of the media used for peening process in MB treatment even though the processing pressure is similar. Therefore the craters like texture created on MB treated surface is more complex as seen in the SEM image. This result in higher surface roughness increase in MB treated surface with compared to WPC treated surface. Dimension control polishing (Material remove only $0.5\text{ }\mu\text{m}$ to $1\text{ }\mu\text{m}$) was performed as post-treatment polishing. Therefore, the surface roughness created during surface treatment has a great effect on the surface roughness after post treatment polishing. Thus, higher surface roughness in MB treated surface was observed with compared to WPC treated surface after post-treatment polishing.

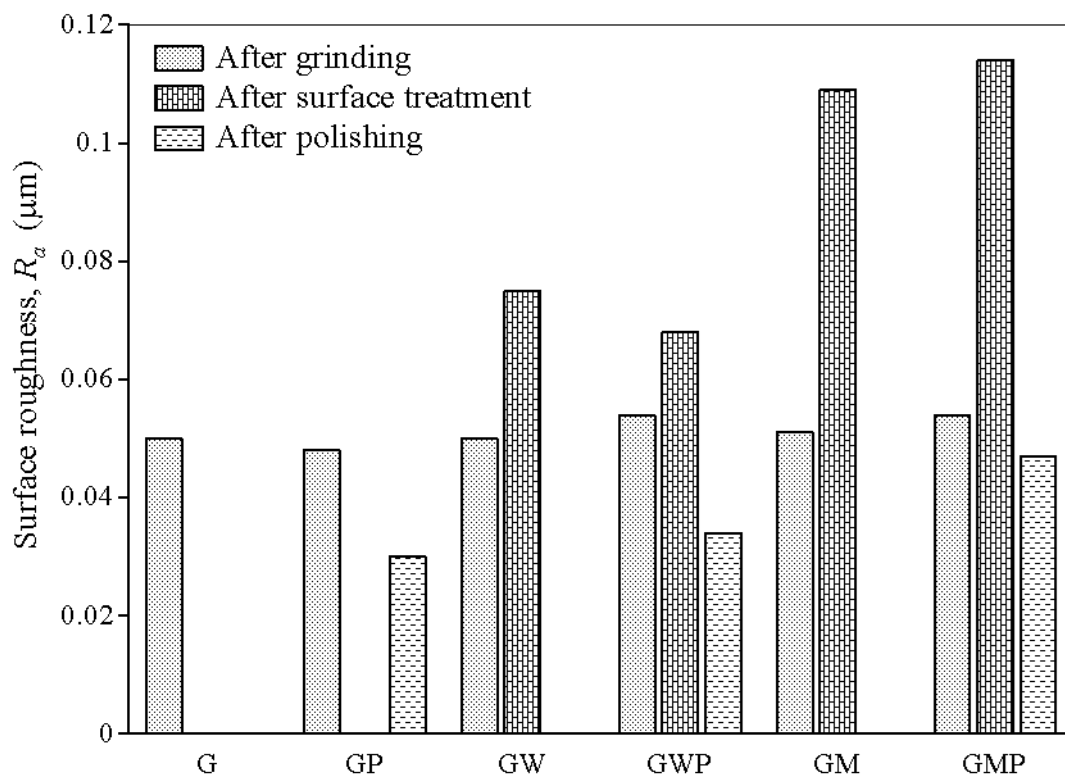


Fig. 5.8 Variation of average surface roughness with surface treatment and polishing.

5.3.2 Residual stress

The variation of the average surface compressive residual stress due to surface treatment and polishing is shown in Fig. 5.9. The initial compressive residual stress of specimen surface was generated by machining and heat treatment processes used in specimen preparation. All specimens showed almost similar initial residual stress. Compressive residual stress has increased in the specimens subjected to surface treatment and the increase is almost similar for both the surface treatment types. The compressive residual stress is about 3.5 times of initial value in current treatment conditions. Compressive residual stress is the result of a difference in plastic deformation between surface and sub-surface. Whenever a media strike on the surface, it creates a dimple like shape on the surface. The surface and a small volume under the dimple are stretched. The rest of the part tries to restore this area to his original shape, stressing this area in compression. Overlapping dimples creates a uniform layer of compressive residual stress [3]. The increase of compressive residual stress due to WPC treatment was identified in the studies of Yonekura et al. [4] and Yamada et al. [5]. Furthermore, Hung et al. [6] and Klocke et al. [7] used MB treatment for their studies and observed that desirable compressive residual stress was generated due to the process.

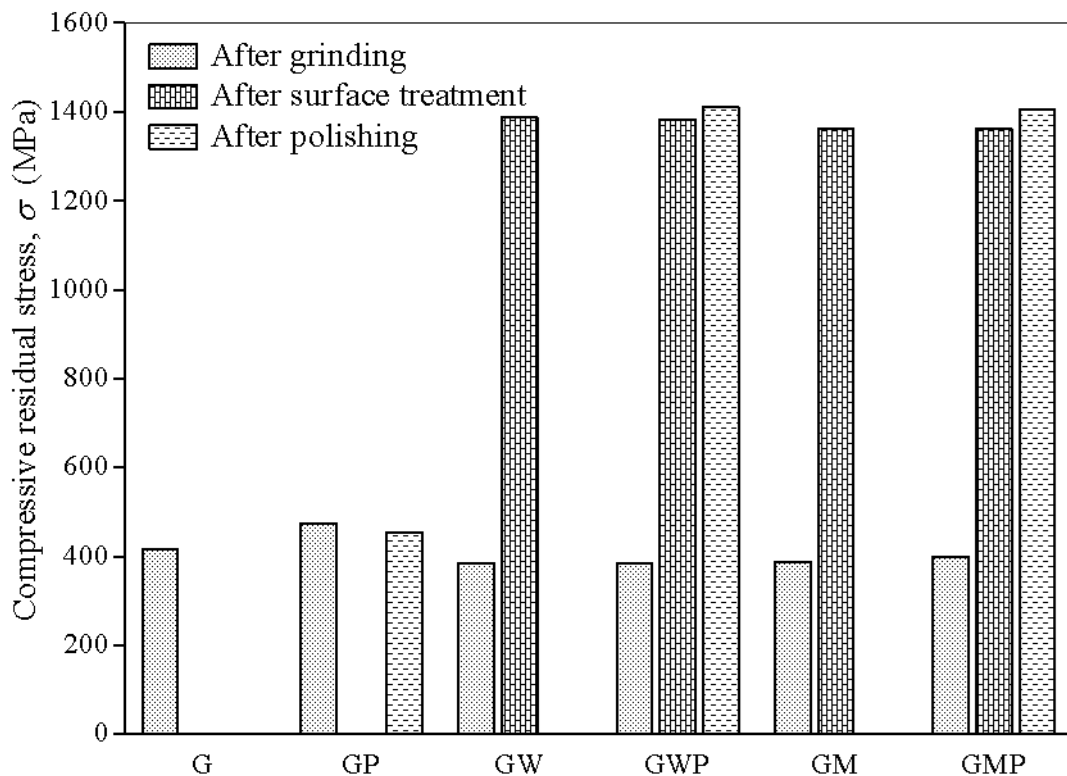


Fig. 5.9 Variation of average surface compressive residual stress with surface treatment and polishing.

The compressive residual stress of surface treated specimens after post-treatment polishing showed a slight increase. Conversely, the specimen polished after the grinding process showed a slight decrease in compressive residual stress. Fig. 5.10 shows the residual stress distribution in the depth direction of the ground and the surface treated specimens. For the ground specimen, the highest compressive residual stress was observed at the surface. In contrast, the peak of the compressive residual stress is slightly below the surface for surface treated specimens. The peak is observed about 1 μm below with a slight increase for both type of surface treatment at current treatment condition. The study by Yonekura et al. [4] on WPC treatment on carburized SCM 420H steel found out that the compressive residual stress initially increases with the depth from the surface before starting to decrease. Furthermore, Hanada et al. [8] found that the maximum compressive residual stress appears about 0.01mm deep from the surface when investigated on the effect of micro shot peening on surface characteristics of High speed tool steel. Additionally, Matsumoto et al. [9] noted that the compressive residual stress in a ground specimen decreased rapidly as the depth from surface increased. Material removal during polishing was 0.5 μm to 1 μm . Therefore, after polishing compressive residual stress of the surface treated specimens reached a higher level than unpolished condition. In contrast, compressive residual stress of ground specimen reached a lower level due to polishing. The forces applying during the polishing process may affect the residual stress variation after polishing.

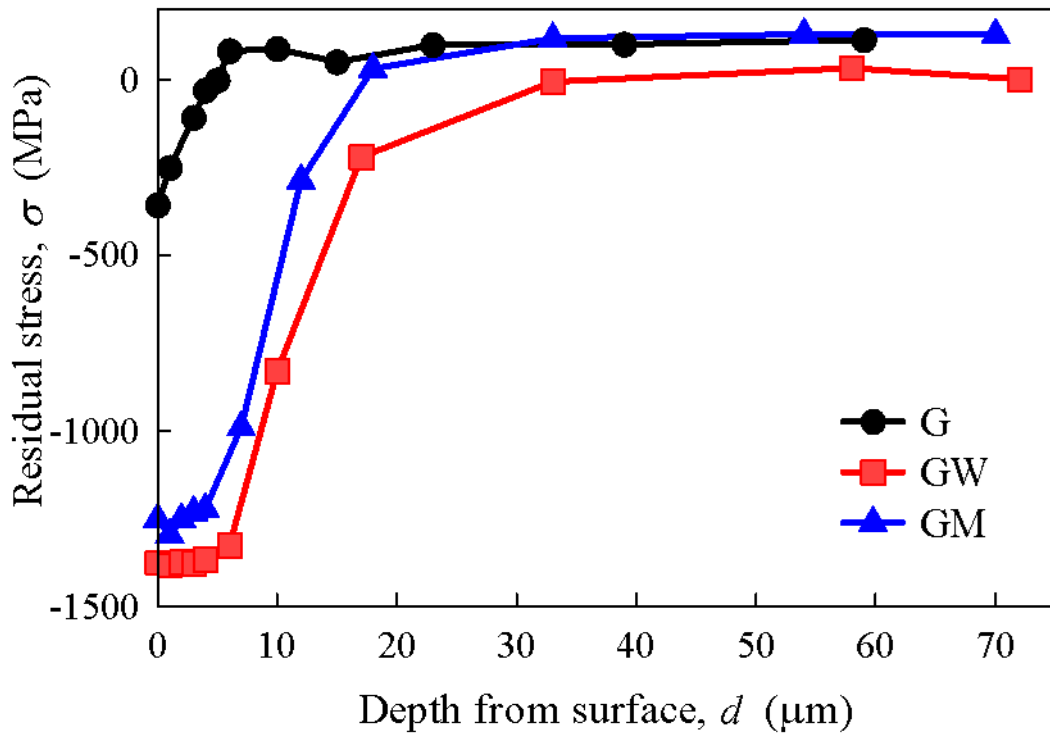


Fig. 5.10 Distribution of residual stress in the depth direction.

5.3.3 Tensile strength and fatigue life

The results of the tensile test for the three sets of specimens with different surface conditions are shown in Fig. 5.11. Even though there is no significant variation in tensile strength based on the surface condition, slight increase was observed due to surface treatment and polishing. The increase in average tensile strength of surface treated and polished specimens were between 2% to 7% with compared to ground specimen. In general, hardness values show a positive correlation with yield strength and tensile strength [10, 11]. The study of Shaid and Hashim [12] showed that steel specimens with rough surface show a lower tensile strength with compared to polished specimens. It is known that compressive residual stress improves the mechanical properties. Surface treatment increases surface compressive residual stress and surface hardness, while polishing reduces the surface roughness. This improvement in surface condition results slight increase in tensile strength of the polished specimens.

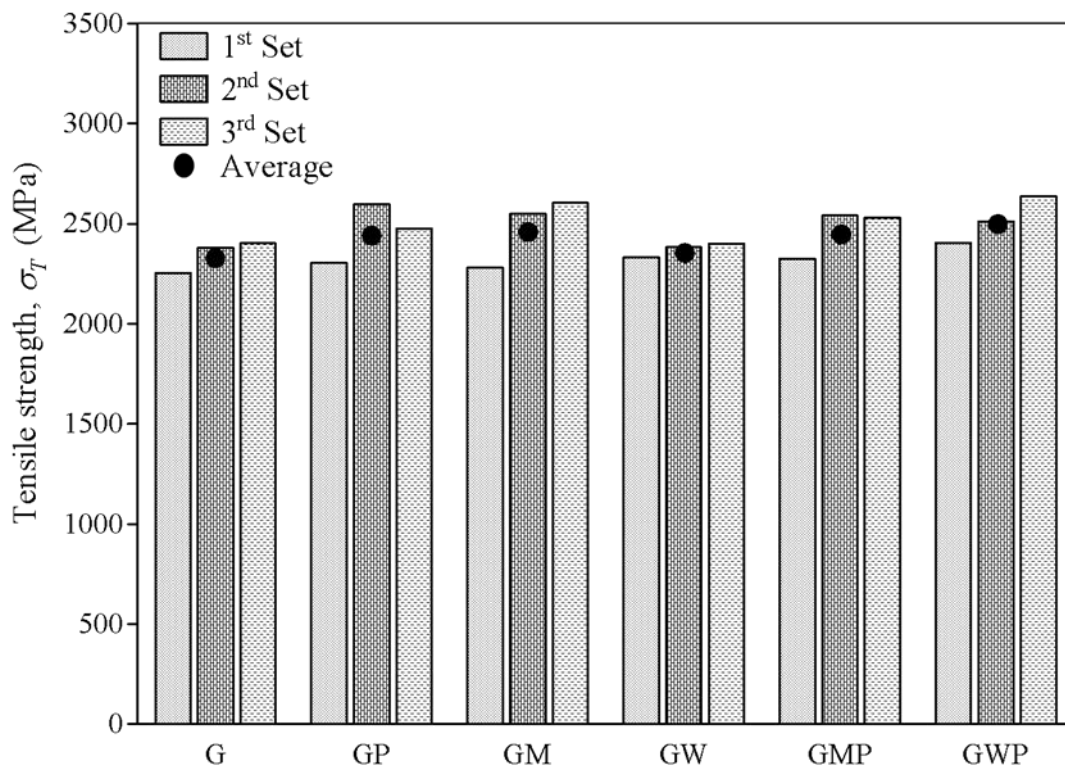


Fig. 5.11 Tensile strength variation with surface treatment and polishing.

Figure 5.12 shows the variation of fatigue life of three sets of specimens with different surface conditions. The results show that the fatigue life largely varies with surface condition. The lowest fatigue life was observed on the specimens that were not surface-treated, G. The highest fatigue life was given by the specimens that were subjected to post-treatment polishing after WPC treatment, GWP. Two out of three GWP specimens were not failed even at 300000

cycles which was set cycle limit. Due to the polishing of the ground surface, a 1.87 times average increase in fatigue life was observed for GP specimens. Surface treatment on the ground specimen was also improved the average fatigue life of the specimens with compared to G specimen. There were 1.68 times and 4.72 times increase in average fatigue life was observed due to MB treatment and WPC treatment, respectively. Post-treatment polishing further increased the fatigue life. An increase of 6.73 times compared to ground condition and 4.01 times compared to surface treated condition were observed for specimens subjected to post-treatment polishing after MB treatment. On the other hand, an increase of 9.27 times compared to ground condition and 1.96 times compared to surface treated condition were observed for specimens subjected to post-treatment polishing after WPC treatment.

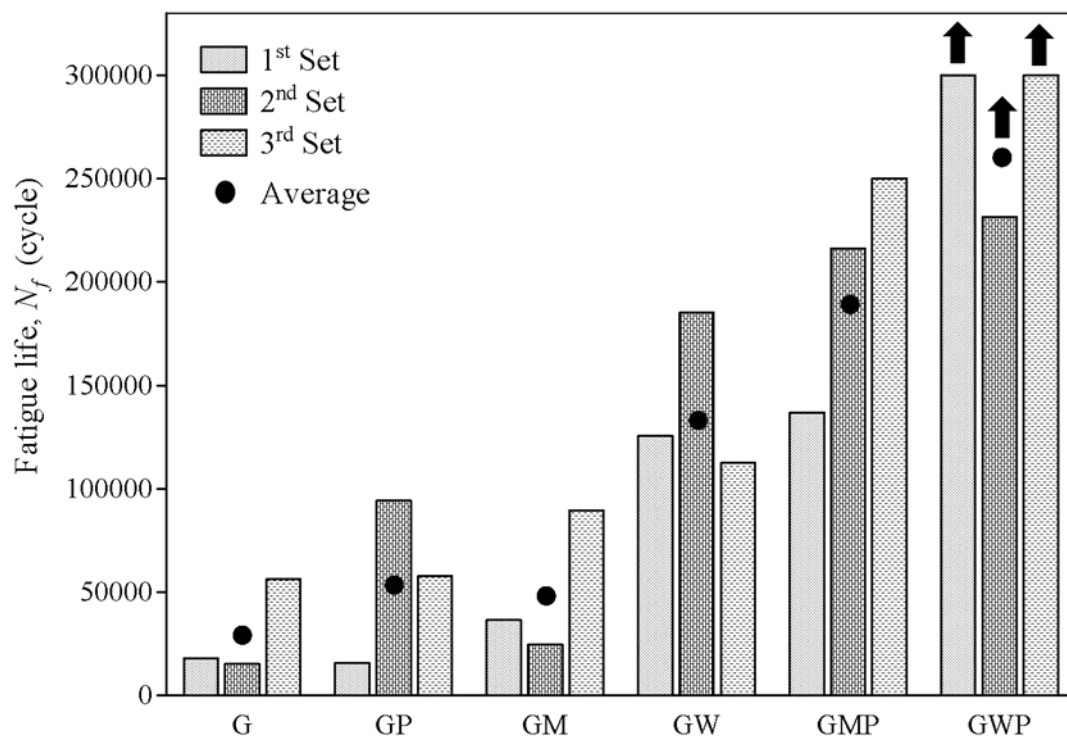


Fig. 5.12 Fatigue life variation with surface treatment and polishing.

The increase in average fatigue life in GP specimens were due to removal of stress concentration areas by the polishing process. It is known that compressive residual stress positively effects of fatigue life. Kamaya and Kawakubo [13] stated that, compressive residual stress generated by the surface treatment has a positive effect on fatigue strength of components due to the reduction of the mean stress value. Therefore, compressive residual stress increase due to WPC and MB surface treatments increases the fatigue life. Due to the difference in surface roughness of WPC and MB treated surfaces, a difference in fatigue life was observed even with almost similar surface compressive residual stresses. During the post-treatment polishing process,

the stress concentration points due to the rough surface created by surface treatment were removed. Furthermore, post-treatment polishing increased compressive residual stress on the surface. Therefore, fatigue life increase was observed in polished specimen after surface treatment due to positive condition created by post-treatment polishing.

The failure of the specimens can be three categories base on the crack initiation; surface initiation, surface initiation at inclusion, and sub-surface initiation at inclusion-fisheye. Subsurface fatigue crack initiation at inclusion dominates the failure of specimens with polished surface failure. On the other hand, surface initiation dominates the failure of specimen with rough surfaces [14]. The fracture surface images of the specimens which had the highest fatigue life in each surface condition are shown in Fig. 5.13. The crack initiation of the specimens that were not polished (G, GM, and GW) is observed from the surface. The crack initiation occurs from the stress concentration points due to the rough surface and propagates to the center.

On the other hand, subsurface crack initiation (fisheye) was observed for the polished specimens (GP, GMP, and GWP). Surface crack was not initiated due to the removal of stress concentration points during the polishing process. The crack initiation for GP is about 5 μm from the surface. Furthermore, the crack initiation of GMP and GWP was about 25 μm from the surface. Sub-surface crack initiations most probably due to an inclusion of the material. Furthermore, Kanazawa and Tange [15] stated that the depth of the crossing point from the specimen surface where residual stress changes from compressive to tensile has a good relationship with the site of the fisheye. According to the residual stress distribution in depth direction shown in Fig. 5.10, residual stress changed from compressive to tensile around 5 μm , 19 μm and 31 μm from the surface for G, GM and GW, respectively. These values are close to the crack initiation depth of GP, GMP and GWP specimens. Therefore, the shift of residual stress can be considered as a reason for sub-surface crack initiation observed in post-treated polished specimens. Furthermore, the study conducted by Lai et al. [16] on the effect of the microstructure and surface roughness of the fatigue strength of high strength steel. Their results indicated that the hardened high strength steel with rough surface failed predominantly by surface crack initiation while the specimens with smoother surface tend to fail by subsurface crack initiation from non-metallic inclusions. This result corresponds to the results of the current experiment.

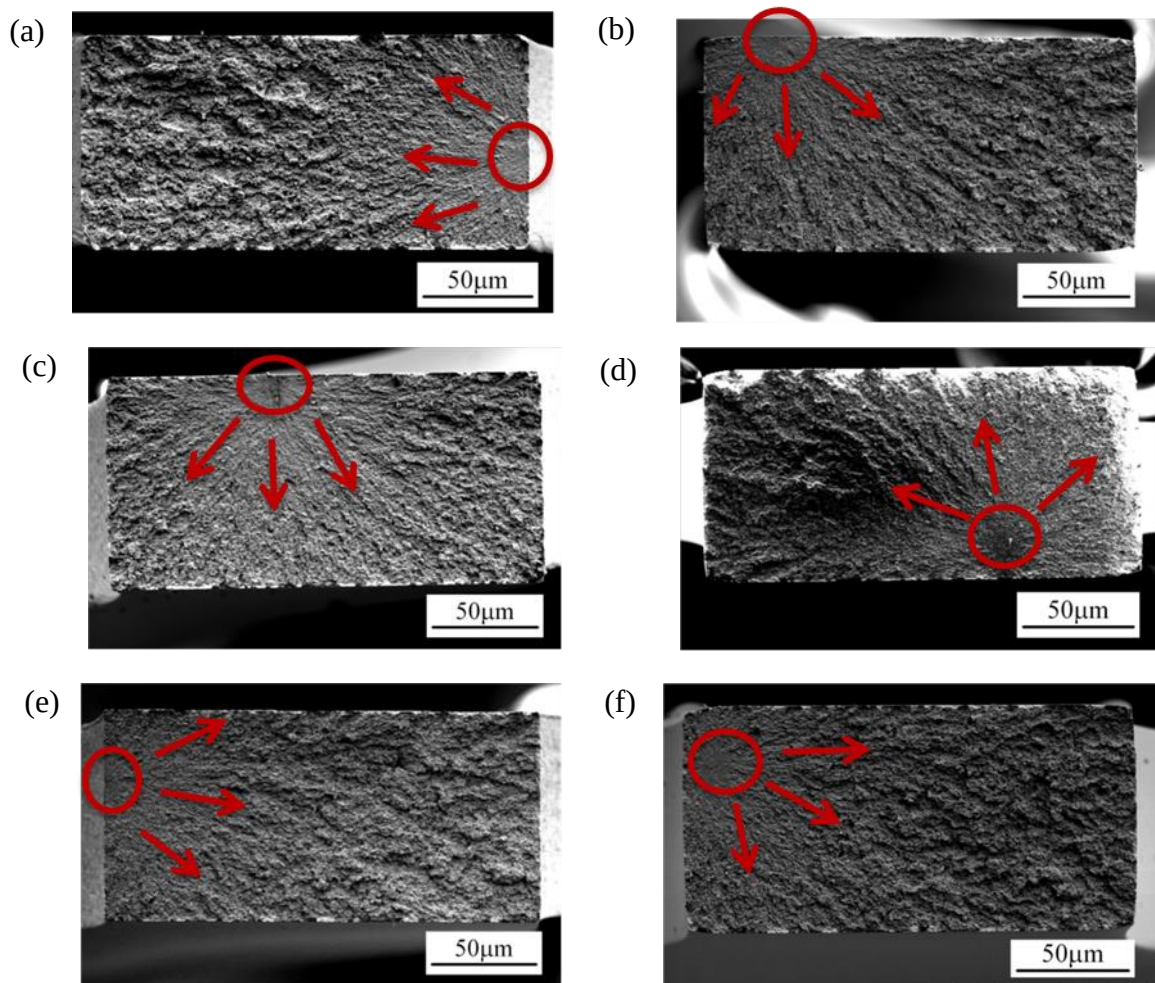


Fig. 5.13 Crack initiation points and propagation direction observed by Scanning electron microscope (SEM) (a) Ground (G); (b) Ground + Polished (GP); (c) Ground + WPC treated (GW); (d) Ground + WPC treated + Polished (GWP); (e) Ground + MB treated (GM); (f) Ground + MB treated + Polished (GMP)

5.3.4 Relationship between surface roughness and residual stress with tensile strength.

Figure 5.14 shows the relationship between surface roughness and the tensile strength of specimens with various surface conditions. Tensile strength did not show a large variation with the variation of the surface roughness. Therefore, a relationship between surface roughness and tensile strength was not identified. The study of the Belenky and Rittel [17], which investigate the relationship between surface roughness and static and dynamic flexural strength of alumina, found that the improving the surface roughness does not contribute to improving the strength.

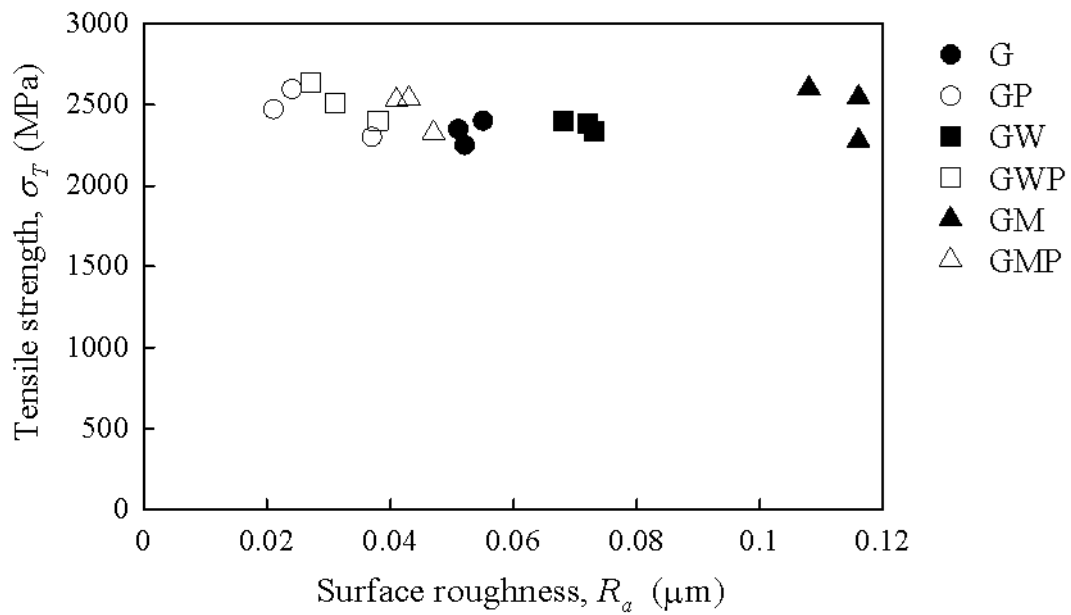


Fig. 5.14 Relationship between the surface roughness and tensile strength.

Figure 5.15 shows the relationship between surface compressive residual stress and the tensile strength of specimens with various surface conditions. Tensile strength did not show a large variation with the variation of the surface compressive residual stress. Therefore, a relationship between surface compressive residual stress and tensile strength was not identified. Lu et al. [18] studied the effect of residual stress on the mechanical behavior of composite. They found that. Residual stress greatly influences the tensile stress when tensile stress is low. However, at high tensile stress, the influence of residual stress is minimal.

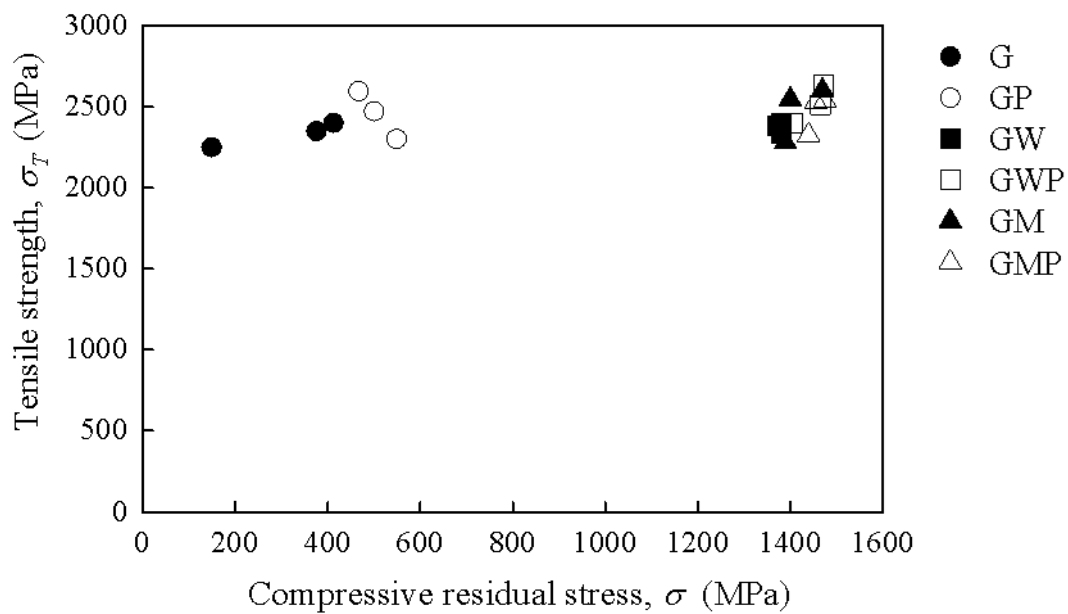


Fig. 5.15 Relationship between the surface compressive residual stress and tensile strength.

5.3.5 Relationship between surface roughness and residual stress with fatigue life

Figure 5.16 shows the relationship between surface roughness and fatigue life of the specimens with different surface conditions. Based on the residual stress levels, the data scattered with shifted positions. A negative linear relationship was identified between the surface roughness and fatigue life for both residual stress levels. The surface roughness increase creates stress concentration areas that crack initiations can be easily occurred. Since the material used was with high hardness, the crack propagation period is very small. Therefore, the failure of the specimen occurs soon after crack initiation. This makes the surface roughness a key factor that decides the fatigue life of the tested material.

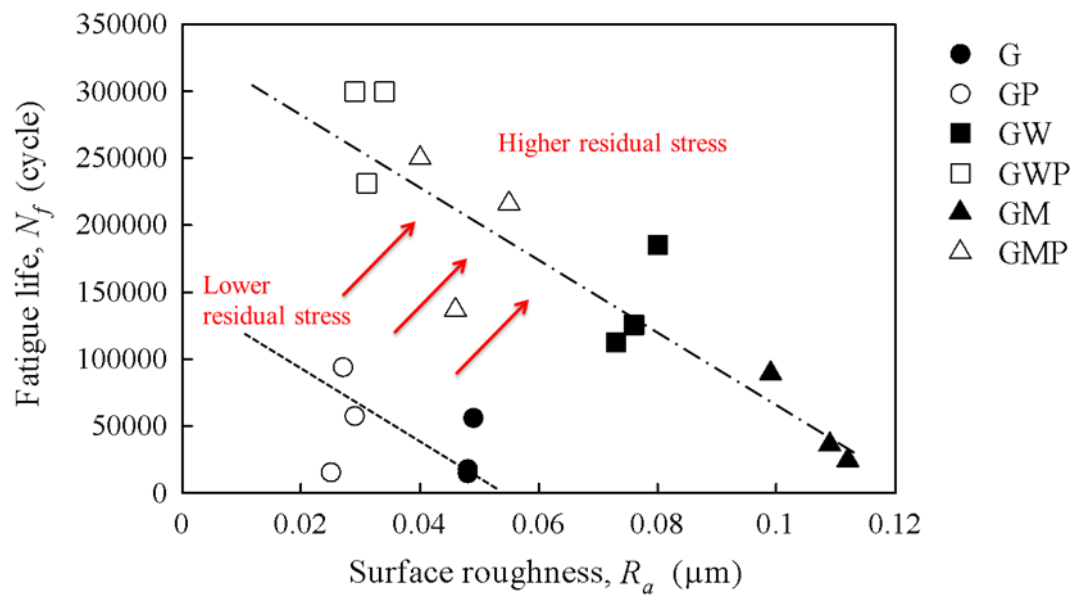


Fig. 5.16 Relationship between the surface roughness and fatigue life.

Figure 5.17 shows the relationship between surface compressive residual stress and fatigue life. Fatigue life varies largely on the same surface compressive residual stress level. Fatigue life showed an increase as the surface roughness reduces in same residual stress levels. Generally, the fatigue behavior under 10^4 cycles discussed based on low cycle fatigue (LCF) and fatigue behavior over 10^4 cycles discussed based on high cycle fatigue (HCF) principles. Since the fatigue life of the specimens in current experiment exceeds 10^4 cycles, the fatigue behavior should discuss under HCF. The high-cycle fatigue (HCF) behavior is significantly affected by surface roughness, especially for high strength metal [19]. Thus, the surface compressive residual stress does not show a clear relationship with the fatigue life in current testing condition.

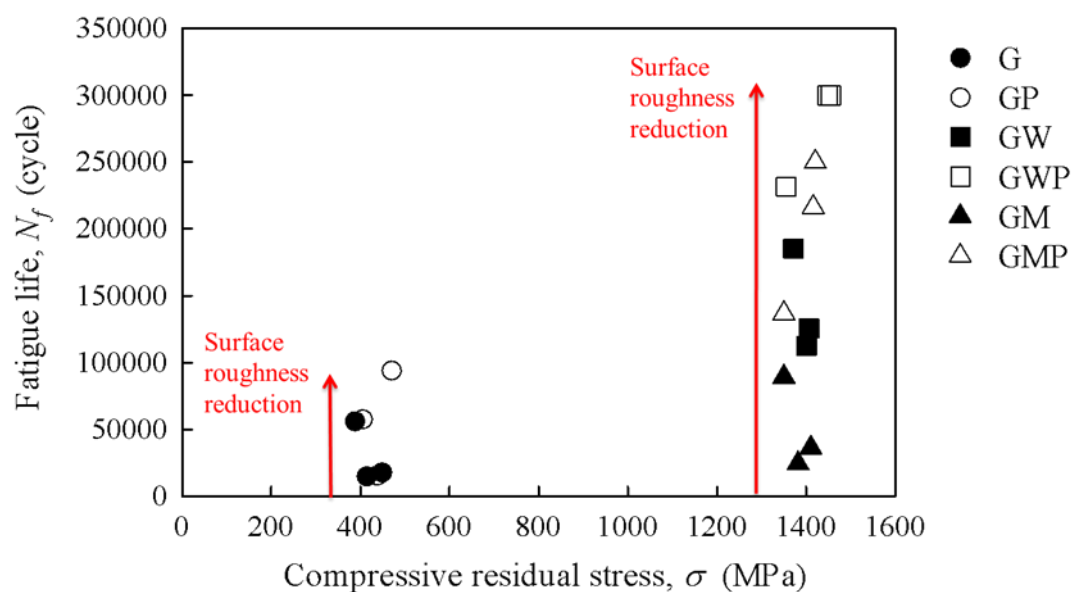


Fig. 5.17 Relationship between the surface compressive residual stress and fatigue life.

5.3.6 Cost efficiency of post-treatment polishing.

The cost of manufacturing the specimens was calculated based on the material and process cost of Zeno Tech Co., Ltd, where the specimens were manufactured. Fig. 5.18 shows the cost incurred for manufacturing each type of specimen. The material, heat treatment, and machining cost until the specimens are ready for surface treatment is JPY 3600 (Japanese yen)/ specimen. The polishing cost was JPY 625/ specimen. The MB and WPC treatment cost were JPY 4000 / specimen and JPY 3000 / specimen, respectively.

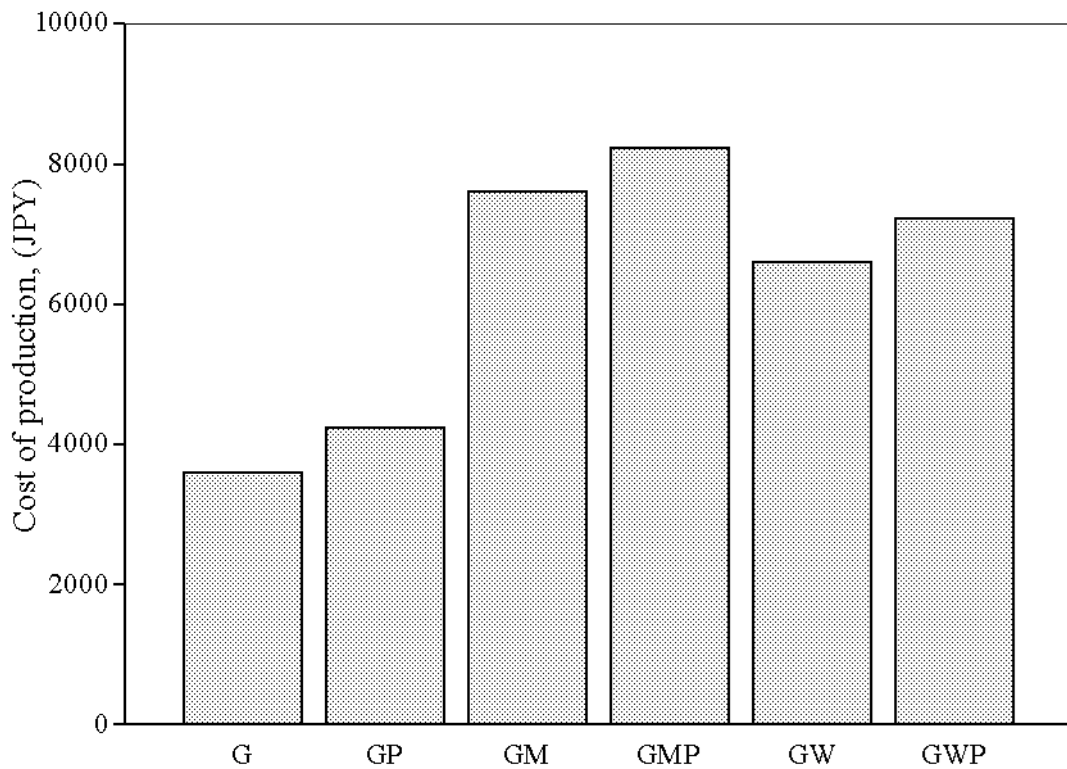


Fig. 5.18 Cost of production of specimens (JPY- Japanese yen).

The cost efficiency of the surface treatment and post-treatment polishing can be calculated by following equation.

$$\text{Cost efficiency} = \frac{\Delta N_f}{\Delta Y} \text{ [cycles/JPY]} \dots \dots \dots (1)$$

Where,

ΔN_f = Increase in fatigue life [cycles]

ΔY = Increase in cost [JPY]

Figure 5.19 illustrates the cost efficiency of surface treatment and post-treatment polishing with compared to ground specimen (G). The cost efficiency of GWP specimen was calculated assuming that they were failed at 300,000 cycles, even though 2 out of 3 specimens of GWP condition was not failed at set fatigue limit of 300,000 cycles. Micro blasted specimen (GM) shows the lowest cost efficiency. Furthermore, GP specimen shows a slightly better cost efficiency with compared to specimens GW and GMP. The best cost efficiency was observed for the GWP specimen. The cost efficiency of GWP was nearly 1.75 times with compared to GP, GMP and GW specimens. On the other hand, it was 13.6 times with compared to GM. Furthermore, GMP also showed a 7.8 times cost efficiency with compared to GM specimen. With these results we can conclude that to achieve the best cost efficiency of surface treatment in terms of fatigue life post-treatment polishing should be performed.

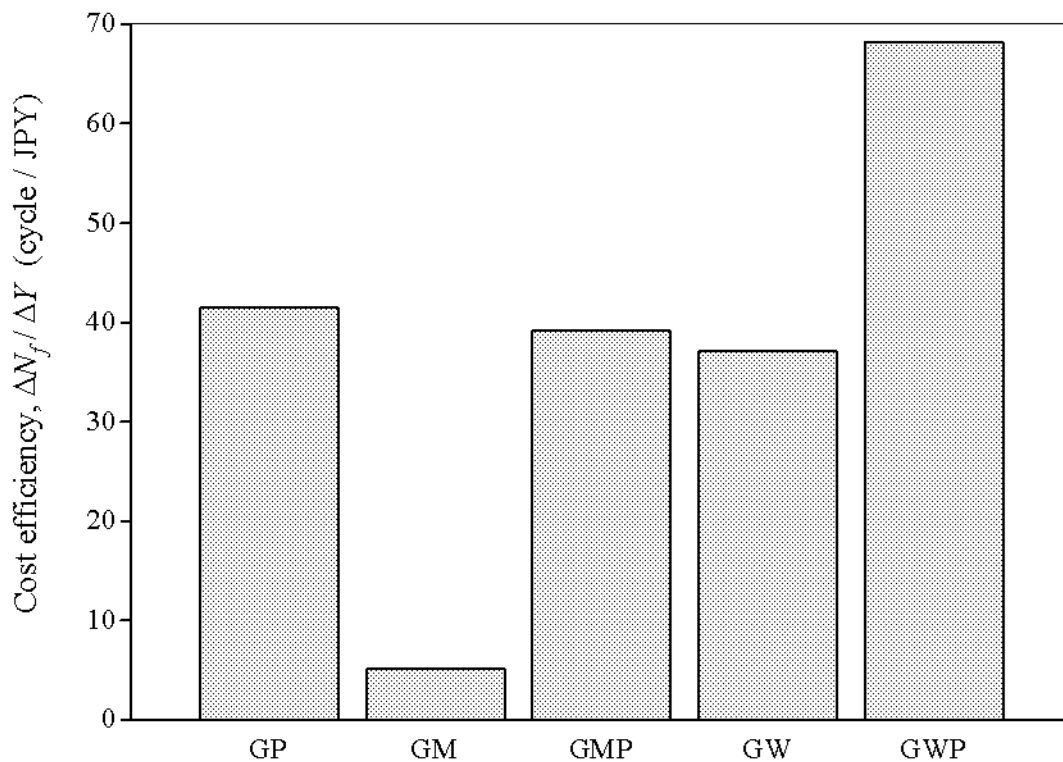


Fig. 5.19 Cost efficiency of surface treatment and post-treatment polishing with compared to ground specimen (G).

Table 5.5 shows the dependence of tensile strength and fatigue life on the parameters evaluated. It was observed that surface roughness, surface compressive stress, nor surface hardness effects on the tensile strength. On the other hand, increases in surface roughness effect negatively on fatigue life while an increase in surface compressive residual stress effect positively. Similar to the tensile strength surface hardness did not show an effect on the fatigue life of the material.

Table 5.5 Dependency of parameters on Tensile strength and fatigue life.

Parameter	Tensile strength	Fatigue life
Surface roughness increase	—	↓
Surface compressive residual stress increase	—	↑
Surface hardness increase	—	—

↑: Positive effect; ↓: Negative effect; —: No effect

The effect of surface treatment and post-treatment polishing on fatigue life based on surface roughness and surface compressive residual stress is summarized in Table 5.6. Due to the surface roughness increase during both types of surface treatment a negative effect was observed on fatigue life. As the post-treatment polishing was performed the surface roughness decreased and a positive effect on fatigue life was observed. Due to the surface roughness increase difference in MB and WPC surface treatment the final effect on the fatigue life due to post-treatment polishing showed a variation. On the other hand, the change in compressive residual stress due to surface treatment was almost similar for MB and WPC. Therefore, the effect on fatigue life was also similar. Due to the slight increase in compressive residual stress during post-treatment polishing, cumulative positive effect can be predicted. Since the effect of compressive residual stress is similar for all surface treatments types in current experimental condition, the total effect on fatigue life is decided by the surface roughness.

Table 5.6 Effect of surface treatment and post-treatment polishing on fatigue life.

	MB	WPC	Post-treatment polishing (PTP)	MB+ PTP	WPC+ PTP
Surface roughness	$\ominus\ominus\ominus$ $\ominus\ominus$	$\ominus\ominus\ominus$	$\oplus\oplus$	$\ominus\ominus\ominus$	$\ominus$
Surface compressive residual stress	$\oplus\oplus\oplus$ $\oplus\oplus$	$\oplus\oplus\oplus$ $\oplus\oplus$	$\oplus$	$\oplus\oplus\oplus$ $\oplus\oplus\oplus$	$\oplus\oplus\oplus$ $\oplus\oplus\oplus$
Total effect on fatigue life	$\oplus$	$\oplus\oplus$		$\oplus\oplus\oplus$	$\oplus\oplus\oplus$ $\oplus\oplus$

$\oplus$: Positive effect to fatigue life; $\ominus$: Negative effect to fatigue life

The summary of the results is present in Table 5.7. Surface roughness, R_a showed a large increase due to the MB treatment while moderate increase due to WPC treatment. On the other hand, polishing showed a moderate decrease in the surface roughness. A large increase in surface compressive residual stress, σ was observed due to MB and WPC treatments. In contrast, post-treatment polishing showed a small increase in surface compressive residual stress. A small increase in hardness was observed due to MB and WPC treatment, while no significant change was observed due to post-treatment polishing. Fatigue life, N_f showed a small increase due to MB, while WPC showed a moderate increase. Post-treatment polishing showed a large increase in fatigue life. Finally, the tensile strength did not show any significant change.

Table 5.6 Summary of the results.

Parameter	Micro blasting treatment	WPC treatment	Post treatment polishing
Surface roughness	↑↑↑	↑↑	↓↓
Surface compressive residual stress	↑↑↑	↑↑↑	↑
Surface hardness	↑	↑	-
Tensile strength	-	-	-
Fatigue life	↑	↑↑	↑↑↑

↑↑: Large increase; ↑↑: Moderate increase; ↑: Small increase;

↓↓: Moderate decrease; -: No effect

Fatigue is one of the main failure modes of cold forging tool. Two factors that control the fatigue behavior of material are residual stress and surface roughness. Due to the mechanical surface treatments, surface compressive residual stress was increased and results a fatigue life increase. Simultaneously an increase in surface roughness, which affects negatively on fatigue life, was observed. Therefore, a larger increase in fatigue life was not observed. The polishing process should be done on cold forging tools with precision and care because they are mainly used for net and near net-shaped part manufacturing. Due to the high cost of cold forging tool improvement in tool life is essential for profit increase. However, the right balance between costs incurred and the tool life increase is important. The mechanical surface treatment is one of the methods used to improve the tool life. The dimension controlled post-treatment polishing proposed by current study minimums the effect on the dimensional accuracy of the tool and reduces the polishing time, which leads to a cost reduction. Furthermore, post-treatment polishing showed a large increase in surface treated tool steel, using the same method on cold forging tool will lead to an increase in tool life. Moreover, post-treatment polishing showed a good balance between fatigue life increase and cost incurred. Therefore, using post-treatment polishing in tool manufacturing will lead to a profit increase. Finally, this method can be used use not only on forging tool or high speed steel, but also any part that subjected mechanical surface treatment intending to increase the fatigue life.

5.4 Summary

Mechanical surface treatment, Micro blasting and Wonder Process Craft/ Wide Peening Cleaning (WPC) were carried out on ground specimens made of heat-treated SKH51 (59–61 HRC) material. Dimension controlled post-treatment polishing was carried out on surface treated specimens. The influences of these treatments on surface roughness, residual stress, hardness, tensile strength, and fatigue life were studied. Finally, the cost-effectiveness of these treatments was discussed. The main findings can be listed, as below:

- Specimen dimension, surface roughness, and residual stress were affected by surface treatment due to the material removal and surface deformation during the process.
- WPC and micro blasting surface treatments increase surface roughness, and post-treatment polishing decreases the surface roughness.
- WPC and micro blasting surface treatments increase compressive residual stress and further increase by post-treatment polishing. The variation of the residual stress of the surface after polishing treatment is largely depends on the manufacturing process subjected by the specimen prior to the polishing process.
- Tensile strength of the material does not largely vary due to surface treatment or post-treatment polishing.
- Fatigue life largely varies with the surface condition created by surface treatment and post-treatment polishing. Polishing and surface treatment increases the fatigue life of the material. Post-treatment polishing significantly improves the fatigue life of the material that was surface treated.
- Post-treatment polishing delivered a better outcome in terms of fatigue life against the costs incurred.

References

- [1] E. Adoberg, V. Podgurski, P. Peetsalu, L. Lind, V. Mikli, P. Hvizdos: Estonian J. Eng. 18(3) (2012) 185-192.
- [2] M. U. Abdullah, S. R. Shah, M. U. Bhutta, R. A. Mufti, M. Khurram, M. H. Najeeb, W. Arshad, K. Ogawa: Proceed. Inst. Mech. Eng. Part D: J. Auto. Eng, (2018) 1-11.
- [3] Shot Peening Applications, 8th Edition, Metal Improvement Co. Inc., Paramus, NJ (2001).
- [4] D. Yonekura, J. Komotori, M. Shimizu, H. Shimizu: Trans. Jpn. Soc. Mech. Eng. A, 68(3) (2002) 509-514.
- [5] T. Yamada, K. Mizobe, K. Kida: Key Eng. Mater. 777 (2018) 366-371.
- [6] N.P. Hung, L.H. Teong, C.M. Yoong: Proceedings of the 1996 Third Biennial Joint Conference on Engineering Systems Design and Analysis. 75 (3) (1996) 47-53.
- [7] F. Klocke, T. Schroeder, E. Bouzakis, A. Klein: Surf. Coat. Tech. 202(4-7) (2007) 1194-1198.
- [8] Y. Hanada, K. Fukauara, S. Kohamada: J. Mater. Process Tech. 201 (2008) 319-324.
- [9] Y. Matsumoto, D. Magda, D. Hoepfner, T. Y. Kim: J. Eng. Ind. 113(2) (1991) 154-160.
- [10] A. Cicek, F. Kara, T. Kivak, E. Ekici, I. Uygur: J. Mater. Eng. Perform. 24 (2015) 4431-4439.
- [11] E. J. Pavlina, C. J. Van Tyne: J. Mater. Eng. Perform. 17 (2008) 888-893.
- [12] M. Shaid, S. A. Hashim: Int J Adhes Adhes. 22 (2002) 235-244.
- [13] M. Kamaya, M. Kawakubo: Jpn. Soc. Mech. Eng. 80 (2014) 1-15.
- [14] J. Lai, H. Huang, W. Buising. 21st European conference on fracture, Catania, Italy: Procedia Structural integrity 2 (2016) 1213-1220.
- [15] K. Kanazawa, A. Tange: Proceedings of fatigue crack paths (FCP 2003), Parma, Italy. (2003).
- [16] J. Lai, H. Huang, W. Buising: Procedia Struct. Integr. 2 (2016) 1213-1220.
- [17] A. Belenky, D. Rittel: Mech. Mater. 54 (2012) 91-99.
- [18] Y. Lu, M. Hirohashi, J. Pan: The 13th international conference on composite materials (ICCM-13), Beijing, China. (2001) No.1220.
- [19] J-l. Wang, Y-l. Zhang, Q-c. Zhao, M-m. Zhang, Z Guan: J. Mater. Res. 32 (3) (2017) 634-643.

Chapter 6

CONCLUSIONS

Variations in the surface roughness, residual stress, and deformation of a tool with the number of cold forging cycles under different forging conditions were studied. A cold forging upsetting process was carried out with specimens that were made of heat-treated SKH51 (59-61 HRC) material as the punch, under ‘with lubrication’ and ‘without lubrication’ conditions, with two different forging loads. The influences of lubrication and forging load on surface roughness, residual stress, and specimen deformation were studied. The forging condition greatly influences the changes in surface compressive residual stress, surface roughness, and deformation of the forging tools during operation. There is a positive relationship between the forging load and all of the above parameters (surface compressive residual stress, surface roughness, and tool deformation). The presence of lubricant during the forging process reduces the increase in surface compressive residual stress and surface roughness of the tool. A uniform distribution of compressive residual stress or surface roughness is not present on the working surface of the tool, for a higher forging load. The use of lubricant in forging changes the deformation behavior of the tools and surface condition deterioration. The downward displacement at the center has a positive linear relationship with average height reduction. The presence of lubrication changes the deformation behavior at higher loads. The surface roughness change depends on both the forging load and lubrication conditions, but compressive residual stress change largely depends only on forging load. The use of lubricant and a moderate forging load will lead to an increase in the tool life, when compared to forging without lubrication (dry forging) at high forging loads. Furthermore, the results of this study can be used in forging tool design and decisions regarding surface treatment conditions in order to improve the tool life and product quality.

The effect of the cyclic contact pressure applied on the tool's surface during forging on the fatigue life of the tool material was studied. Heat-treated SKH 51 (59-61 HRC) tool steel specimens were forged with three set loads to achieve three contact pressures values on the specimen surface. Influence of the magnitude of the contact pressure on dimension change, surface hardness, surface roughness, and surface residual stress was studied. Forged and unforged specimens were subjected to tensile and axial fatigue tests, and then the fracture surfaces were examined. There is a positive relationship between dimensional change, surface hardness and the surface compressive residual stress with the contact pressure. No significant relationship was observed between surface roughness and the contact pressure. The tensile strength of the specimens forged with lower and medium contact pressures increased with compared to the unforged specimen while the specimen forged with higher contact pressure decreased. Fatigue life improved when the specimen was forged with lower and medium contact pressures. Conversely, the fatigue life decreased as the specimens forged with high contact pressure. Assuming that all specimens are homogeneous, the fatigue life of the tool steel varies

depending on the contact pressure applied on tools during the forging process.

Finally, the investigation was carried out to study the effect of post-treatment polishing on fatigue life of WPC treated and MB treated SKH 51 high-speed tool steel (59-61 HRC). Mechanical surface treatment, Micro blasting and Wonder Process Craft/ Wide Peening Cleaning (WPC) were carried out on ground specimens made of heat-treated SKH51 material. Dimension controlled post-treatment polishing was carried out on surface treated specimens. The influences of these treatments on surface roughness, residual stress, hardness, tensile strength, and fatigue life were studied. Specimen dimension, surface roughness and residual stress were affected by surface treatment due to the material removal and surface deformation during the process. WPC and micro blasting surface treatments increase surface roughness and post-treatment polishing decreases the surface roughness. Furthermore, WPC and micro blasting surface treatments increase compressive residual stress and further increase by post-treatment polishing. The variation of the residual stress of the surface after polishing treatment is largely depends on the manufacturing process subjected by the specimen prior to the polishing process. Tensile strength of the material does not largely vary due to surface treatment or post-treatment polishing. Fatigue life largely varies with the surface condition created by surface treatment, and post-treatment polishing. Polishing and surface treatment increases the fatigue life of the material. Post-treatment polishing significantly improves the fatigue life material that was surface treated. Post-treatment polishing has a very good positive relationship between the costs incurred to the fatigue life increase.

Future research can be built on the current work by conducting fatigue experiment on heat treated high speed steel with different surface residual stress and surface roughness to build a relationship between fatigue life and the above parameters. These data can also use to build a methodology to predict the fatigue life of high speed steel based on the combination of initial surface roughness and surface residual stress. Furthermore, this study can be extended to the fatigue behavior of high speed steel at elevated temperatures, because during the cold forging process, the tool temperature can reach up to 200 °C. Cold forging tools subjected to fatigue and wear at the same time. By developing an experimental setup to demonstrate this condition, more accurate fatigue life prediction can be done for conditions that both fatigue and wear occurs at the same time.

LIST OF PUBLICATIONS

Refereed papers:

- (1) Effect of Lubrication and Forging Load on Surface Roughness, Residual Stress, and Deformation of Cold Forging Tools
Nuwan Karunathilaka, Naoya Tada, Takeshi Uemori, Ryota Hanamitsu, Masahiro Fujii, Yuya Omiya, Masahiro Kawano
Metals, Vol.9, Issue7, Paper No.783 (18 pages) (2019).
(Chapter 3 in the thesis)

Other papers:

- (1) Effect of Contact Pressure Applied on Tool Surface During Cold Forging on Fatigue Life of Tool Steel
Nuwan Karunathilaka, Naoya Tada, Takeshi Uemori, Ryota Hanamitsu, Masahiro Kawano
Procedia Manufacturing, Vol.15, pp. 488-495 (2018).
(Chapter 4 in the thesis)

Presentation in international conferences:

- (1) Effect of Post-treatment Polishing on Fatigue Life of WPC and Micro-abrasive Blasting Treated Tool Steel
Nuwan Karunathilaka, Ryota Hanamitsu, Naoya Tada, Takeshi Uemori, Junji Sakamoto, Masahiro Kawano
13th Int. Conference on Mechanical Behaviour of Materials, RMIT University, Melbourne, Australia, 11 June 2019.
(Chapter 5 in the thesis)

Presentation in national conferences:

- (1) Study on Surface Roughness and Residual Stress Change During Cold Forging
Nuwan Karunathilaka, Naoya Tada, Takeshi Uemori, Toshiya Nakata, Masahiro Kawano
日本機械学会中国四国支部第 55 期総会・講演会講演論文集, No.175-1, 303 (2017).
(Chapter 3 in the thesis)

- (2) Effect of Surface Treatment on Tensile and Fatigue Properties of High Speed Tool Steel
Nuwan Karunathilaka, Ryota Hanamitsu, Naoya Tada, Takeshi Uemori, Junji Sakamoto,
Masahiro Kawano
日本材料学会第 68 期学術講演会講演論文集, pp. 217-218 (2019).
(Chapter 5 in the thesis)
- (3) 精密ショットピーニング処理と研磨を施した高速度工具鋼の疲労寿命
花光峻太, ヌワンカルナティラカ, 多田直哉, 上森武, 坂本惇司
日本機械学会中国四国支部第 57 期総会・講演会講演論文集, No.195-1, 205 (2019).
(Chapter 5 in the thesis)

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