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RESEARCH ARTICLE

Investigation of fatigue behavior of collets with material standard SAE 4140 and 50CrMo4 by ANSYS finite element method and fatigue test device

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Abstract

In this study, collets having the same geometry in SAE 4140 and 50CrMo4 material standards and collets having different geometry in 50CrMo4 material standards were examined by ANSYS. Finite element method and subjected to fatigue test under 25 bar hydraulic pressure with 2.2 kW motor with Volt brand. Results received by Siemens brand remote control and finally the comparison has been made.

1. Introduction

With the rapid development of power machinery equipment, while meeting the requirements of high efficiency, lightweight, and high reliability of equipment, the overall design requirements are put forward for the long life of its key components. In view of the fact that many components suffer from fatigue failure under cyclic loading below the traditional fatigue limit, it is necessary to study the fatigue characteristics of high strength steels alloy in long-life regime [1].

The well-known effects from crack geometry and residual stresses from press fit and heat treatment are short crack behavior [2] and load sequence effects under variable amplitude loadings [3–8].

Steel structures can normally be subject to various damages during service. Some of these damages corrosion and fatigue cracking, which are generally age-related. Predicting fatigue in mechanical components is extremely important to avoid dangerous situations. Fatigue begins with the onset of the crack, then the small crack becomes a complete fracture [9]. In this study, it was aimed to observe the increase in cycle life with material standards and design change by learning the fracture formation in sample by ANSYS finite element method.

Machine parts and components used in industry work under repeated stresses and vibrations that are smaller than static strength during use. Because of this, after a certain repetition, cracking and subsequent rupture occurs. This is called fatigue. Fatigue stress is a brittle fracture, it is very difficult to predict where and when. Under repeated stresses, significant plastic cracks without deformation and this crack spreads over time, ending with sudden breakage [10–12].

Fatigue was first observed in the early 1800s by cracks in components in bridges and railways subjected to repetitive loads by researchers in Europe. As the use of metals became widespread with the increasing use of machinery in the later times, fatigue became a more important issue.

Today, the desire to use high strength materials has increased the importance given to fatigue. Approximately 80% of the damages in the machines are thought to be caused by fatigue [13, 14].

The first fatigue test was carried out by Wohler on the railway axes in the 1850s. As shown in Figure 1, there is a lower fatigue limit for steel, while others do not. This is because steel is a material that can undergo working hardening or otherwise hardening. However, in non-steel materials, the strength of the fatigue curve decreases as the number of repetitive stresses increases due to the absence of hardening. At the end of this decreases, the material goes breaking [15, 16].

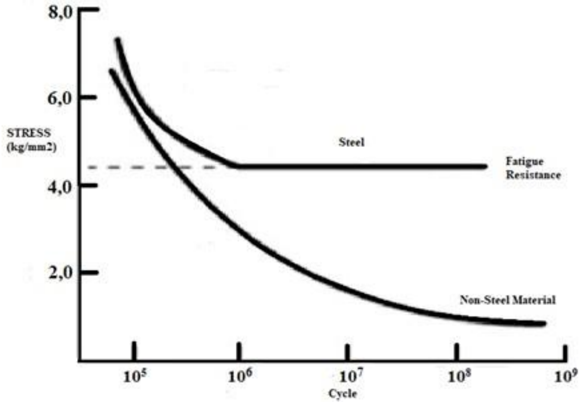

Figure 1. Wohler Fatigue Diagram

There are many reasons that affect the fatigue performance of machining parts. Factors affecting fatigue strength should be well known. These factors are related to stress, geometry of the part, properties and external environment [10].

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The tools that enable the cutting tools to be connected to the spindle easily and securely are called tool holders. Collet holders are one of the most widely used types of holders on the market. The reason for this is that it is easily available, cheap compared to other holders, easy to use, many tools such as guide, drill, end mill and reamer can be connected to this holder. Each time the tools are inserted into and removed from the collet and each part of the tool is operated, the collet is affected by this situation and remains under repetitive stresses. This causes the fatigue, which causes a sudden break after a certain time

2. Materials and methods

In this study, collets having the same geometry in SAE 4140 and 50CrMo4 material standards and collets having different geometry in 50CrMo4 material standards were examined by ANSYS finite element method and subjected to fatigue test under 25 bar hydraulic pressure with 2.2 kW motor with Volt brand. Results received by Siemens brand remote control and finally the comparison has been made.

As a tool holder, it was aimed to design a collet with a higher fatigue strength and a new collet collar with a new 50CrMo4 material standard with new chemical and physical properties was produced. In this experiment, the fatigue strength of the collets was tested and the analysis was made considering the differences between them.

As shown in Figure 2 and Figure 3, the only difference between them is not only their chemical properties but also the physical design of the new collets. In order to ease the loads on the ends, 4 side channels were opened next to the main channels.

Figure 2. SAE 4140 Pens

At Table 1 and Table 3, the chemical properties of the previous collet and the newly manufactured collet are shown in Table 2 and Table 4 the mechanical properties are shown.

Table 1. SAE 4140 Chemical properties

Element	Ratio (%)
Cr	0.80 - 1.10
Mn	0.75 - 1.0
C	0.380 - 0.430
Si	0.15 - 0.30
Mo	0.15 - 0.25
S	0.040
P	0.035

Table 2. SAE 4140 Mechanical properties

Tensile Strength	655 MPa
Yield Strength	415 MPa
Shear Modulus	80 GPa
Elasticity Modulus	190-210 GPa
Poisson's Ratio	0.27-0.30

The test consists of 3 main parts. These; The electric motor specified in Table 5, which produces a hydraulic pressure of 25 bar acting on the collets, is the control that allows us to observe the number of times the lathe collets tested and the lathe collets tested in Table 1, 2, 3 and 4 are subjected to mechanical and chemical properties.

Figure 3. 50CrMo4 Pens

2.1 Material

The materials of the collets used in the experiment are SAE 4140 and 50CrMo4.

Table 3. 50CrMo4 Chemical properties (%)

C	Si	Mn	Cr	Mo	Other
0.50	0.25	0.62	1.04	0.18	Pb

2.1.1 Electric Motor

As can be seen in Figure 4, the engine that applies hydraulic pressure to the collets in the experiment and the properties of this motor are given in Table 4.

Figure 4. Motor used in the test

Table 4. 50CrMo4 Mechanical properties

Radius r (mm)	< 16	>16 – 40	>40 – 100	>100 – 160	>160 – 250
Thickness t (mm)	< 8	8< t <20	20< t <60	60< t <100	100< t <160
0.2% Yield Strength Rp 0.2 [N/mm²]	min. 900	min. 800	min. 700	min. 650	min. 600
Tensile Strength Rm [N/mm²]	1100 – 1300	1000 - 1200	900 - 1100	850 - 1000	800 - 950
Elongation A5 [%]	min. 9	min. 10	min. 12	min. 13	min. 13

Table 5. Properties of motor

Power	Housing material	Body Type
2.2 kW	Aluminum	100-4 Type

2.1.2 Control unit

In this experiment, the Siemens SIMATIC S7-1200 controller given in Figures 5 and 6 was used to see how many times the collets were tested.

Figure 5. Siemens SIMATIC S7-1200

Figure 6. Siemens SIMATIC S7-1200

The test pieces were tested by applying 25 bar hydraulic pressure of 2.2 kW Volt engine. Collet's life is calculated by breaking the test pieces as a result of repeated stresses. As a result of this experiment, the fatigue strength of the parts was revealed. On the Siemens control, the number of times the test is repeated until it is broken, waiting in forward time (300ms), waiting in behind time (500ms).

2.2 Experimental and Structural Analysis

Firstly, the old collet was analyzed with SAE 4140 material in ANSYS software. Then, 50CrMo4 material was used as material in the same collet. Finally, the newly designed collet with 50CrMo4 material was analyzed.

In the test setup, old collet with SAE 4140 material standard and new collet with 50CrMo4 material standard were tested.

2.2.1 ANSYS finite element method analysis

In this experiment, collets were designed with SolidWorks software and then fatigue and static structural analysis was performed in ANSYS Workbench program. The finite element model with the SAE 4140 material standard collet's mesh consists of 1579795 nodes and 1125047 elements. And the average element quality is 0.896980. The finite element model of the former collet with 50CrMo4 standards consists of 1147139 nodes and 811281 elements. And the average element quality is 0.89462. The finite element model with a 50CrMo4 standard collet's mesh consists of 1497266 nodes and 1063726 elements. The average element quality is 0.89758. The highest tensile strength of SAE 4140 old collet is 132.12 MPa, The highest stress in the old 50CrMo4 standard was 112.13 MPa while the new stress in the new 50CrMo4 standard was 171.62 MPa. The main reason for this difference is the design difference between the collets. Figures 7, 8 and 9 show the static structural analysis results of 2.5 MPa pressure applied to the collets.

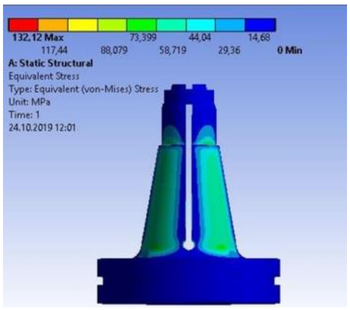

Figure 7. SAE 4140 standard old collet static structural analysis

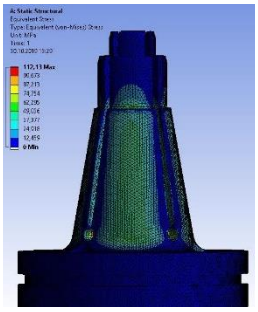

Figure 8. 50CrMo4 standard old collet static structural analysis

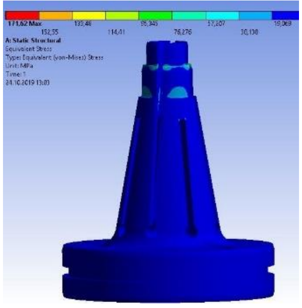

Figure 9. 50CrMo4 standard new collet static structural analysis

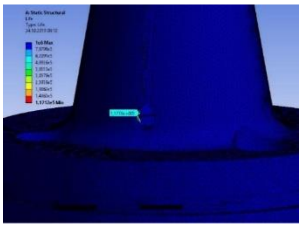

Figure 10. SAE 4140 standard old collet life analysis

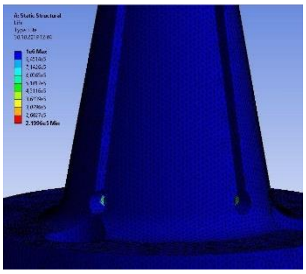

Figure 11. 50CrMo4 standard old collet life analysis

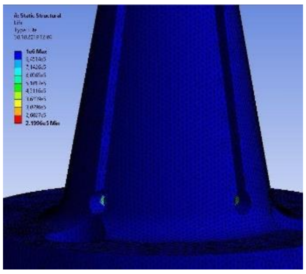

Figure 12. 50CrMo4 standard new designed collet life analysis

2.2.2 Experimental analysis in test setup

In this experiment, the arrangement of the test device manufactured to test the old design SAE 4140 and the new design 50CrMo4 collets is as shown in Figure 13.

Figure 13. Fatigue testing device

3. Results and discussion

In the experiment, fatigue test was performed by applying the 25 bar hydraulic pressure to the collets, which are given in Table 5. With the operation of the motor, 25 bar hydraulic pressure is transmitted to the collets mounted on the hydraulic system. The collet is activated by this pressure. The collet starts to expand by increasing the volume from bottom to top with the help of pressure. With this process, the collet is provided to hold the spindle, so collet act as a holding tool.

In this experiment, the collets were subjected to repeated pressure several times to test how many cycles they would break. Thus, the fatigue strength of the collet is taken into consideration. The test cycle is shown on the Siemens controller. A comparison was made between the collets and the data obtained from controller.

The collet is likely to break suddenly as a result of increased stresses and cracking from a point. Because 50CrMo4 material has a hard structure and is a brittle material. The collet can be broken from the bottom or from the top. This depends on where the collet forms the first crack.

Mechanical parts are subjected to repeated loads, the resulting cyclic stresses can lead to fatigue crack initiation. The crack initiation period usually starts with nucleation of micro-cracks whose lengths are comparable with the microstructural features of treated material that is the size of crystal grains. From the standpoint of the microstructure of the material, micro-cracks may be initiated along slip bands by dislocation motion, along grain boundaries or along inclusion interfaces [17]. The further propagation of such micro-cracks is usually termed as ‘short crack growth’ and is governed by interactions between local microstructural features and by the resolved stress state acting as a crack driving force at the crack tip. The significance of these interactions usually extends only for a few crystal grains, when the crack reaches a typical length valid for long cracks. The micro-crack nucleation and its growth until formation of engineering initial crack is in engineering applications usually termed as ‘crack initiation period’. In particular, for high-cycle fatigue and high-strength materials, up to 90% of component’s fatigue life can be determined by the phase of micro-crack nucleation and the propagation of short cracks on microstructural level. Therefore, the appropriate number of stress cycles required for formation of initial ‘long crack’ can be treated as an appropriate fatigue life in such cases [18]. This cracks usually starts on the surface and is transmitted to the middle parts with slip errors. In addition, if the material has micro-cracks and the stress build-up in the cracks is enough to advance the crack, the crack advances. Thus the wear is gradually spread over the entire cross-section. After decomposition progresses sufficiently with wear, the rest of the section becomes unable to withstand the stress and the material breaks. It is not desirable that the collet break from the tip during operation. Because it is possible to damage the part it holds when it breaks from the tip.

Fatigue can be overlooked as it does not make a significant plastic deformation on the material, which is dangerous because it does not give warning.

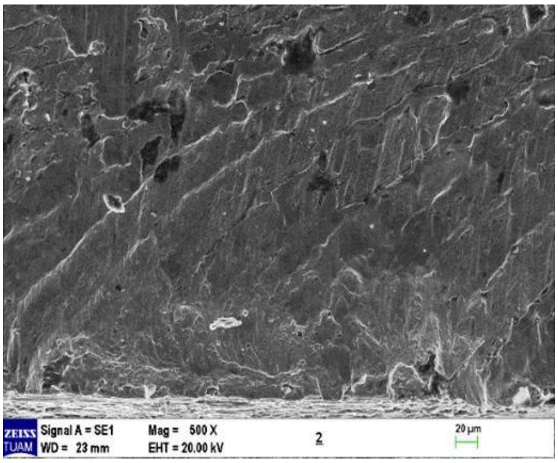

Figure 14. Electron microscope image of SAE 4140 old design collet

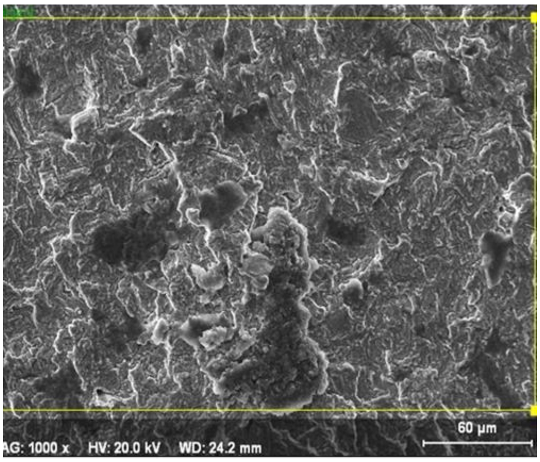

Figure 15. Electron microscope image of SAE 4140 old design collet

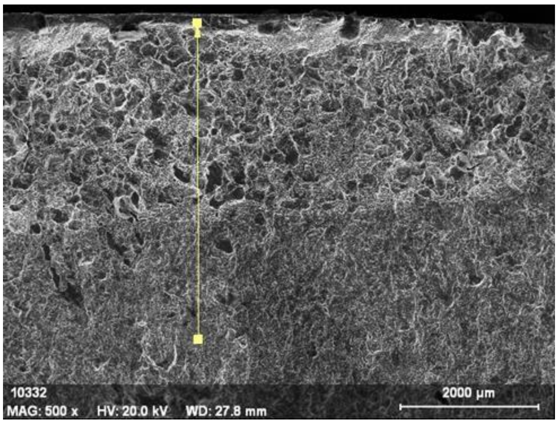

Figure 16. Electron microscope image of 50CrMo4 new design collet

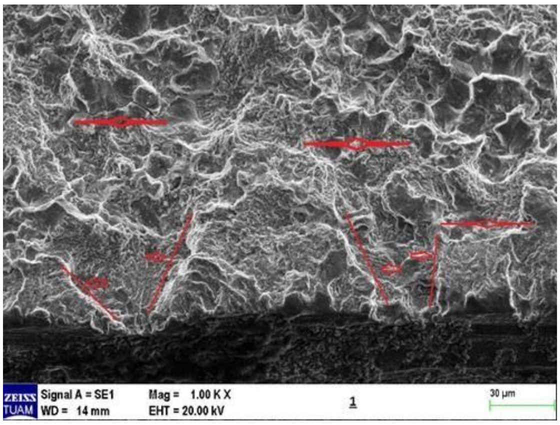

Figure 17. Electron microscope image of 50CrMo4 new design collet

The most prominent feature of fatigue is the formation of cracks. If the material is sufficiently ductile, excessive energy storage is required for fatigue behavior. These cracks can be tested by periodic maintenance. However, since the 50CrMo4 material is hard and brittle, a crack is expected to occur suddenly and a rupture like knife cutting may occur in the material. Such brittle fracture phenomena can be found in aircraft wings, steel bridges. Fatigue is one of the most important material factors that must be taken into consideration as the fractures in the structures including this type of society will not only damage the material.

In order to prevent fatigue or delay a material, either very high surface quality should be produced and crack formation should be prevented, or a ductile material should be produced and the energy required for crack formation should be kept high.

The collets exposed to fatigue were examined by scanning electron microscopy. Scanning electron microscopy images of the collets examined are shown in Figures 15 and 17.

In Figures 14 and 15, observed the fracture formation and sudden fracture of the collet with the material standard of SAE 4140, which visualized by electron microscope.

In Figures 16 and 17, observed fracture formation and sudden fracture of the collet with the material standard 50CrMo4, which visualized by electron microscope.

According to the ANSYS finite element method, life time 117120 cycles for SAE 4140 standard collet and 219960 cycles for old collet with 50CrMo4 standards were obtained.

However, since the tool holder collets are used in mass production, the desired life value is at least 300000 cycles. Improved life value with a new design because the needed value could not be captured. 50CrMo4 steel was used in this new design and 305590 cycles were obtained in the analysis results. However, since never fully know the fatigue strength of a material, it was found that the collets were experimentally tested and different results were obtained.

According to the experiment, when look at Table 6, 50CrMo4 collet under 25 bar pressure, 338 thousand 502 repeated test results measured in Siemens control, as shown in Figure 18 collet was broken from the tip.

The collet with SAE 4140 material standard was broken in 96 thousand 148th cycle. As shown in figure 19 collet was broken from the tip.

Collet diameter, hydraulic pressure acting on collet, hardness of material, brittleness of material and fatigue strength played an active role in this experiment.

The main reason of the fracture of the collet is washer which is placed top of the collet. The collet which is under pressure, expands after that collet pressurize to washer and washer forces back to the collet. Because of that cracks occurs. The collet was broken as the crack advances where the maximum load is acting and the crack length reaches the maximum value.

As a result, in this experiment, the new collet with 50CrMo4 standard under 25 bar hydraulic pressure was broken under repeated stresses in 338502 cycle. SAE 4140 material standard old design collet broken under repeated stresses in 96148 cycle.

Table 6. Clamp test

Material Standard of Collet	Applied Pressure (bar)	Waiting in Forward Time (ms)	Cycle
SAE 4140	25	300	96.148
50CrMo4	25	300	338.502

Figure 18. Fractured 50CrMo collet

Figure 19. Fractured SAE 4140 collet

Thus, the fatigue strength of the redesigned collet with 50CrMo4 material standard given in Figures 2 is higher than that of SAE 4140 material standard collet given in Figure 3.

4. Conclusions

In this study, the life values of a collet with SAE 4140 material standards, the same collet with 50CrMo4 material standards and a new design collet with 50CrMo4 material standards were compared. In this comparison, the ANSYS finite element method and the experiments carried out at the experimental level were taken into consideration.

50CrMo4 material standards in the results obtained from the new design collet life values have met the desired values. The results obtained by ANSYS Finite Element Method gave very close values to the results obtained in the experiment.

As a result, changes in material and part design influenced the result. 50CrMo4 material standards and newly designed collet provide desired life values.

Also, ANSYS finite element method gives very efficient results in determining the life of the parts.

As a result of the study, it was understood that the first collet design was wrong. It was observed that the collet with 50CrMo4 material was higher fatigue life with the material change.

Acknowledgments

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Author contributions

In this study, Tuğrul Soyusinmez carried out the new collet design and fatigue tests of the collets. Oğuzcan Güzelipek carried out of the Electron Microscope scanning and investigation of the findings. Furkan Çetin carried out the Static Structral & Fatigue life analysis.

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