Chapter

Durability Assessment Considering Residual Stress

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Abstract

The relative movement between the cylinder block and the piston may cause a seizure, and this seizure problem can be solved by pressing the bushing into the cylinder block. However, if the rates of shrink fit are insufficient, the copper bushing will be detached from the cylinder block, and if the rates of shrink fit are excessive, a residual stress higher than yield stress will be generated and adversely affect the durability of bushing and the cylinder block. Therefore, in this study, a clear and quantitative rate of shrink fit is presented to solve the above-mentioned problems, and the durability assessment process of mechanical parts where residual stress occurs is performed. Through this study, analytical technique that can predict the residual stress clearly according to the rates of shrink fit was obtained and durability assessment was completed based on the quantitative residual stress according to the rates of shrink fit.

Keywords: durability assessment, cylinder block, copper bushing, shrink fit, seizure

1. Introduction

The cylinder block of the main pump is an important part of the hydraulic system and generates high-pressure hydraulic fluid through relative motion with pistons. At this time, there may occur a seizure problem [1] in which the surface of each component is adhered. And the problem may become a serious problem leading to the shutdown of the entire machine. Therefore, in order to prevent this shutdown, the cylinder block may be fabricated by copper or the copper bushing may be pressed into the cylinder block. Among these two methods, manufacturers mainly use the method of pressing the copper bushing into the cylinder block to reduce the production cost. However, if the proper rate of shrink fit can not be found when pressing the copper bushing, it may lead to disconnection of the bushing or breakage of the cylinder block in the use environment of the machine, resulting in the shutdown of the entire machine, such as seizure. Therefore, in this study, the method of setting the rate of shrink fit analytically was confirmed, and the durability assessment method and the process of the cylinder block considering the residual stress generated after the pressing copper bushing were constructed.

2. Antiseizure cylinder block

A typical cylinder block manufacturing method is shown on the left of **Figure 1**. At this time, the production process of each process does not generate residual

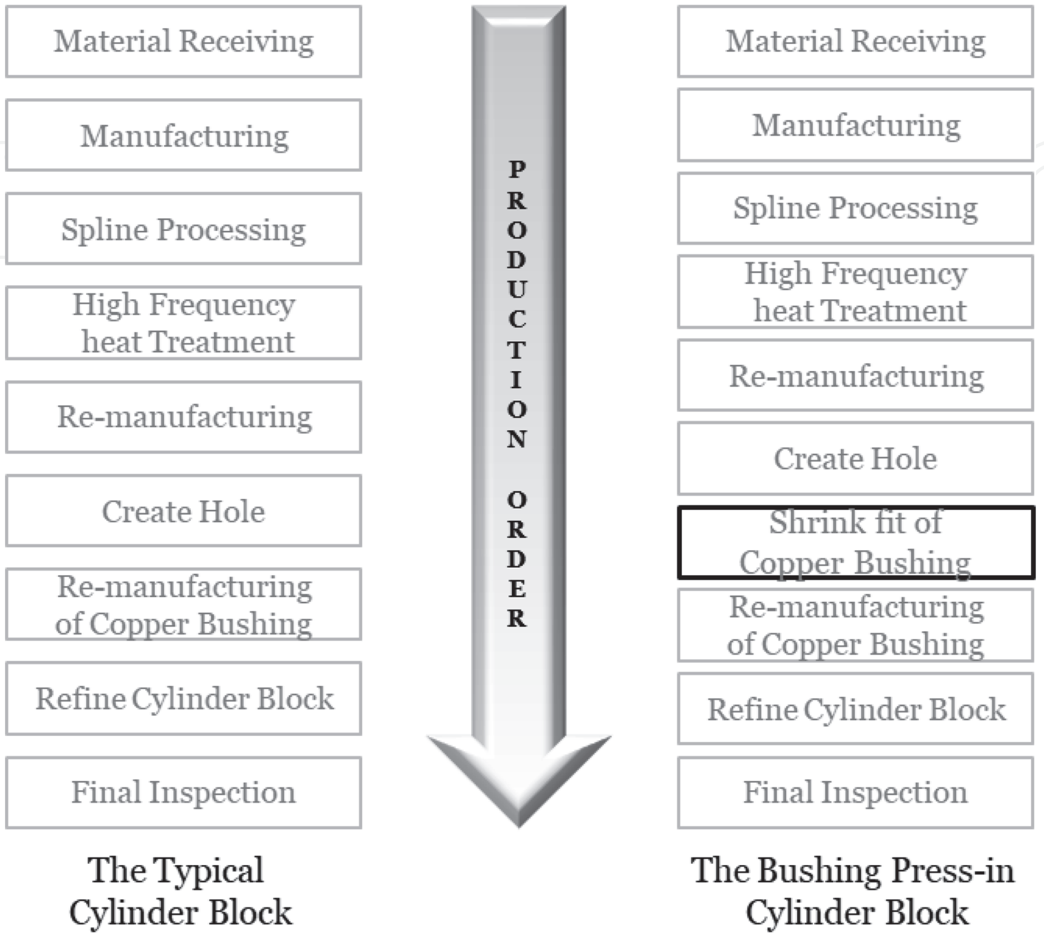

Figure 1.
Comparison of production processes.

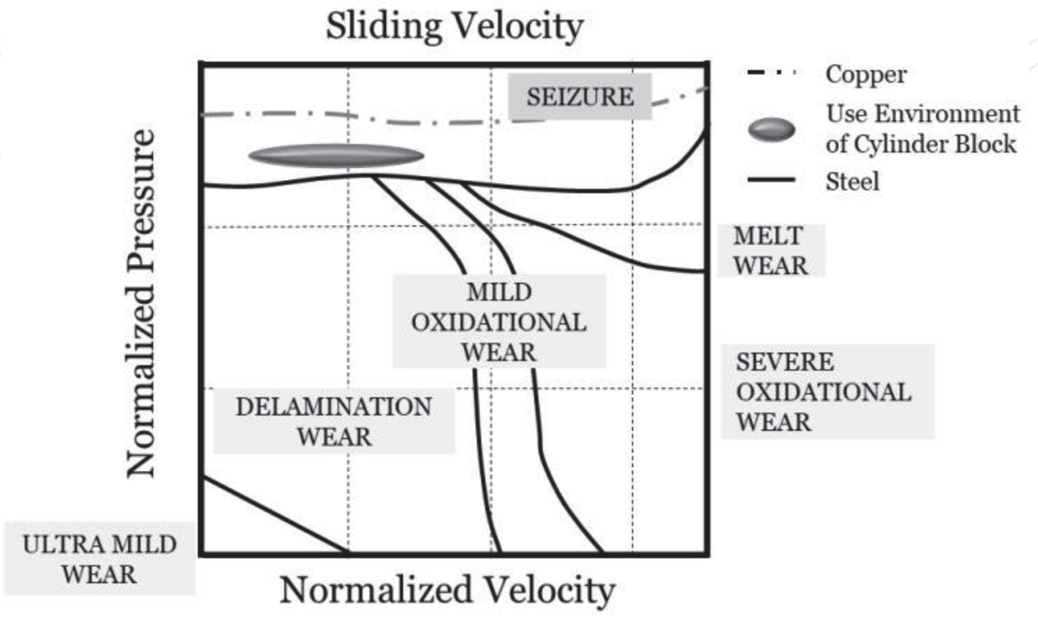

Figure 2.
Wear-mechanism map.

stress enough to have a large effect on the final product [2]. However, when a copper bushing is inserted into the cylinder block to prevent the seizure between the cylinder block and the piston (on right of **Figure 1**), and residual stresses corresponding to the yield stress of the material before using the cylinder block are expected to exist.

If the copper bushing is not inserted, there is a high possibility that the zone of occurrence of the seizure and the operating area of the cylinder block overlap (**Figure 2**). As a result, if a failure occurs due to the seizure, the total non-operating time of the equipment becomes longer. This leads to a decline in equipment reliability. Therefore, if the durability of the cylinder block is not adversely affected even if the cost is somewhat high, it is considered necessary to insert the copper bushing even if residual stress occurs to improve the reliability of the main pump.

3. Methods for durability assessment of cylinder block

In general, standard, measurement, experiment and simulation can be considered as methods for durability assessment. The above methods will be described with respect to the cylinder block in which the residual stress is present.

In the case of the standard, the reliability of the evaluation result can be secured based on the authority of the standard, but the accuracy of the product with complicated shape is degraded in order to guarantee the performance. The reason is that the standard contains some assumptions and simplifications in the formulas for general use.

In case of measurement, there is an advantage that it can confirm the accurate state in real time when using, but there is a disadvantage that it is only possible to check the local state instead of the total state. In addition, there are many difficulties in measuring a cylinder block having a relatively small size as well as a rotating body. Also, there is a risk that the location of the high stressed portion, which is an evidence for durability safety, should be selected only by experience.

Experiments provide a relatively complete assessment of the product as a whole, but it takes time and expense to derive the results of the experiment. Especially, the improvement process and the short processing period, which are often derived when the product development stage is the basic design, make the experiment only used in the final product development stage. These characteristics make the experimental method difficult to use for the purpose of this study (predicting the residual stress and evaluating the durability thereof), which is the working area of the basic design.

Finally, in the case of simulation, the overall evaluation of the product is possible and it is possible to respond quickly to the improvement. However, as shown **Figure 3**, unlike the measurement and the experiment, simulation is difficult to consider stochastic effect. Stochastic effects of products not confirmed by

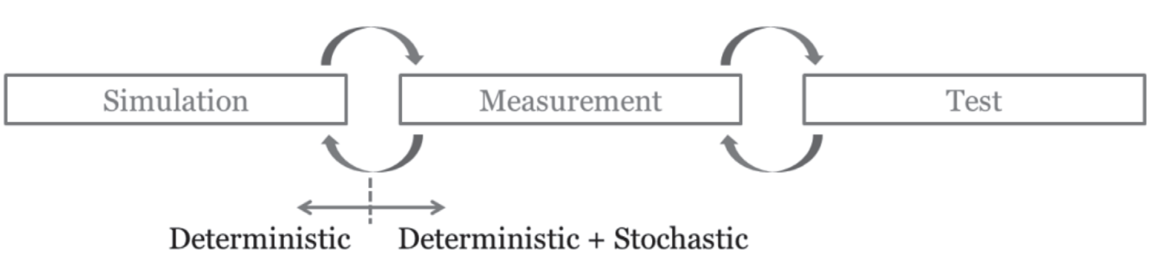

Figure 3.
Deterministic and stochastic in evaluation method.

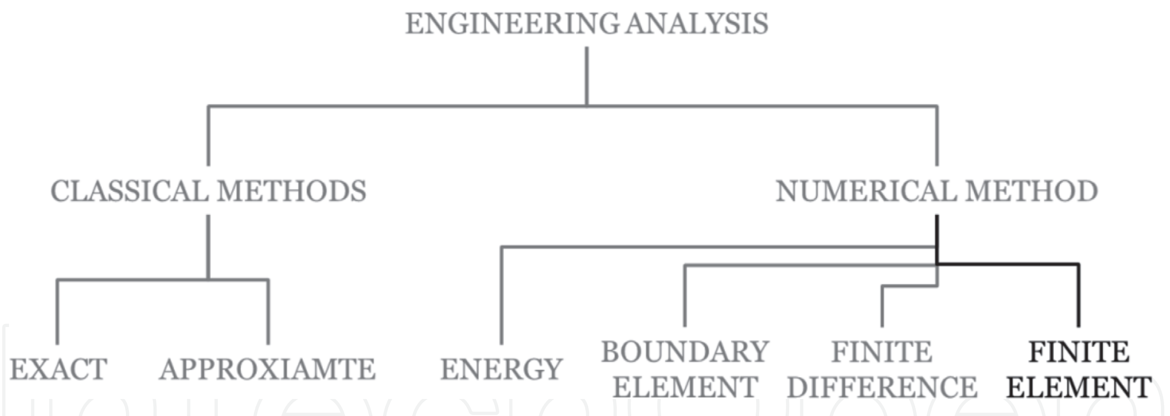

Figure 4.
Methods for engineering analysis.

simulation methods are expected to be confirmed in the final tests performed prior to final product launch.

The simulation used in this study is structural simulation. The Finite Element Method (FEM) was used as shown in **Figure 4**). The finite element method is one of the powerful methods to numerically solve wide engineering problems. Solve the equation of the virtual works (Eq. (4)) using the equilibrium equations and boundary conditions equation (Eqs. (1)–(3)) in the engineering problem domain. Simulations use the weighted residual method as a way to solve this equation of virtual work linearly. By using this weighted residual method, it gives an approximate solution of the matrixed problem. At this time, since the method used to solve the matrixed problem is the node and the element, the know-how of element setting that does not distort the coordinate system of problem is important for solving the problem.

3.1 Residual stress according to rates of shrink fit

As mentioned above, when the copper bushing is inserted into the cylinder block to prevent the sticking, residual stress is expected before use of the product. The amount of residual stress is expected to be proportional to the rate of shrink fit. The small rate of shrink fit is likely to cause detachment of the bushing, and the large rate of shrink fit is expected to adversely affect the durability of the copper bushing and cylinder block (**Figures 5** and **6**). Therefore, it is important to select the rate of

Figure 5.
Bushing expected departure direction [3].

Figure 6.
Crack of cylinder block.

shrink fit suitable for the size and material of the cylinder block and copper bushing before use.

3.2 Material property check

The shape and material have a great influence on the residual stress as well as the rate of shrink fit when the copper bushing is pressed into the cylinder block. In order to predict the accurate residual stress, a characteristic test was performed on the material except for the shape selected through the design [4]. The reason for this is that, in the case of metallic materials, the material properties such as yield stress and tensile stress vary depending on the production method of the material. Therefore, in order to perform accurate durability assessment, the above-mentioned yield stress and tensile stress value should be basically confirmed. The test results of yield stress and tensile stress are shown in **Figure 7** and **Table 1**. Experimental results were derived from other common aspects that copper

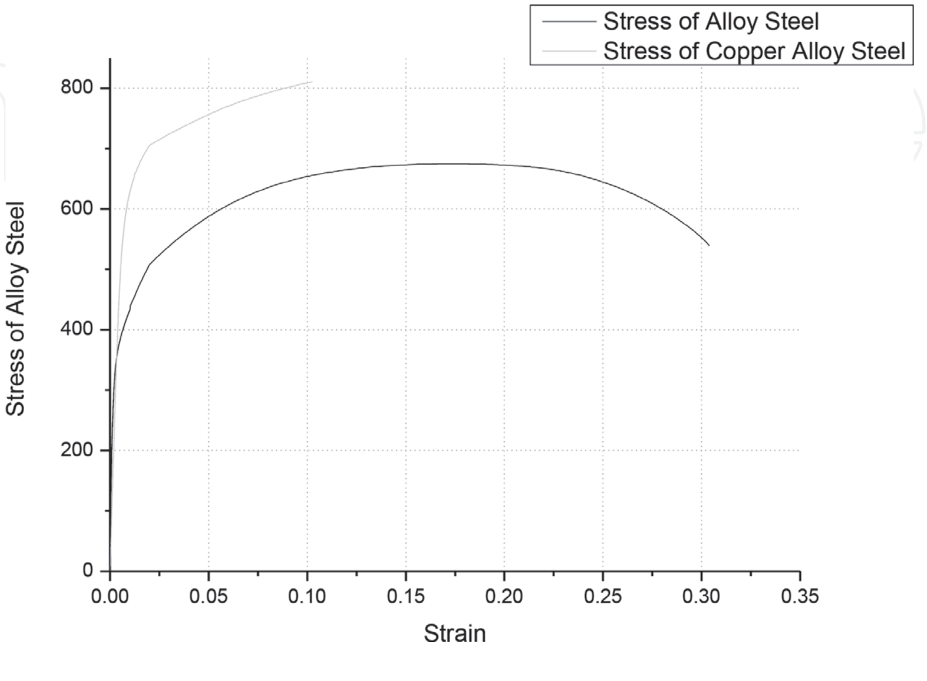

Figure 7.
Material property test results.

bushings generally exhibit the characteristics of ductile materials and alloy steels exhibit characteristics of brittle materials [5]. The results of the material properties of **Table 1** were used to evaluate the durability of the precise cylinder block. **Figure 7** shows the result of the measurement, not the literature, and the confirmed values are shown in **Table 1**.

The residual stress acts as a mean stress at the time of durability assessment, and safety is different as shown in **Figures 8** and **9**. Therefore, in **Figure 9**, the result of **Table** 1 will be used to draw the Haigh diagram baseline clearly.

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \text{(alternating stress)} \tag{1}$$

$$\sigma_m = \left(\frac{\sigma_{max} + \sigma_{min}}{2} \text{mean stress}\right) \tag{2}$$

In addition to the Haigh diagram, there are five other diagrams to easily assess the durability of a product and to illustrate it. The expressions for expressing diagrams are the same as **Table 2**. Goodman, Gerber, SAE, Soderberg and Modified Goodman shown in **Table 2** are shown in **Figure 10**. As you can see in **Figure 10**, Soderberg, Modified Goodman, SAE, Goodman and Gerber are listed in the most conservative order of product evaluation for durability. The most similar form to Haigh diagram is Modified Goodman.

The Haigh diagram (**Figure 11**) can be accurately draw as following:

Point 1: The right limit of the Haigh diagram is generally given by the tensile strength of the material.

Points 2 and 3: For ductile materials, the second point is defined as the intersection between the straight line $\sigma_o = \sigma_y$ and the straight line through the alternating stress limit of the material ($\sigma_{A,tsc}$, R = −1) and its pulsating stress limit ($\sigma_{A,tsc}$, R = 0).

	Alloy steel	Copper alloy steel
Tensile strength	194	226
Yield strength	100	161
Elongation (%)	25	5.45

Table 1.
Value of test results.

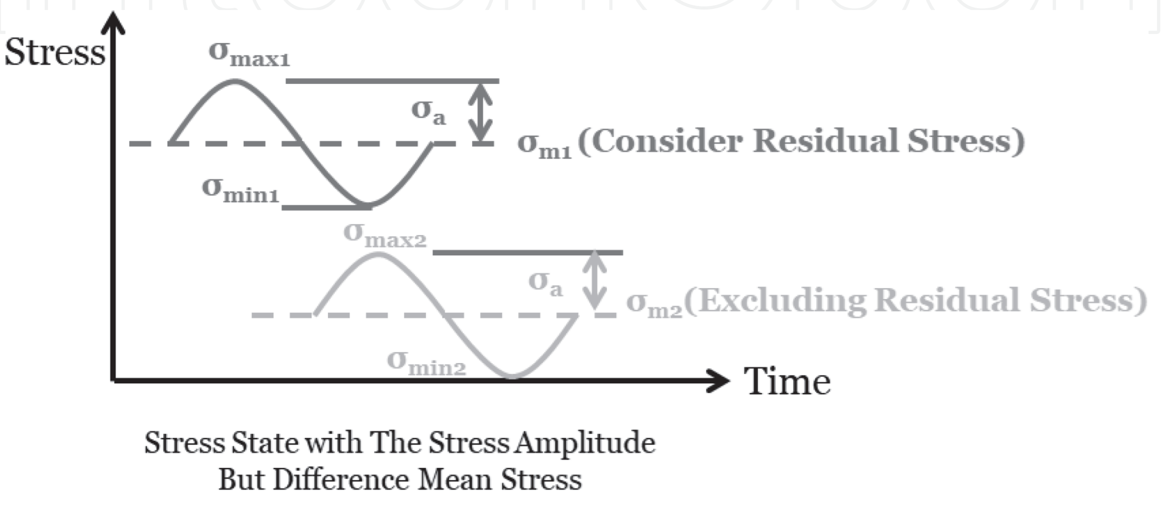

Figure 8.
Important of residual stress.

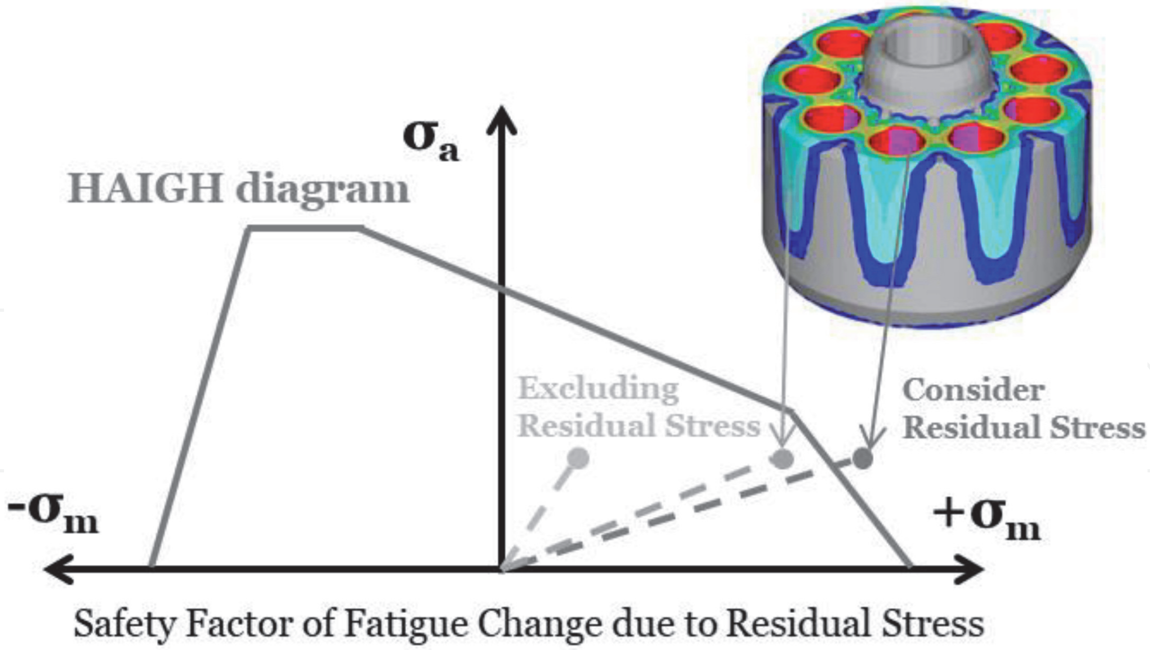

Figure 9.
Important of material property.

Point 3 is identical with point 2. For GG the points 2 and 3 are, as a result of experiments, defined as:

Point 2: $\sigma_m = 0.88 \cdot \sigma_{UTS}$, $\sigma_0 = 0.34 \cdot \sigma_{A,tsc}$ and.

Point 3: $\sigma_m = 0.76 \cdot \sigma_{UTS}$, $\sigma_a = 0.48 \cdot \sigma_{A,tsc}$.

Point 4: Pulsating stress limit (amplitude) of the material.

Point 5: Alternating stress limit of the material under tension/compression.

Point 6: For ductile materials, point 6 is defined as the intersection of the straight line $\sigma_1 = -\sigma_y$ with the lengthening of the straight line from point 4 to point 5. For GG an average inclination of the straight line of 30 degree is derived from known compression pulsating stress limits, which, together with a straight line $R = -\infty$, give point 6. If the compression pulsating stress limit of the material is known, point 6 can be derived from it.

Point 7: For GG, point 7 is determined by half of the length of an orthogonal straight line through the intersection of the compression-fracture border line with the straight line $R = -\infty$. For all other materials, point 7 is identical with point 6.

Point 8: It is the intersection of a horizontal straight line through point 6 with the straight line $\sigma_l = \sigma_{c,C}$.

Fracture theory	**Goodman**	**Gerber**	**SAE**
Equation	$\frac{\sigma_a}{S_e}+\frac{\sigma_m}{S_u}=1$	$\frac{\sigma_a}{S_e}+\left(\frac{\sigma_m}{S_u}\right)^2=1$	$\frac{\sigma_a}{s_e}+\frac{\sigma_m}{S_f}=1$
Yield theory	**Soderberg**	**Modified Goodman**	
Equation	$\frac{\sigma_a}{S_e}+\frac{\sigma_m}{S_y}=1$	$\frac{\sigma_a}{S_e}+\frac{\sigma_m}{S_u}=1\left(for\ \frac{\sigma_a}{\sigma_m}\geq\beta\right)$ $\frac{\sigma_a+\sigma_m}{S_y}=1\left(for\ \frac{\sigma_a}{\sigma_m}\leq\beta\right)$	

Subscript notation: a = alternating, y = static tensile yield, m = mean, u = static tensile ultimate, e = modified material constant, $\beta = S_e(S_u - S_y)/S_u(S_y - S_e)$, σ_a = alternating stress in enviroment condition, σ_m = mean stress in enviroment condition, S_e = modified stress of material, S_f = fatigue limit of material in environment condition, S_y = yield stress of material, S_u = ultimate stress of material.

Table 2.
Types of HAIGH Diagram.

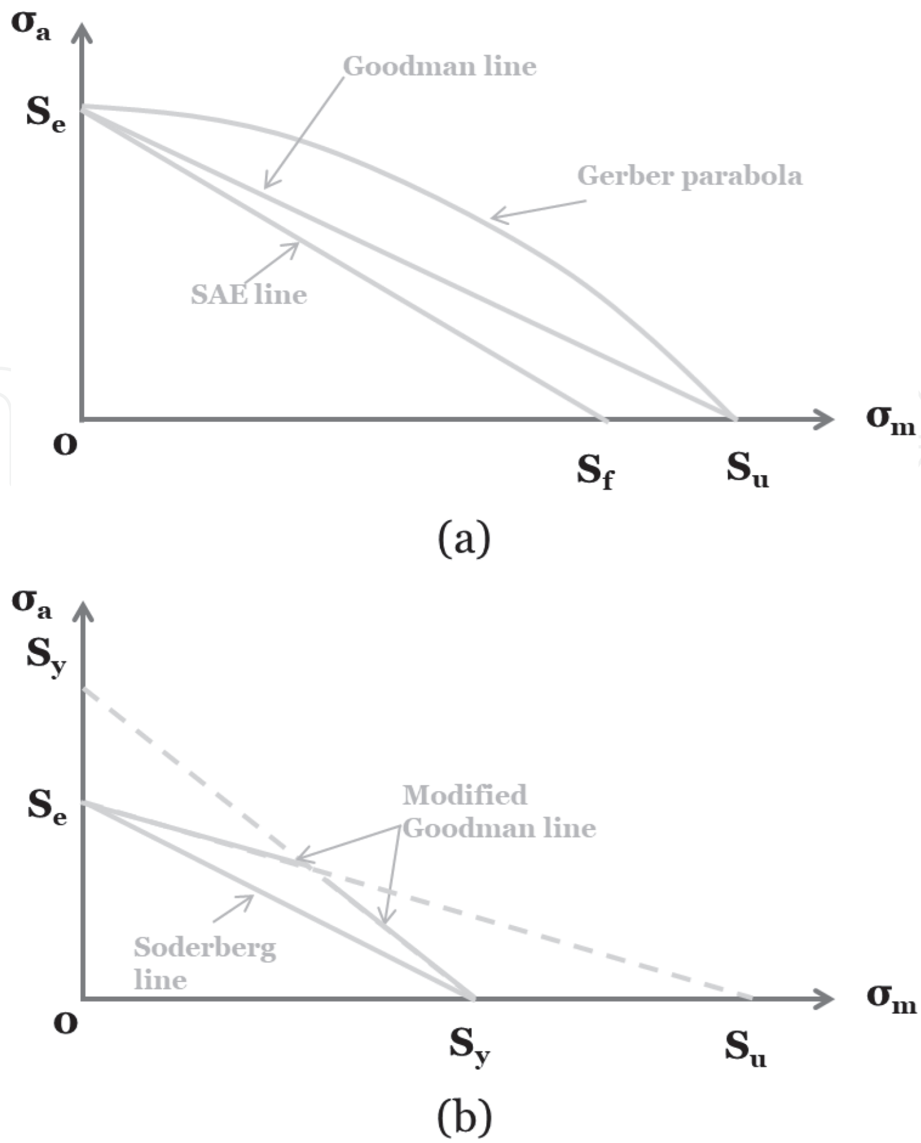

Figure 10.
Fatigue lines to various fracture theories. (a) Fracture theory, and (b) Yield theory.

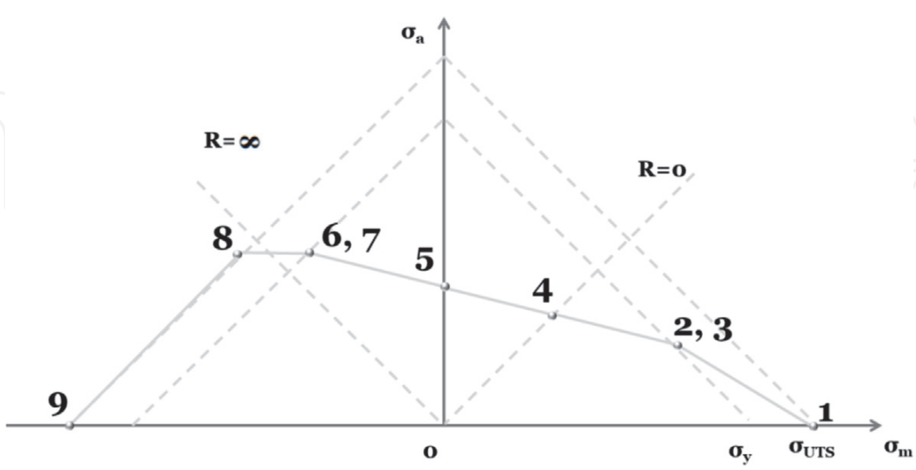

Figure 11.
Drawing method of Haigh diagram.

Point 9: The left limit of the Haigh diagram is given by the ultimate stress limit under compression of the material.

However, the S-N curve and the S-S curve can be changed by the size effect, the relative stress gradient, and the temperature effect, which are exactly the values of

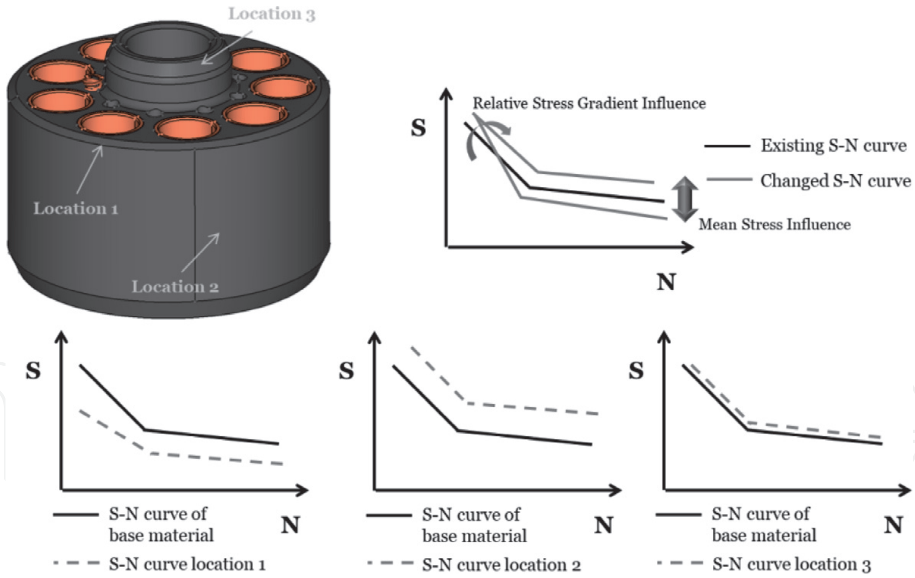

Figure 12.
Change curved because of fatigue parameter.

σ_a and Se necessary for drawing the Haigh diagram as shown in **Figure 12**. In order to consider the fatigue factor, more complicated calculations must be accompanied. Therefore, it is recommended to use the fatigue program for efficient and accurate fatigue safety factor evaluation.

3.3 Verification of simulation method

The purpose of this study is to quantitatively predict the residual stresses that are necessary before actual cylinder block for use. Therefore, it is important to set up an appropriate method of simulation, which is an economic evaluation method, before production. For this purpose, this study compares the surface pressure distribution of the simulation with the surface pressure prediction calculated as (**Figure 13** and Eq. 3) [6].

$$\mathrm{p} = \frac{\delta}{\frac{b}{E_h}\left(\frac{b^2+c^2}{c^2-b^2}+\nu_h\right)+\frac{b}{E_s}\left(\frac{a^2+b^2}{b^2-a^2}-\nu_s\right)}\ \textit{Face Pressure} \tag{3}$$

E_h = modulus of elasticity for hole material,
ν_h = Poisson's ratio for hole material,
E_s = modulus of elasticity for shrink material,
ν_s = Poisson's ratio for shrink material
which is obtained by setting the following stress conditions (**Figure 14** and Eqs. (4) and (5)).

$$\frac{d\sigma_r}{dr}+\frac{\sigma_r-\sigma_\theta}{r}=0\ \textit{Equilibrium Equation} \tag{4}$$

$$\varepsilon_r=\frac{du}{dr},\varepsilon_\theta=\frac{u}{r}\ \textit{Strain} \tag{5}$$

σ_r = radial stress,
σ_θ = tangential stress,
ε_r = radial strain,
ε_θ = tangential strain,
u = displacement of radial direction

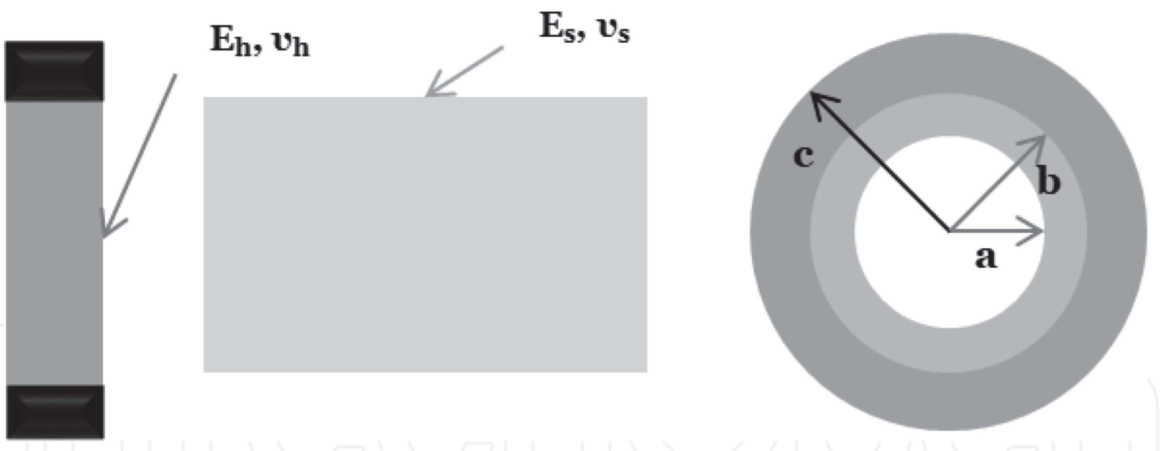

Figure 13.
State of shrink fit.

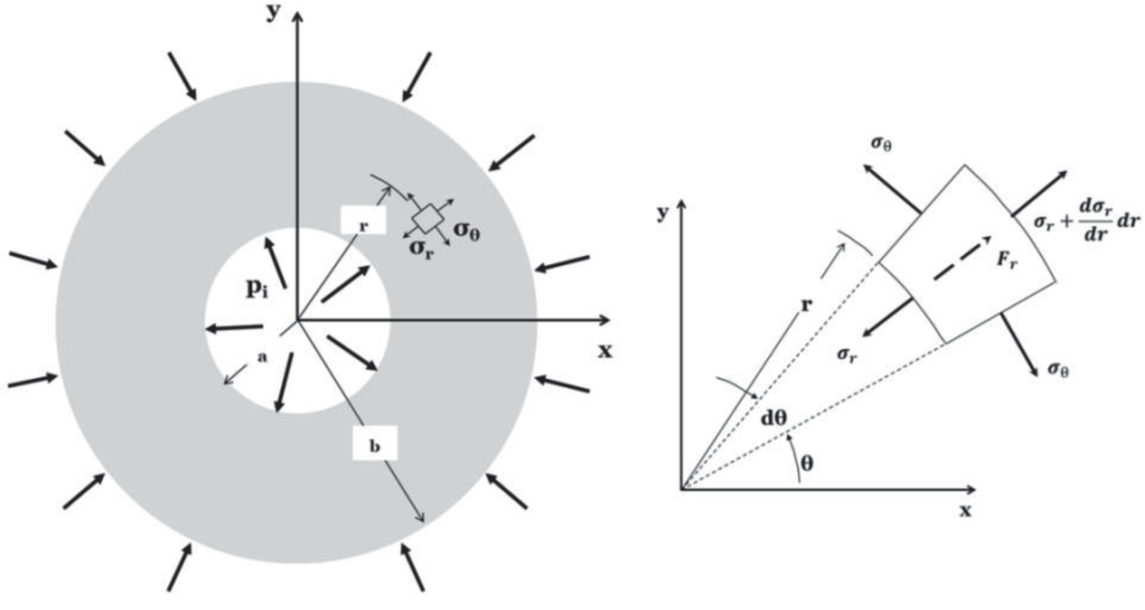

Figure 14.
Stress state.

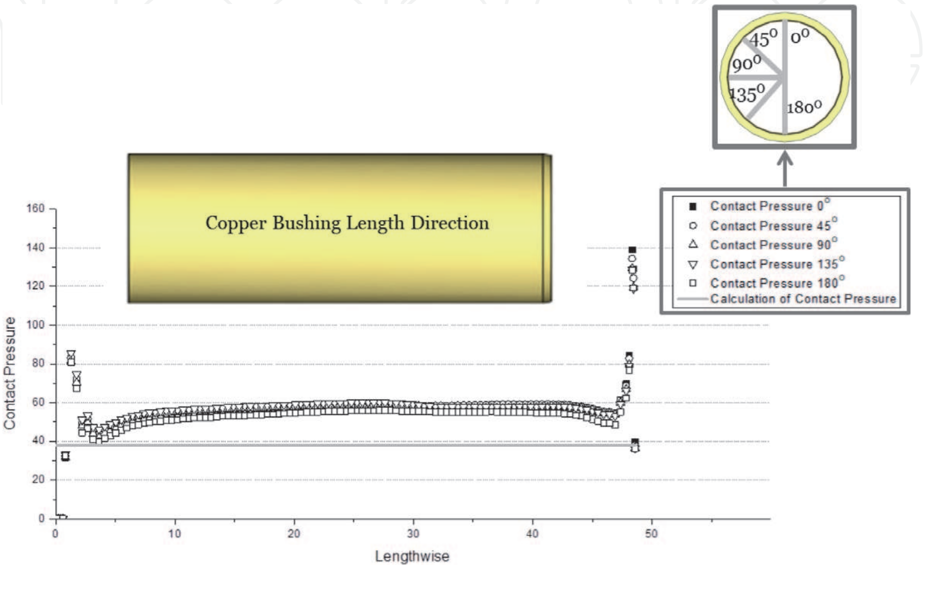

Figure 15.
Check of surface pressure.

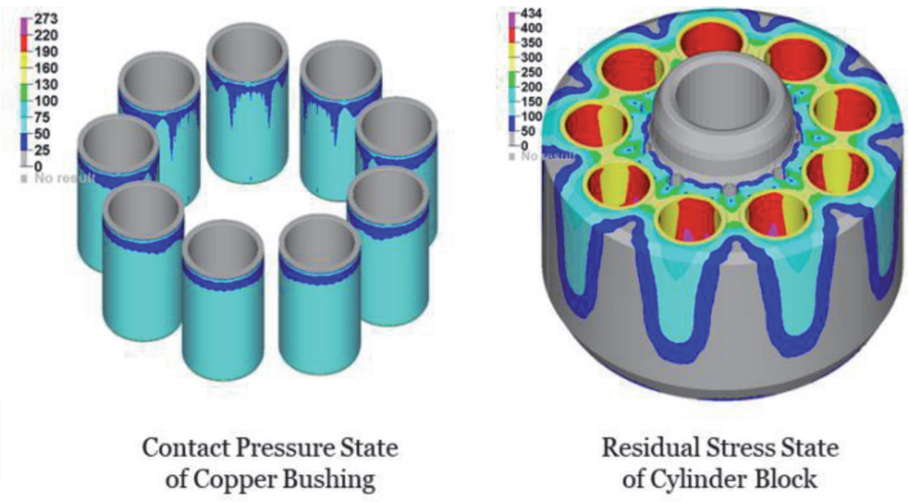

Figure 16.
State of contact pressure and residual stress.

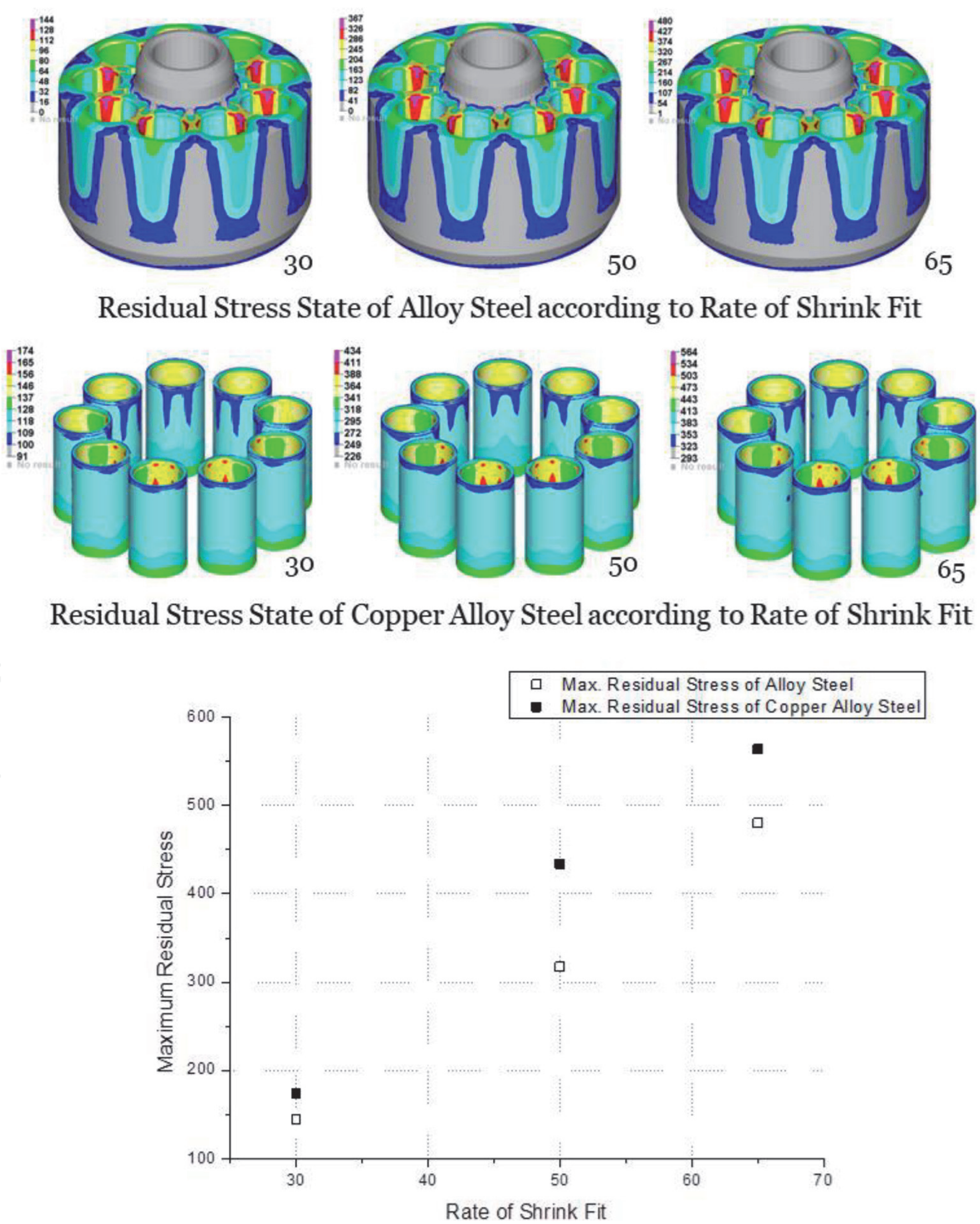

Figure 17.
Relationship between rates of shrink fit and residual stress.

The resulting equation assumes axial symmetry and does not take into account shear stress inherently. In addition, the constant surface pressure in the longitudinal direction is calculated, so it is not suitable for the shape of the cylinder block which is the object of this study, but it is judged to be suitable as the relative standard of the surface pressure to be derived from the structure simulation.

3.4 Estimate residual stress using simulation

The residual stress of the derived cylinder block using the structural simulation is shown in **Figure 15**. In order to determine the suitability of the simulation results, the surface pressure of the bushing was confirmed by angle. The surface pressure distribution of the simulation results follows the general shape [7] of the Hertz contact theory and most of the length of the surface pressure is higher than the constant value derived from the numerical formula (Eq. 5). The reason is that the shape of the cylinder block is not perfectly symmetrical and shear stress is generated almost everywhere (**Figures 16** and **23**).

In addition, the shape and numerical value of the residual stresses were checked within the range of possible shrink fit to confirm the aspect of the change in the residual stress with respect to the rate of shrink fit [8]. As a result, as shown in **Figure 17**, the shape of the residual stress was less dependent on the rate of shrink fit, and the numerical value of the residual stress was almost linearly related to the rate of shrink fit. Therefore, it was possible to set the rate of shrink fit and the residual stress in a linear relationship within the range of the producible shrink fit. In this study, it was possible to select the rate of shrink fit optimized for the use environment by using this relationship. If the relationship between the rate of shrink fit and the residual stress was nonlinear, then the simulation was additionally performed to find out the sections having linear relationship to find the optimal design.

4. Durability assessment considering residual stress

The residual stress results derived from the above simulation are high as the yield stress of the cylinder block and the bushing, so the residual stress was used as the mean stress before the cylinder block was used for accurate durability assessment. Unlike the above situation, when the residual stress is low, there are few reasons to consider it. This is because, as shown in **Figure 18**, there is no difference in the durability assessment result according to the load size when the residual stress is low. In conclusion, the cylinder block, which is the subject of this study, has

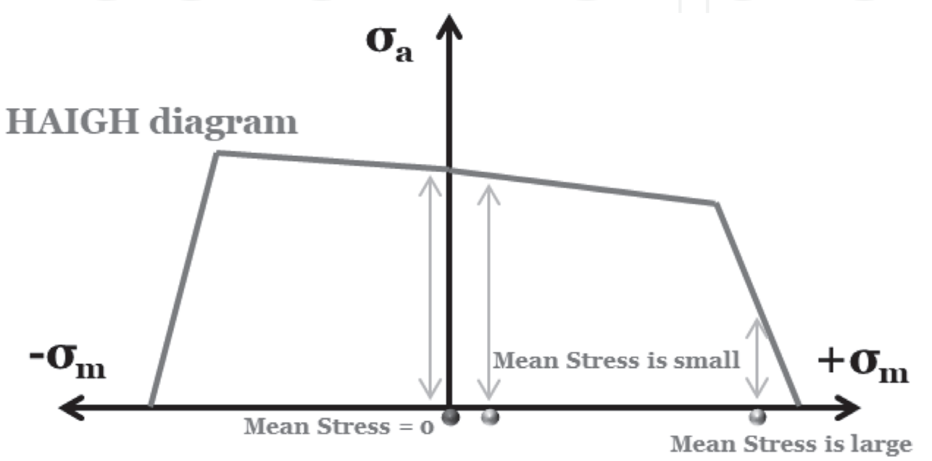

Figure 18.
Mean stress influence on HAIGH diagram.

a high residual stress value. Therefore, in this study, the durability assessment was performed considering the residual stress. In addition, in this section, realistic load and boundary conditions considering the use environment are examined to improve the reliability of the structural simulation results.

4.1 Simulation condition of cylinder block

The cylinder block is fixed from the shoe plate of the main pump and rotates about the rotation axis. At this time, the shoe plate has a certain angle, and the stroke of the piston is generated through this. As a result, during one revolution of the cylinder block, the working fluid flows into the piston through the top dead center and the bottom dead center, and the high-pressure operating fluid what the user wants is discharged [9]. At this time, the cylinder block can be divided into a low-pressure suction portion and a high-pressure discharge portion, which is a main working load condition acting on the cylinder block. In order to quantitatively confirm the magnitude of this high pressure, this study uses the swash plate angle of the main pump, the position of the piston end when the cylinder block is rotated and the AMESim program. As a result, realistic loads such as **Figures 19** and **20** were obtained.

In addition, the boundary condition as shown in **Figure 21** was set in consideration of the operating condition of the cylinder block. The boundary conditions were fixed in the axial direction where the stopper was located, and the angle of the spline portion was fixed to prevent rigid body motion of the cylinder block. In this case, the accuracy of the simulation is ensured by applying the centrifugal force to the influence of the rotational speed of the cylinder block while rotating the cylinder block.

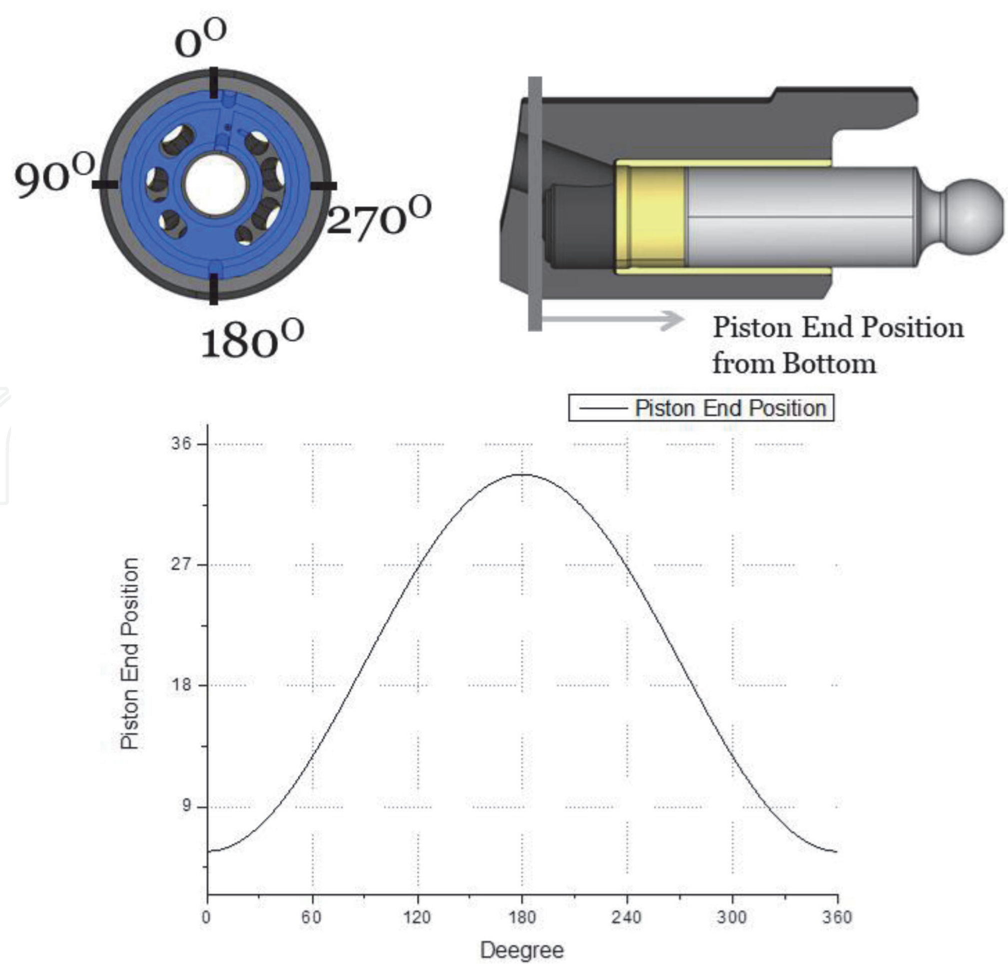

Figure 19.
Piston end position from bottom for simulation.

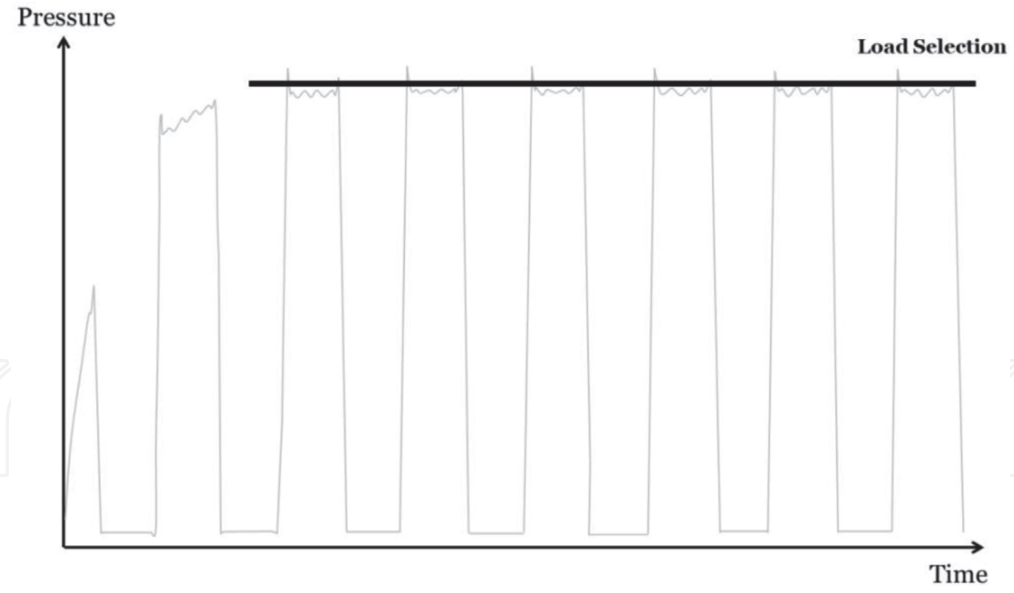

Figure 20.
Working load of main pump.

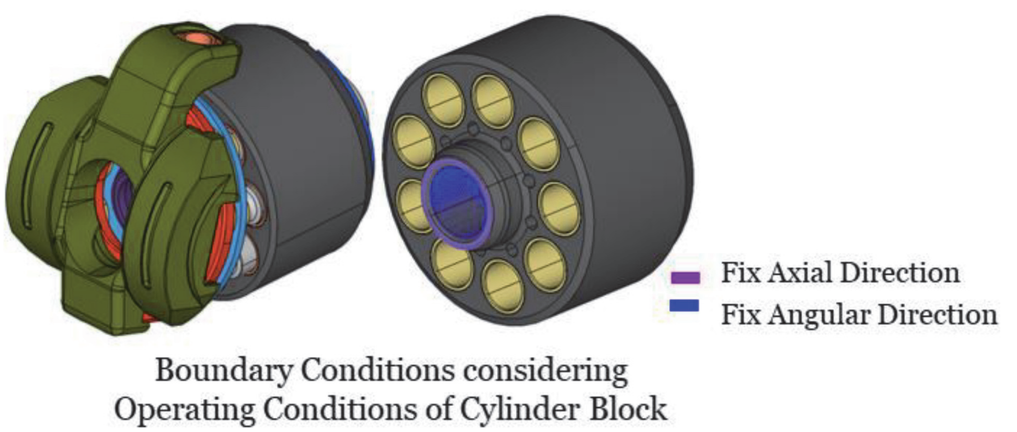

Figure 21.
Boundary condition for FEM.

4.2 Comparison of simulation results considering residual stress

During operation of the main pump, the load acting on the cylinder block does not act as a cyclic symmetry, and the load distribution during rotation varies. Therefore, in this study, the time when the cylinder block receives the highest load during rotation is selected and analyzed (**Figure 22**). The reason for this is that the cylinder block will rotate and receive a load at this peak time periodically at the lowest stress (0 MPa).

The results of the residual stress analysis obtained above are mapped to the structural simulation model and the results shown in **Figure 23** can be obtained by using the above described simulation conditions and methods. It can be confirmed that there is a considerable difference by comparing it with the stress value of the simulation method which does not consider the residual stress (**Figure 24**).

4.3 Durability assessment of cylinder block considering residual stress

The durability assessment of the cylinder block was finally evaluated by using the stress simulation result considering the residual stress, the use environment and the allowable stress which is one of the characteristic values of the material. At this

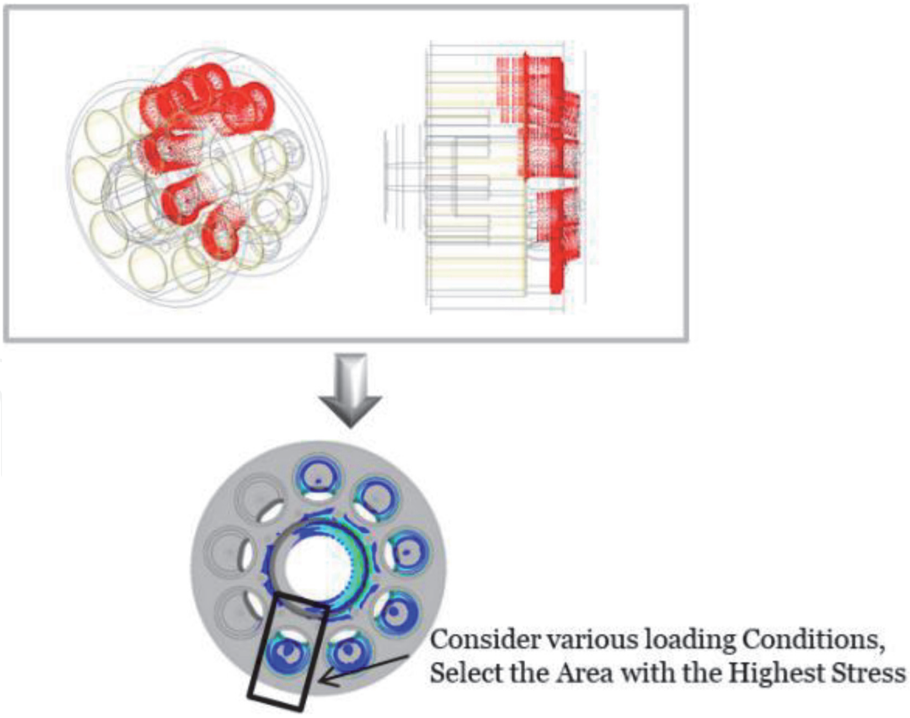

Figure 22.
Extreme situation during usage.

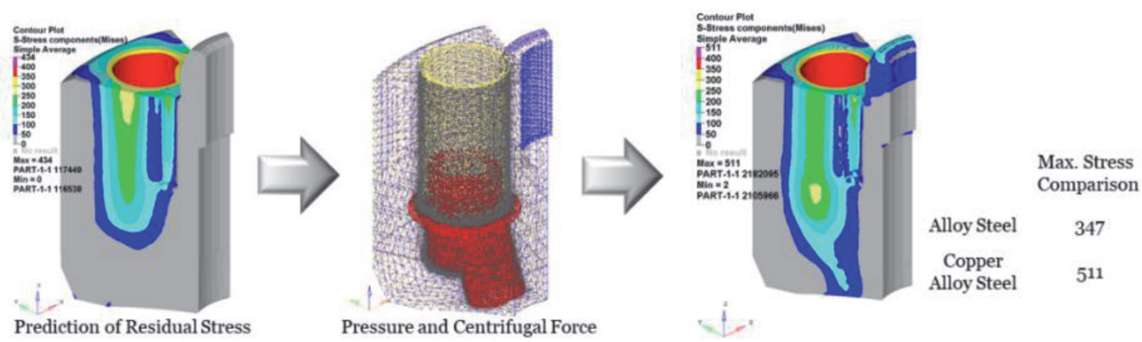

Figure 23.
Durability assessment results of cylinder block.

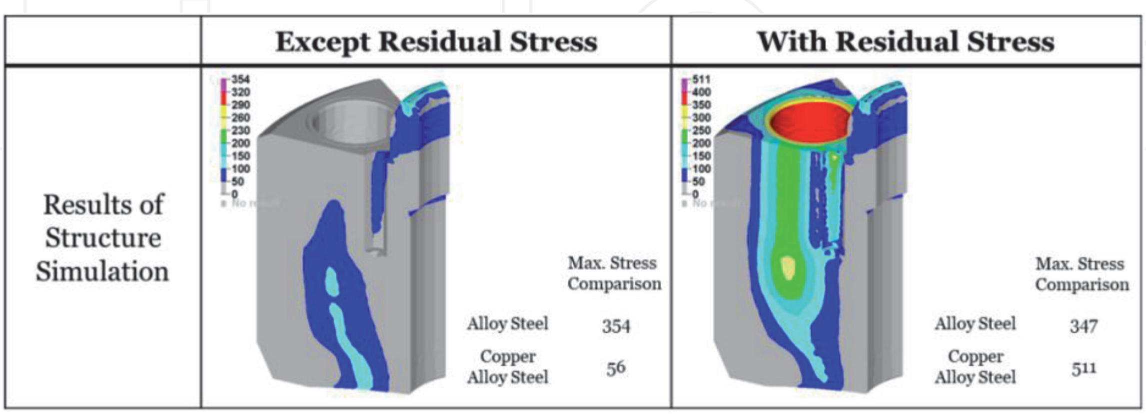

Figure 24.
Comparison of durability assessment results.

time, among the many durability assessment methods, the mean stress is constant in the cylinder block, and the stress condition during use is relatively simple, so that it is calculated according to the criterion of σ_m = C in **Figure 25**. Finally, in order to improve the accuracy of fatigue safety assessment, size factor, slope of surrounding stress, survival probability and surface roughness were considered [8]. As a result, quantitative fatigue safety factor as shown in **Figure 26** was obtained.

The residual stresses and assessment methods mentioned in the above studies can often be different from the residual stresses in welding and their more complicated assessment methods. This is because, in the case of welding, the change of the metal structure due to the introduction of heat energy occurs, and thus a complicated residual stress is formed. However, the residual stress generated in this study is not related to the residual stress due to the temperature change and is related to

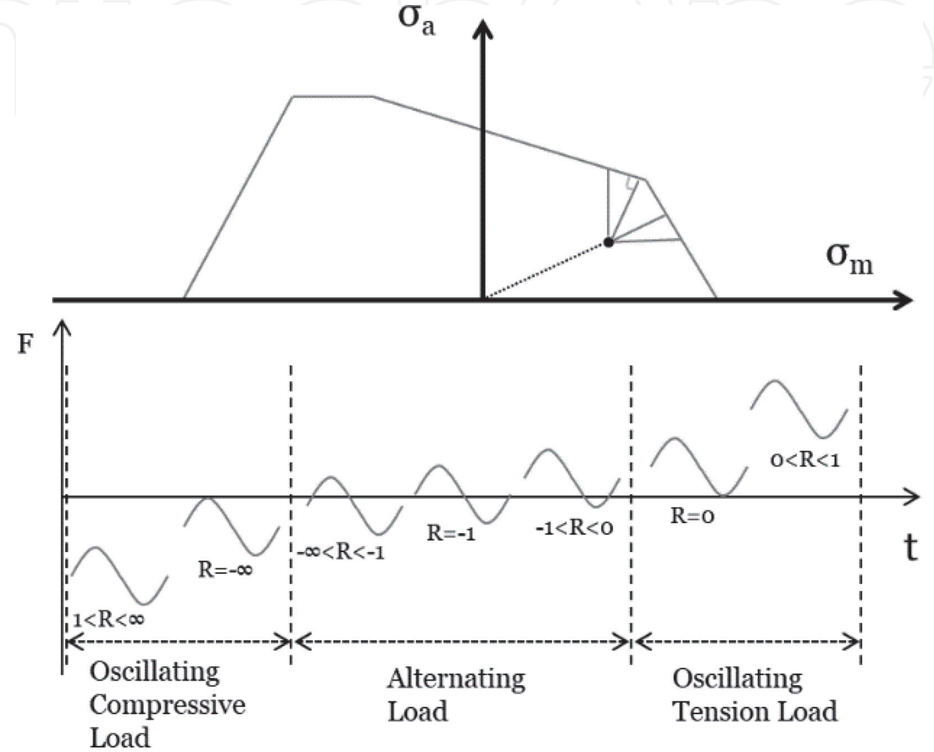

Figure 25.
Method for durability assessment.

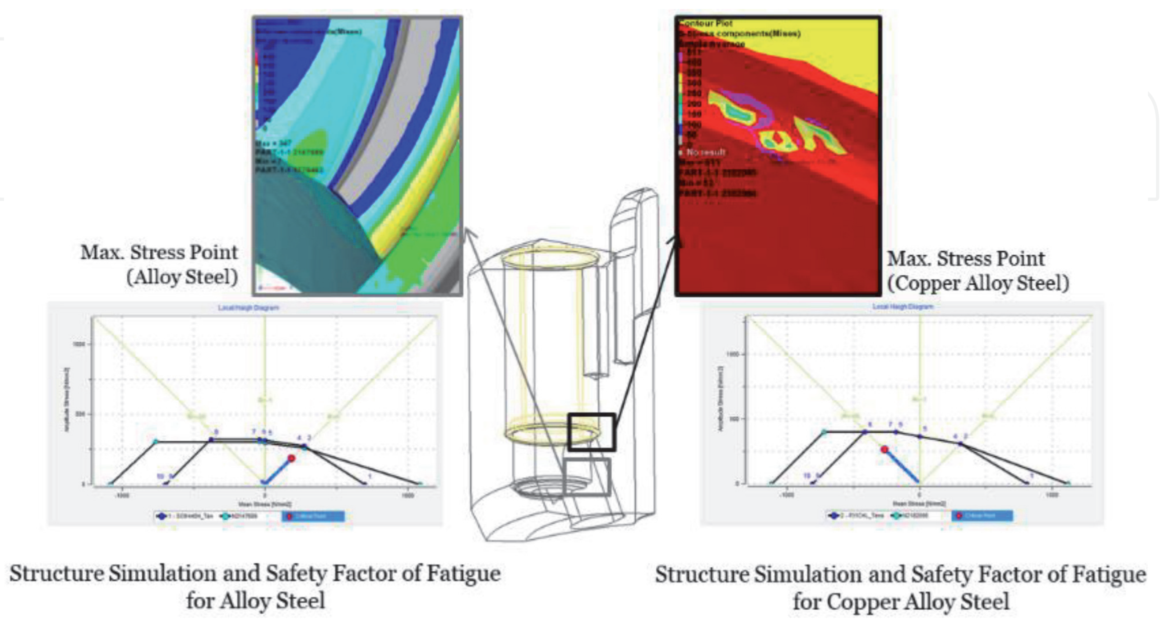

Figure 26.
Quantitative result values.

the shrinkage and relaxation of the existing material. Therefore, it is possible to perform a definite durability assessment only by the basic relationship between the basic load and the material (**Figures 27** and **28**) [10].

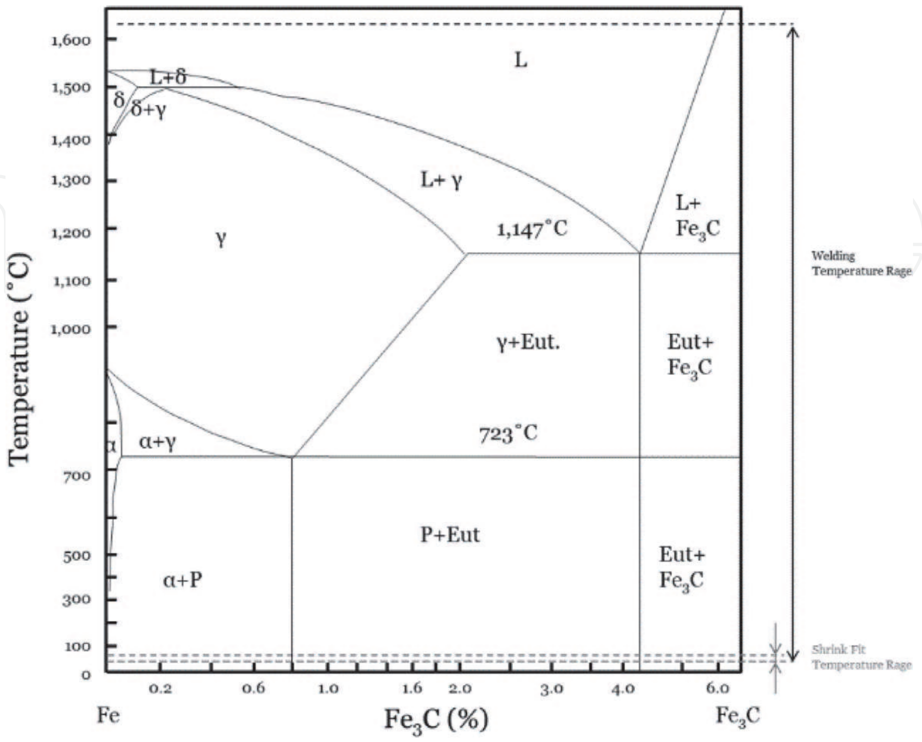

Figure 27.
Phase diagram of Fe-Fe_3C.

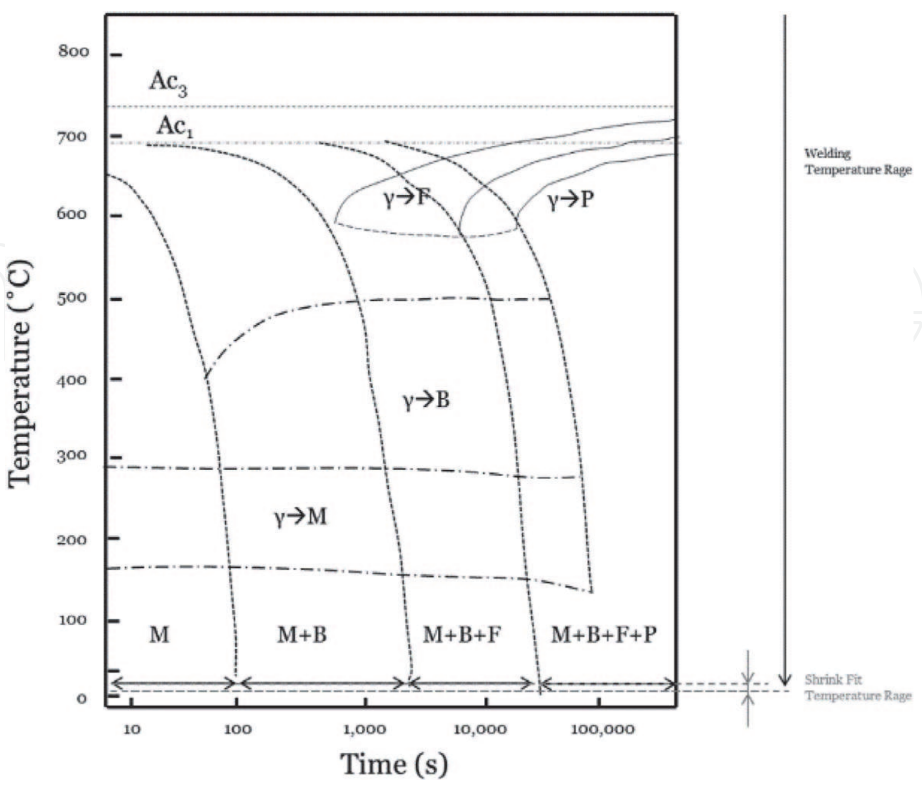

Figure 28.
Continuous cooling transformation diagram.

5. Conclusion

This study was carried out to find methods for quantitatively confirming the durability of the product during the increasingly diverse production process. And, the cylinder block in which the bushing was inserted for seizure was selected as the standard product. As a result, it was possible to establish durability assessment methods and processes for machine parts where large residual stress is generated by shrink fit during production process. The results of this study will contribute to the durability assessment considering the residual stress of machine parts which does not change the material structure due to thermal energy input unlike welding.

In addition, this study examined existing durability assessment methods and confirmed the merits and demerits of evaluation methods. Based on these advantages and disadvantages, this study also presented limitations of the durability assessment method considering the residual stresses presented. This will prevent indiscreet use by specifying the use environment of the durability assessment considering residual stress as a result of this study. In addition, a verification method is proposed to use the simulation for complex shapes and to ensure the reliability of the simulation results. This will provide efficient development and forecasting directions for the industry unlike current development of shrink fit that has been developed depending on existing people and facilities.

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