

The Effects of Overload on the Fatigue Life

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Abstract: Automotive vehicles undergo various ranges of road loads according to the driving conditions. Sometimes it experiences unusually large overload such as pot-hole impact or curb strike whose forces are several times of the vehicle weight. Those overloads may induce plastic deformations at some components and these plastic deformations reduce the fatigue life of the components. In some cases, the fatigue crack initiation points may be changed due to the residual stresses which were generated by the overloads. Predicting the fatigue life by general fatigue analysis methodology, which uses linear stress analysis results and linear damage accumulation rule, is very difficult if any component contains residual stresses. This study was performed to assess the effects of overload on the fatigue behavior of automotive suspension components and to develop a fatigue analysis methodology predicting the fatigue life under overload. Fatigue tests were performed for aluminum knuckle with the application of single overload whose magnitude is large enough to generate plastic deformations on the knuckle. The fatigue life of knuckle was reduced and crack initiation points were changed after applying single overload. Those phenomena could not be predicted by adopting linear stress analysis and Miner's linear damage accumulation rule. By using non-linear stress analysis results and considering residual stress, it was satisfactory to predict the reduction of fatigue life and change of crack initiation points.

Keywords: Overload, Fatigue Life, Plastic Strain and Residual Stress.

1. Introduction

Automotive vehicles undergo various ranges of road load according to the driving conditions. Especially when it travels over irregular road such as pot hole or when it bears curb strike, the vehicle endures overloads which are several times of its own weight. Those overloads may induce plastic deformations at some components of the vehicle. The fatigue damage of those components will highly increase and hence fatigue life decrease because of residual stresses which were generated by the overloads. Sometimes fatigue crack initiation area may change. During the fatigue tests of new vehicle, engineers often find that crack initiation area of same components changed from vehicle to vehicle depending on the test modes (Kyeong, 2007). Most of these phenomena are due to the overload applied to the vehicles during the tests.

Single or multiple overloads applied on specimens affect the fatigue life of those specimens. Tensile overload on a notched specimen decreases the crack growth rate due to the compressive residual stress at notch tip generated by the overload. Compressive underload accelerates the crack growth rate due to the tensile residual stress at notch tip generated by the underload (Lang, 1999). Single tensile overload of stress equal to yield stress of the material applied on a smooth specimen decreases the total fatigue life of the specimen (Zheng, 1995), (McEvily, 2001). Bending overload both shorten the fatigue life of specimens subjected to torsional loading and lower the torsional fatigue limit (Bonnen, 1999). Periodically applied overload of yield stress level also shorten the

fatigue life of specimens (Pompetzki, 1990) and reduce the fatigue limit to one half of the constant amplitude fatigue limit (Bonnen, 2001).

Although much effort has been given to the study of the effect of overload, it is difficult to get enough information about the fatigue behavior of complex mechanical components subjected to multi-axial loads such as automotive chassis components because most of those studies were conducted for the application of simple load on simple shape specimens, for example, tensional, compressive, bending and torsional load applied on standard specimens. This study was performed to assess the effects of overload on the fatigue life of mechanical components whose geometry are not simple. It shows how the fatigue life and crack initiation points of automotive chassis component change after the application of single overload. And this study also suggests a methodology of fatigue analysis to predict such behaviors.

Front knuckle made of aluminum alloy was selected as a research object and fatigue test was performed on the knuckle with and without single overload. The single overload was applied ahead of fatigue test. Three levels of overload were applied according to the magnitude of plastic strain generated on the knuckle by the overload. And the effect of the level of plastic strain on the change of fatigue life was observed. If any plastic strains were generated on the knuckle by the overload, fatigue life of the components was reduced and the crack initiation areas moved to other area. If the overload cannot generate any plastic strain, it does not have any effect on the fatigue behavior of knuckle.

Fatigue analysis was performed to predict fatigue life of knuckle. The analysis results were compared with the test results. General fatigue analysis methodology which uses linear stress analysis results and ϵ -N curve of the material could not predict such phenomena if any plastic strains were generated by overload. So, new methodologies of fatigue analysis that use the non-linear stress analysis results and ϵ -N curve was suggested. Abaqus/Standard was used for linear and non-linear stress analysis. And FE-SAFE was used for fatigue analysis.

The front knuckle is made of aluminum alloy and manufactured by cast forging. It was used as it received for the test. Mechanical properties of aluminum alloy A356CF-T6 are listed in Table 1.

Table 1. Mechanical properties of aluminum alloy.

A356CF-T6	
Young's modulus (MPa)	73,500
Yield strength (MPa, 0.2% offset)	220.0
Ultimate strength (MPa)	303.0

2. Static strength test and analysis

The purpose of static strength test is to find the break strength of the knuckle. Test results was compared to Finite Element analysis results to verify the reliability of the analysis.

2.1 Test setup and FE model

As the knuckle is mounted on hub, those mounting bolt holes were fixed on testing jig and load was applied on the upper arm mounting point. All these jigs and hydraulic actuator were included in FE model. Boundary conditions and loading conditions of analysis are same as those of test. See Figure 1 for test setup and FE model.

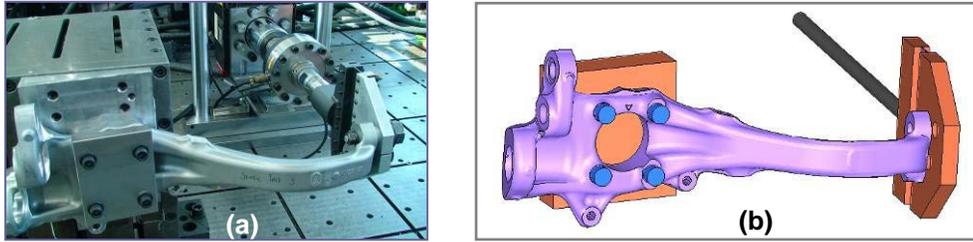


Figure 1. (a) Test setup, (b) FE model.

2.2 Test and analysis results

The failure area of knuckle in static strength test is near hub mounting bolt as in Figure 2. The force-displacement curve show good agreement between the tested and analyzed results, Figure 3, and the difference of breaking forces between test and analysis is less than 2.0%. It can be said that the reliability of analysis was achieved from this results. The force-displacement curve made it possible to define the level of overload because the analysis results can give enough information of plastic strain of the knuckle.



Figure 2. Strength test results.

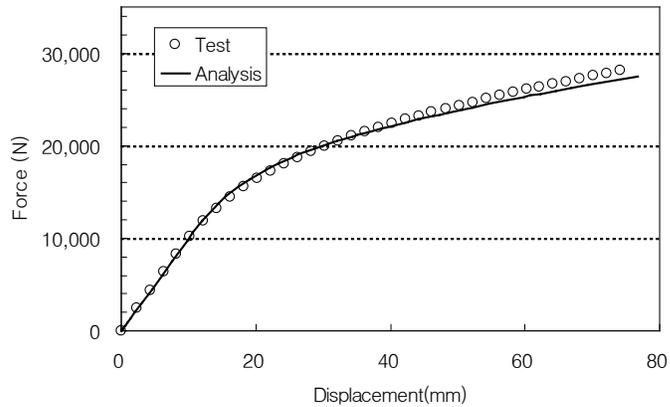


Figure 3. Force-displacement curve

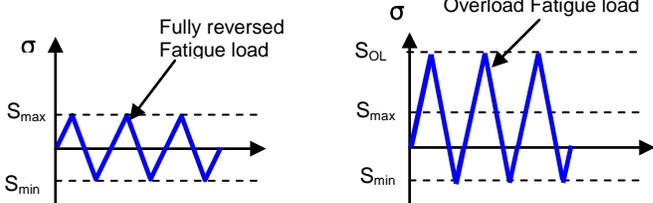
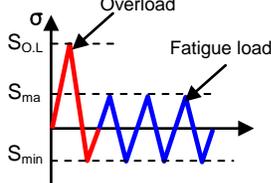
3. Fatigue test

3.1 Test conditions

Test setup is same as that of static strength test as in Figure 1. The fatigue life is defined as the number of cycles to the final breaking to pieces of the knuckle. Two cases of testing loads were applied; constant amplitude loading case (hereinafter CA case) and mixed amplitude loading case (hereinafter MA case). In CA case, six levels of fully reversed constant amplitude load, whose stress ratio is -1, and four levels of overload fatigue load, whose stress ratio is larger than -1, were applied. The maximum stress of overload fatigue is fixed to the same value as the S_{OL} of MA2, where S_{OL} is the nominal stress of the knuckle under overload.

The MA case is a combination of single overload and fully reversed constant amplitude fatigue load. Single overload was applied before constant amplitude fatigue test. Three levels of overload were used according to the S_{OL} . Magnitudes of the plastic strains at the hub mounting bolt area under those three overloads are 0.0%, 1.2% and 2.0%. Plastic strains at neck area are 0.0%, 1.0% and 2.0% for each S_{OL} . Each case is referred to as MA1, MA2 and MA3. The maximum stress of MA1 is 98% of the yield stress. The minimum stress of the overload step is same as the minimum stress of following constant amplitude fatigue load. The fatigue load of MA case is same as the fatigue load of CA case for same S_{min} . Test and loading conditions are listed in Table 2.

Table 2. Test conditions and test loading.

Test Condition	Test loading
Constant Amplitude Loading (CA case)	 <p>The figure shows two stress-time graphs for Constant Amplitude Loading. The left graph, labeled 'Fully reversed Fatigue load', shows a sinusoidal wave oscillating between stress levels S_{min} and S_{max}. The right graph, labeled 'Overload Fatigue load', shows a sinusoidal wave oscillating between S_{min} and S_{OL}, where S_{OL} is higher than S_{max}.</p>
Mixed Amplitude Loading (MA case)	 <p>The figure shows a stress-time graph for Mixed Amplitude Loading. It starts with a red peak labeled 'Overload' reaching S_{OL}, followed by a blue sinusoidal wave labeled 'Fatigue load' oscillating between S_{min} and S_{ma}.</p>

3.2 Test results

1) Constant amplitude loading case

Fatigue failures of knuckle under constant amplitude loading were occurred at the mounting bolt area (Figure 4). The final fatigue life of fully reversed constant amplitude fatigue and overload fatigue were plotted on Figure 5. Horizontal axis of figure 5 represents fatigue life in log scale and vertical axis represents fatigue stress amplitude of mounting bolt area in linear scale. The reason of using linear scale for stress is to show the test results more clearly by magnifying the interval of stress amplitude. The fatigue lives of fully reversed constant amplitude fatigue load and stress amplitude are in the relation of inverse proportion as expected. On the other hand, the fatigue life of overload fatigue is nearly unchanged regardless of the minimum fatigue stress.



Figure 4. Failure mode of CA case fatigue test.

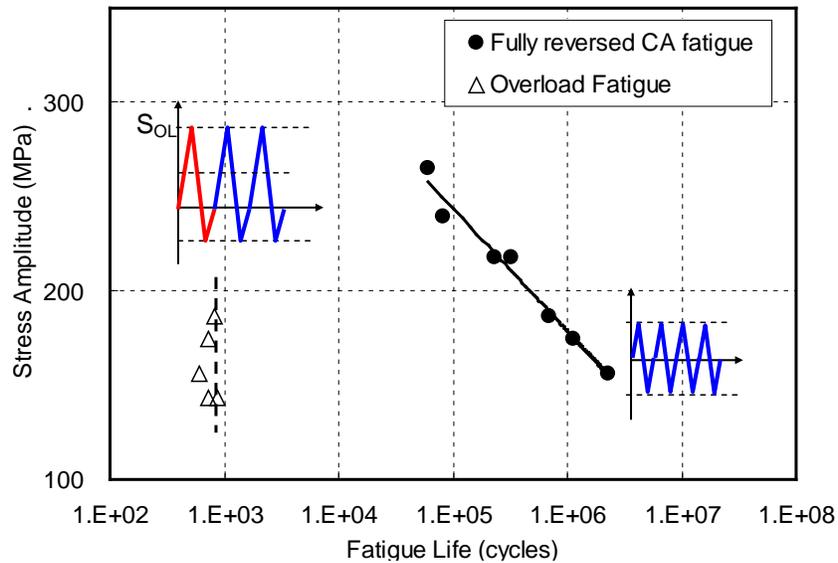


Figure 5. Stress-Life curve for test results of CA case.

2) Mixed amplitude loading case

In MA1 case, where the maximum stress under overload is within elastic range, failure occurred at the mounting bolt area and fatigue life was same level as that of fully reversed constant amplitude fatigue of CA case. In MA2 and MA3 case, where maximum plastic strain of mounting bolting hole is over 1.0%, fatigue lives were reduced to 20 ~ 30% of the fatigue lives of fully reversed constant fatigue of CA case. The slopes of stress-life curve for MA2 and MA3 case increased as the maximum plastic strain increase. And failure modes of MA2 and MA3 case changed from mounting bolting area to neck area for all the S_{min} as in Figure 6. The stress-life curves of MA cases are plotted on Figure 7 with the comparison of fully reversed constant amplitude load fatigue lives. Each overload of MA1, MA2 and MA3 case will be referred to as OL1, OL2 and OL3.

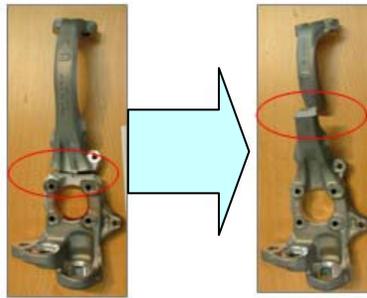


Figure 6. Change of failure mode by overload.

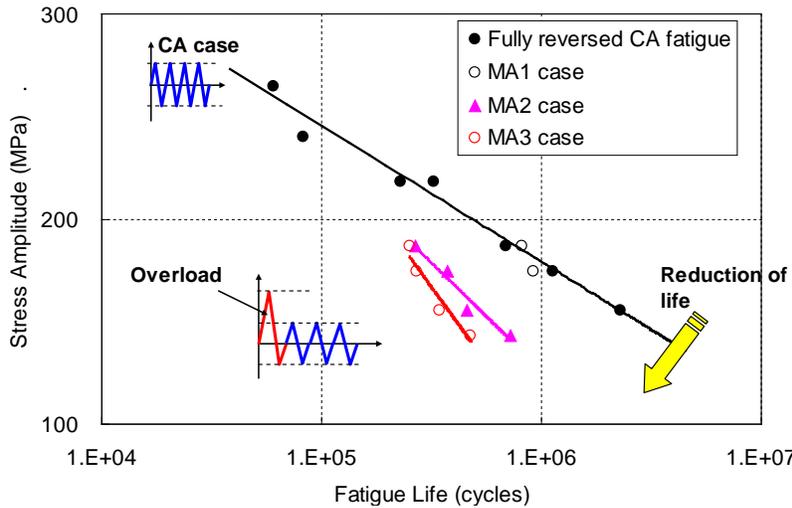


Figure 7. Stress-Life curve of fatigue test for CA case and MA cases.

The reason of the reduction of fatigue life and change of failure mode after overloading is residual stresses induced at mounting bolting area and neck area by the overload. It is well known that tensile residual stress shorten the fatigue life and compressive residual stress increase the fatigue life. The neck area undergoes compressive plastic deformation and mounting bolt area undergoes tensile plastic deformation during the overload step. After unloading the overload, tensile residual stress remains on the surface of neck area and compressive residual stress remains on the surface of mounting bolt area. The tensile residual stress on the surface of neck area accelerated the initiation of fatigue crack and the compressive residual stress on the surface of mounting bolt area decelerated the initiation of fatigue life and hence failure mode changed from mounting bolt area to neck area.

If the fatigue life of MA2 case were predicted by summing the fatigue damages of CA case, fully reversed constant amplitude load fatigue and overload fatigue, according to Miner's linear damage summation rule, the predicted fatigue life of MA2 case shows no meaningful difference with the fatigue life of fully reversed constant amplitude load fatigue of CA case (Figure 8). But the real test result of MA2 case show remarkable difference with the predicted fatigue life as in Figure 8. This error is mainly due to the linear assumption of damage summation. This says that there is something non-linear phenomena involved in the mixed amplitude fatigue case. As mentioned before, the non-linear factor is residual stress induced by the overload, which is ignored in the Miner's linear damage summation process.

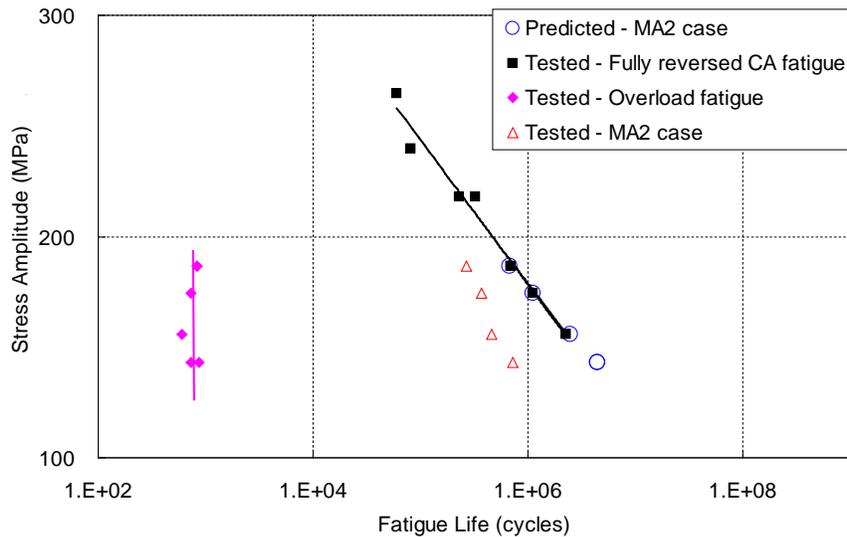


Figure 8. Comparison of predicted and tested fatigue life; MA2 case by linear damage summation.

4. Fatigue analysis

4.1 Basic information

All of the jigs and actuator were included in FE model and same boundary conditions as test were applied, Figure 1(b). ABAQUS/Standard was used for linear and non-linear stress analysis and FE-Safe was used for fatigue life calculation. Strain-life method was applied to the fatigue life calculation. As the residual stress is important factor that influence on the reduction of fatigue life and change of failure mode, material non-linearity was considered in stress calculation of overload to get the residual stress and strain.

4.2 Analysis results

1) Constant amplitude loading case

The results of fatigue analysis for CA case predicted that fatigue crack will initiate at the mounting bolt area, same as test results. The predicted fatigue lives are in good agreement with the test lives for fully reversed constant amplitude load fatigue and overload fatigue, Figure 9.

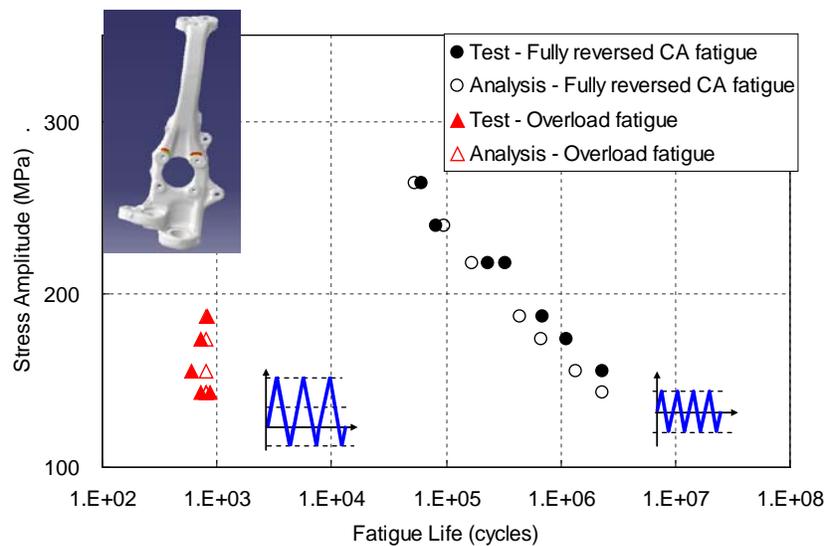


Figure 9. Comparison of analysis and test results of CA case.

It was verified that tensile residual stress was induced at neck area and compressive residual stresses at mounting bolt area after overload as expected from test results. The residual stress generated at mounting bolt area and neck area is compared in Figure 10 for each loading step. As the maximum stress under overload (S_{OL}) increase, residual stress also increase. For same overload,

large absolute of S_{min} decrease the residual stress. The reason is that the reverse loading step offset the stress of overload. The increasing rate of residual stress at neck area is larger than the rate at mounting bolt area.

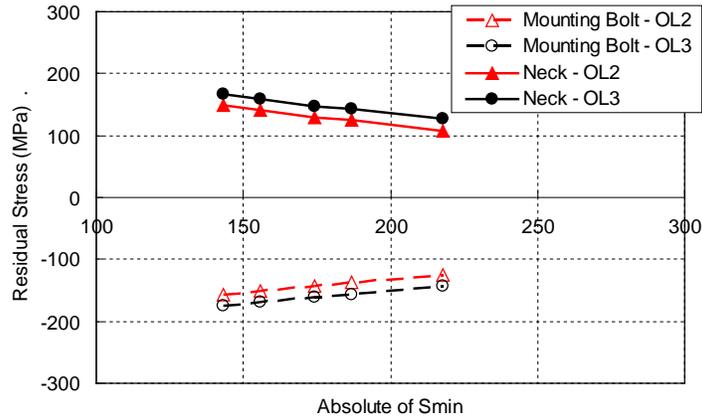


Figure 10. Residual stresses of overload cases.

2) Mixed amplitude loading case

Transient fatigue analysis is required for MA case fatigue analysis to consider the residual stress or residual strain. Fatigue crack area was predicted to be the mounting bolt area for MA1 case, where S_{OL} is within yield stress. For MA2 and MA3 case, where S_{OL} is larger than yield stress, it was predicted that fatigue crack will initiate at neck area (Figure 11). The reason of the change of fatigue crack initiation area is the tensile residual stress left on the surface of neck area after overloading.



Figure 11. Crack initiation area of MA2 and MA3 case.

Calculated fatigue life of mounting bolt area and neck area is plotted on Figure 12 with the comparison of the calculated fatigue life for fully reversed constant amplitude load fatigue of same

area. The calculated fatigue life of fully reversed constant amplitude load fatigue is plotted in straight lines for both areas. The fatigue life of mounting bolt area and neck area of MA1 case is nearly unchanged compared to the fatigue life of CA case. The fatigue life of neck area for MA2 and MA3 case decreased remarkably compared to the fatigue life of CA case. The fatigue life of mounting bolt area for MA2 and MA3 case slightly increased compared to the fatigue life of CA case. These phenomena are due to the tensile residual stress at neck area and compressive residual stress at mounting bolt area generated by overload.

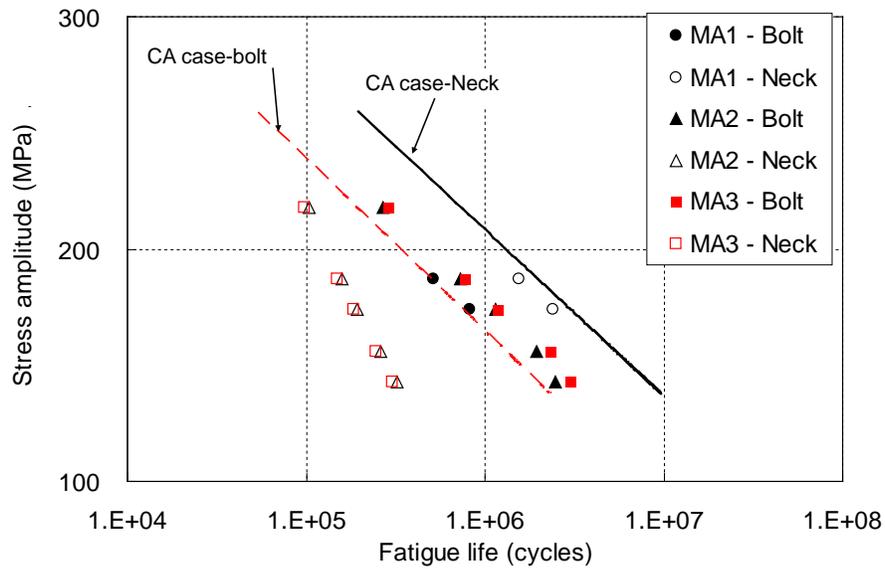


Figure 12. Fatigue analysis results of MA case with the comparison of the analysis results of CA case.

Calculated fatigue life and test results for MA2 and MA3 were plotted on Figure 13 with the comparison of calculated fatigue life at mounting bolt area and neck area, which are plotted in straight lines. Results of MA2 cases are represented by solid marks and MA3 case are hollow mark. Although the analysis predicted the change of failure mode after overload very well, the calculated lives are 40 ~ 50% smaller than test results. The reason of this under estimate is the difference of failure criteria between test and analysis; final broken life for test and crack initiation life for analysis.

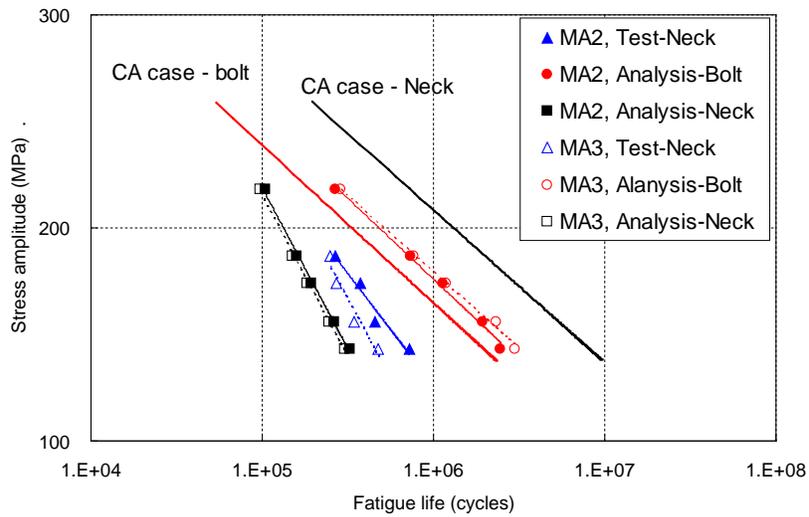


Figure 13. Fatigue analysis results of MA2 and MA3 case with the comparison of test results.

5. Conclusions

1. Overload of plastic strain larger than 1.0% applied to aluminum knuckle shorten the fatigue life because of tensile residual stress.
2. Fatigue failure mode could be changed due to the residual stress induced by overload.
3. Overload of stress not larger than yield stress have little influence on fatigue life and do not change the failure mode.
4. Miner's rule cannot be used in fatigue life prediction when overload generate plastic strain larger than 1.0%.
5. To predict the change of failure mode and to get the accurate fatigue life non-linear stress analysis results must be used rather than linear stress analysis results.

6. References

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