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Research

INVESTIGATION OF THE EFFECT OF BENDING PROCESS ON FATIGUE LIFE AND MECHANICAL STRENGTH OF HEAVY COMMERCIAL VEHICLE DRAG LINKS

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ABSTRACT

In heavy commercial vehicles, the part that enables the wheels to turn left and right by transferring the movement from the steering box to the wheel via the pitman is called the steering drag link. In order to obtain the desired form in the production of bended drag links, the pipe material is subjected to bending process from certain points by various methods. During this bending process, plastic deformation occurs in the material. In this study, the effect of plastic deformation in tie rod bending on the life of the drag link was investigated. The amount of plastic deformation in the bending region was determined as %12 by performing tie rod bending simulation in a Finite Element Analysis (FEA) software. The fatigue behavior of the %6 and %12 pre-strained material was determined and compared with the fatigue behavior of the undeformed material. Fatigue analyses were carried out in the finite element environment by modeling the drag link as Functionally Graded Material (FGM). In addition, the drag link physical fatigue tests were also carried out and the numerical and experimental results were compared. It was observed that the results of the drag link fatigue analysis modeled as FGM were closer to the experimental values.

Keywords: Drag link, Pipe bending, Plastic deformation, Steering system, Fatigue

1. INTRODUCTION

The drag link is an important part of the steering system that provides the wheels to turn right and left by transmitting the movement from the steering wheel to the wheels. Drag link generally consists of connecting two rod ends with each other by means of a connecting rod. Connecting rods of drag links are generally produced from pipe materials due to their lightness and low cost. Drag links are bent at different offset amounts due to their distance from other components within the scope of vehicles' steering systems and legal regulation requirements. Even if statically high-strength materials are used in drag links, they can be damaged at lower loads when exposed to repeated loads on the vehicle. The process of premature failure or damage of a component as a result of repeated loading is called metal fatigue [1]. In case the vehicles encounter different road conditions, various tensile and compressive stresses may occur on the drag link. These variable stresses produce fatigue, causing microcracks to occur, and the tie rod may be damaged by cracking in the future [2].

DP600 steel material with pre-strain applied in different directions has higher yield strength and fatigue resistance than material without prestrain [3]. Koh and Baek [4] performed a fatigue damage analysis to estimate the fatigue life of a steering drag link. Monotonic tensile and low cycle fatigue tests were performed for the STKM12C steel pipe used in the drag link. In addition, FEA studies were performed to determine the regional stresses and strains in critical bending regions. To verify the FEA results, they experimentally measured the amount of strain in the bending regions by placing a strain gauge on the drag link bend regions. Fatigue life was estimated using a combination of material properties, stress analysis and local strain approach. They performed the drag link fatigue test at 3 different loads and observed that a crack first formed in the bending region and then the crack propagated and the tie rod broke along the cross-sectional area. Lee et al. [5] investigated the fatigue properties of low-carbon steel pipes bent at small radius using the district induction heating method. The microstructure, hardness, high cycle fatigue and residual stress properties of the inner and outer wall sections of the bent pipe in the bending region were compared with the unbent raw pipe properties. They stated that deformed bending walls show better fatigue properties. Budak and Pekedis [6] investigated the effect of pre-deformation on fatigue strength by performing fatigue tests and finite element analyzes for a pre-deformed automobile tie rod end without any pre-deformation. In the finite element analysis, it was seen that the critical regions formed in the rod ends matched the damage regions observed as a result of the experimental tests. The numerical and experimental results they obtained indicate that the pre-deformation affects the fatigue life of the rod end negatively and should be taken into account during the design. Uludamar et al. [7] performed the finite element analysis of a

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drag link and determined the stress values and safety coefficient on the part. They also calculated the resulting stresses theoretically and compared the results. Falah et al. [8] performed a damage analysis of a broken rod end ball joint. They conducted an assessment to determine the cause of the damage to the tie rod end of an SUV that had run for about two years and less than 30,000 km. Visual inspection, chemical analysis, hardness measurement and metallographic examination were performed on the part. They stated that the joint neck region was damaged due to fatigue and crack initiation due to insufficient material and improper heat treatment. Güvenç and Botsalı [9] investigated the fatigue life of the tie rod end, which is a part of the steering system, using computer aided engineering tools. By determining the points where fatigue can occur on the tie rod end in the finite element environment, strain gauges were placed in the critical areas of the tie rod end of a passenger vehicle. The vehicle was exposed to different road conditions and 400 km of road data were collected. According to the calculations they made in the Computer Aided Engineering (CAE) environment using these data, they concluded that the part life is infinite for 300,000 km of data. To confirm this result, they performed an experimental simulation of the tie rod end and said that the results were compatible with each other. Peng et al. [10] investigated the effect of pre-strain on mechanical properties for 316L austenitic stainless steel. They compared the mechanical properties of the samples to which they applied different pre-strain values between 0% and 35%. They showed that the yield points increased, the elongation decreased, and the maximum stress remained constant with increasing pre-strain.

In this study, the effect of plastic deformation occurring during drag link bending process on drag link fatigue behavior was investigated. Ansys finite element software was used to determine the amount of plastic deformation that occurs during the bending process.

Although there are fatigue analysis studies for drag links in the literature, plastic deformation from the bending process is generally ignored in these analyses. In this study, the plastic deformation occurring during the bending process was determined and used as an input in the analyses.

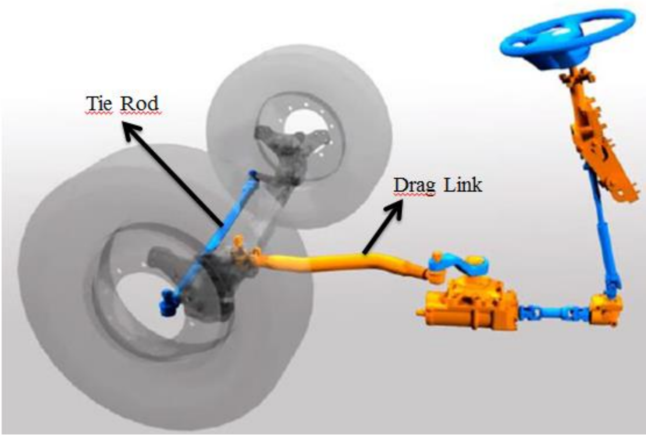

Figure 1. Heavy commercial vehicle steering system [11]

2. MATERIAL AND METHOD

2.1 Materials

In order to determine the fatigue behavior of the drag link pipe material, EN 10025-2 S355JR+N in solid form equivalent to the drag link pipe material EN 10305-1 E355+N was used. The chemical composition of these materials are shown in Table 1.

Table 1. Chemical compositions of E355+N and S355JR+N materials (wt %) [12,13].

Content (%)	E355+N	S355JR+N
C (max)	0.22	0.24
Si (max)	0.55	0.55
Mn (max)	1.60	1.60
P (max)	0.025	0.035
S (max)	0.025	0.035

2.2 Experimental Procedures

The tensile and fatigue test specimens required to determine the mechanical properties of E355+N pipe material and S355JR+N solid material were prepared according to the relevant standards. In addition to the S355JR+N material fatigue tests to determine the drag link fatigue behavior, the drag link bending operation will be simulated in the finite element software in order to see the effect of plastic deformation during the bending operation. The plastic strain obtained as a result of the analysis will be applied to the S355JR+N material as a pre-strain, and the fatigue tests of the samples will be performed separately.

Tensile Tests

In order to determine the mechanical properties of E355+N pipe material, tensile samples were prepared according to DIN 50125 standard on E355+N seamless pipe material with an outer diameter of 52 mm and a wall thickness of 7 mm. Pipe material drawing sample geometry is shown in Figure 2.

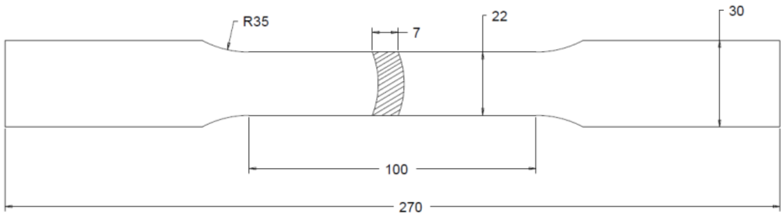

Figure 2. Tensile specimen geometry created according to DIN 50125

The tensile specimen geometry prepared according to the DIN 50125 standard for the determination of the mechanical properties of the S355JR+N solid material is shown in Figure 3.

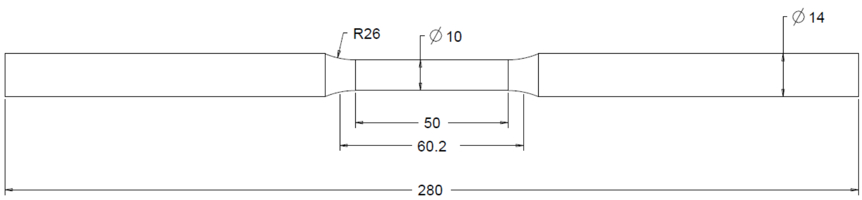

Figure 3. DIN 50125-A 10x50 tensile specimen geometry

Tensile tests were carried out in the tensile testing device with a load capacity of 600 kN shown in Figure 4.

Figure 4. Tensile test device

Fatigue Tests

20 fatigue specimens were prepared according to ASTM E466 from S355JR+N material to be used in fatigue tests. The fatigue specimen geometry is shown in Figure 5.

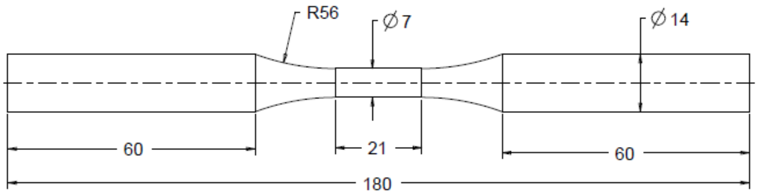

Figure 5. Geometry of fatigue test specimen acc. to ASTM E466

10 specimens without pre-strain were tested in the uniaxial fatigue test device shown in Figure 6. It was tested in 5 different loads (9 kN, 8 kN, 7 kN, 6 kN, 5 kN) at a frequency of 5 Hz until it broke, by making two repetitions at each load value. The plastic deformation that determined as a result of the pipe bending simulation was applied to 10 fatigue specimens and the fatigue test of the specimens was carried out at the same load and frequency values.

Figure 6. Uniaxial fatigue test device

Drag Link Fatigue Tests

Actual fatigue tests of drag links were carried out. The fatigue test setup is shown in Figure 7. Accordingly, the drag link was fixed from the rod end on one side and subjected to axial loading from the rod end on the other side. Fatigue tests were carried out at 5 Hz frequency of a total of 4 tie rods, two for each, at 2 different loads (20 kN, 25 kN).

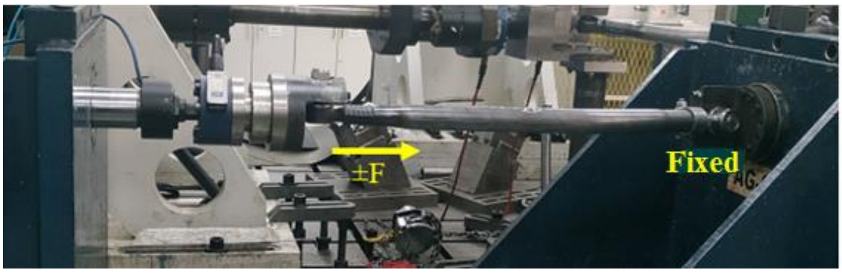

Figure 7. Drag link fatigue test setup

2.3 Finite Element Simulations

Bending Process Simulation

The amount of plastic deformation in the pipe bending region was determined by simulating the manual press pipe bending process in the ANSYS software. The cad model required for the analysis was modeled in the Creo Parametric 3.0 software. The pipe bend analysis setup is shown in Figure 8.

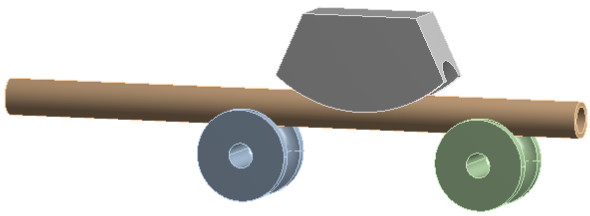

Figure 8. Pipe bending setup with manual press method

Multilinear kinematic hardening module of ANSYS software is used. Nonlinear analysis was performed by using only the plastic values of the actual stress-strain curve of the S355JR+N material as input to the analysis. Pipe domains were meshed with tetrahedrons mesh as shown in Figure 9. Bending die and support rollers were defined as rigid. The support roller is free to rotate around its own axis, and the bending die is released to move in the vertical +Y axis. The bending die was retracted after 35 mm displacement and the pipe was released.

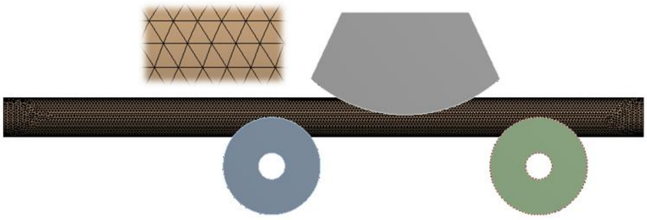

Figure 9. Bending setup mesh state

Drag Link Fatigue Simulation

Since the drag link has different strain levels in the bending region during the drag link bending, fatigue analysis was performed by modeling the drag link as functional grades. The simulations performed using the parts modeled in the FGM structure give consistent results with the experimental results [14]. While creating the functionally graded model, the model was created by considering the wall thickness changes that occur in the inner and outer walls of the bending region in the real environment. At the same time, analyzes were made for the one-piece model without any pre-strain. Figure 10 and Figure 11 show the cad images of no pre-strain model and functionally graded drag link.

Figure 10. Drag link cad image without pre-strain

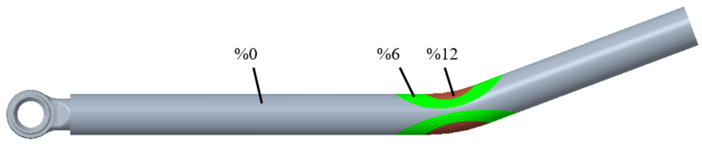

Figure 11. Functional graded drag link cad image

Fatigue analyzes were carried out by fixing the drag link from the inner surface of the housing in the Ansys finite element software and subjecting it to different loads from the housing center on the opposite side. Drag link domains were meshed with tetrahedrons mesh with 707836 elements as shown in Figure 12.

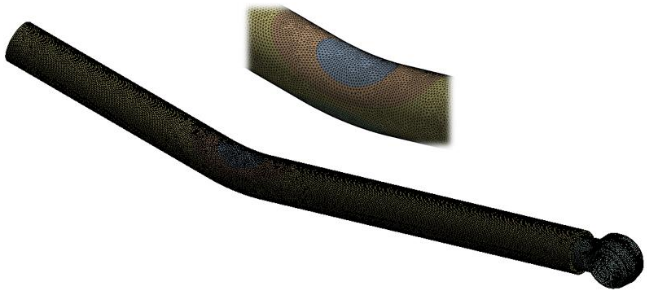

Figure 12. Mesh state of drag link fatigue analysis

3. RESULTS AND DISCUSSION

Tensile Tests

The tensile curves obtained for E355+N and S355JR+N material as a result of tensile tests are shown in Figure 13 and specific points of curves are given in Table 2.

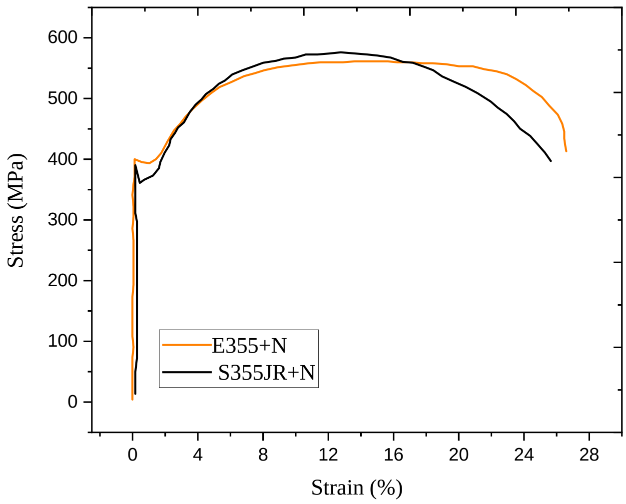

Figure 13. E355+N and S355JR+N materials tensile test curves

Table 2. Tensile test results of E355+N and S355JR+N materials

	Sample Type	Yield Stress (MPa)	Max Stress (MPa)	Elongation (%)
E355+N	Pipe	393.42	560.91	26.59
S355JR+N	Bar	392.52	575.60	25.64

It has been observed that the yield and tensile strength values obtained from the tensile tests are very close to each other. The differences between the values are negligible. Accordingly, it was concluded that S355JR+N material can be used to determine the fatigue behavior of the drag link pipe material.

Material Fatigue Tests

The stress-cycle number (S-N) curves of the unprestrained (0%) and strained (12%) S355JR+N samples are shown in Figure 14. It is seen that the specimens subjected to pre-strain show better fatigue resistance. Higher pre-strain applied material undergoes more plastic deformation. Thus, it shows a higher yield strength feature. In addition, using the interpolation method between 0% and 12% curves, a curve with 6% pre-strain was created.

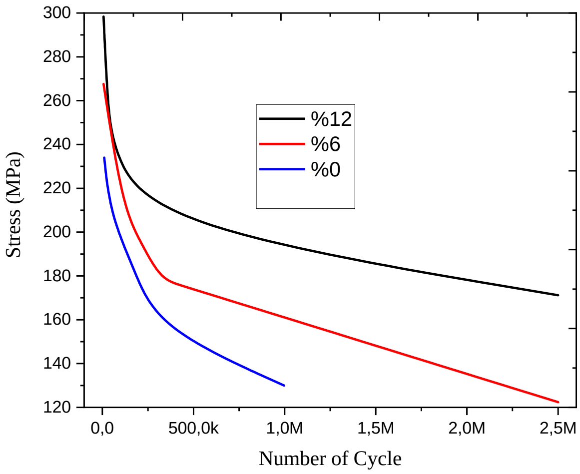

Figure 14. S-N curves of S355JR+N specimens with prestrain level of %0,%6 and %12

Drag Links Fatigue Tests

The tests were continued until the target value of 1.000.000 cycles, which is accepted as infinite life in drag link fatigue tests. The test conditions and test results applied to the drag links are shown in Table 3. It was observed that the drag links that could not reach the target value were damaged by cracking from the inner walls of the bending areas.

Table 3. Drag links experimental fatigue test results

Part No	Fatigue Load (kN)	Frequency (Hz)	Cycle Number	Result
1	20	5	1.000.000	No damage
2	20	5	1.000.000	No damage
3	25	5	449.515	Broken from the bend
4	25	5	524.212	Broken from the bend

Bending Process Simulation

During the bending analysis, pipe bending was ensured by making the bending mold make a translational movement in the vertical direction of 35 mm in the first 3 steps, and the pipe was released by pulling in the opposite direction in the last two steps. As a result of the analysis, approximately 12% plastic deformation was observed in the inner and outer walls of the bend region as seen in Figures 15 and 16 in the pipe bend region. Accordingly, fatigue tests were carried out by applying 12% pre-strain to 10 of the samples produced for the fatigue test of S355JR+N material.

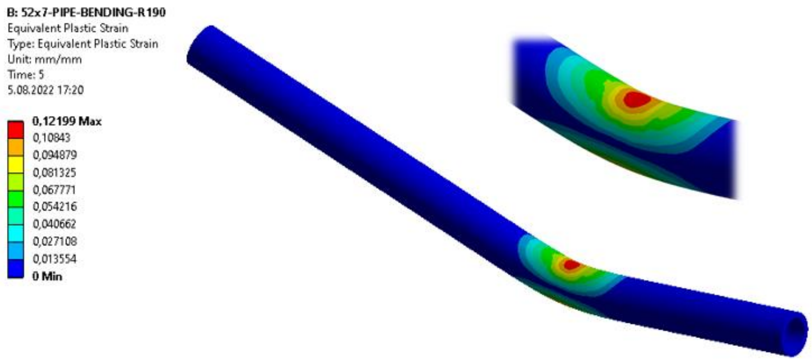

Figure 15. Plastic deformation distribution of the bending inner wall after bending

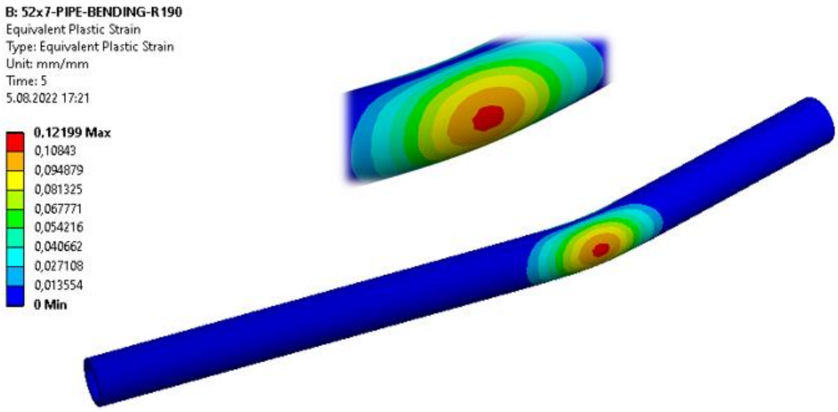

Figure 16. Plastic deformation distribution of the bending outer wall after bending

Drag Links Fatigue Simulation

As a result of the analysis, it was seen that the drag link without pre-strain and the FGM model, which were analyzed at different load values, were damaged at the bending points. It was observed that while the drag link with 0% pre-strain provided the target 1.000.000 cycles at 14 kN load value, the functional graded drag link reached the target 1.000.000 cycles at 20 kN.

Figure 17 shows the stress condition at 14 kN load value for the model with 0% strain. The maximum stress occurred as 129.12 MPa on the inner wall of the bending zone.

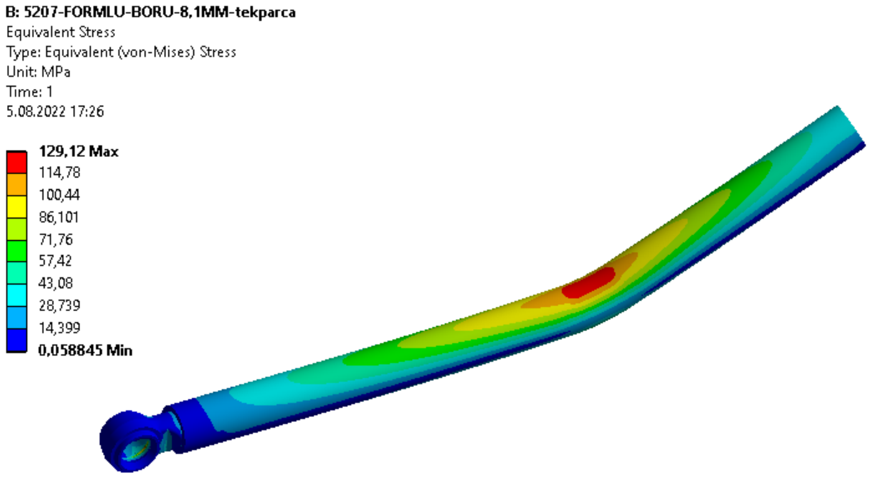

Figure 17. Stress state of the drag link at 14 kN load value

In Figure 18, the life distribution of the drag link with a 14 kN load applied in terms of number of cycles for the model with 0% pre-strain is shown. The part reaches the target number of 1,000,000 cycles at this load value. Each point on the part provides the target cycle number value.

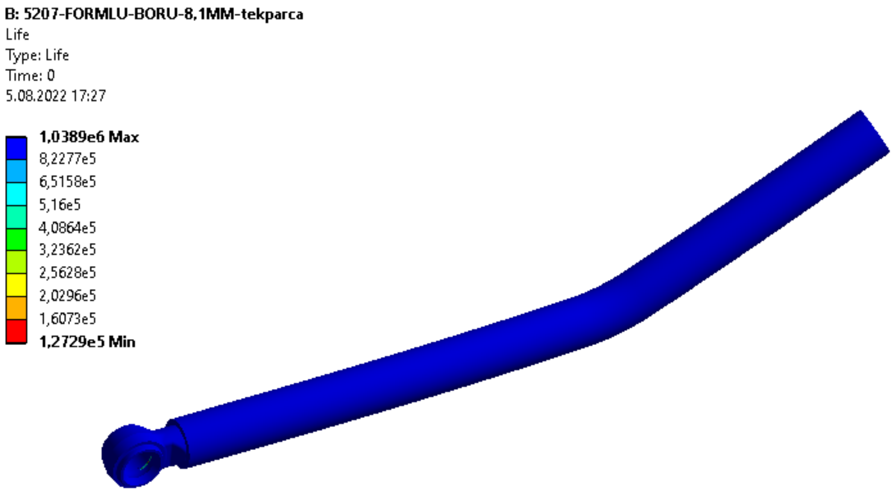

Figure 18. Cycle number distribution of drag link at 14 kN

Fatigue analysis was performed at 20, 22 and 25 kN load values for the drag link modeled as FGM. It has been observed that the drag link at a load of 20 kN provides the targeted 1.000.000 cycles.

Figure 19 shows the stress state occurring at a load of 20 KN. The maximum stress was 179.45 MPa on the inner wall of the bending zone.

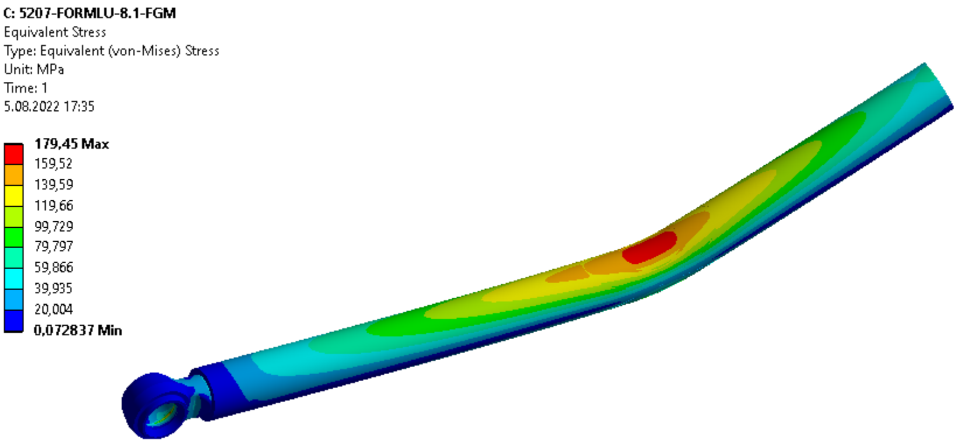

Figure 19. Cycle number distribution of drag link at 20 kN

Figure 20 shows the life distribution of the drag link with 20 kN load in terms of number of cycles. The part has more than 1.000.000 cycles targeted. Each point on the part provides the target cycle number value. The drag link modeled as a single piece provides 1.000.000 cycles at 14 kN, while the drag link modeled as FGM provides more than 1.000.000 cycles at 20 kN.

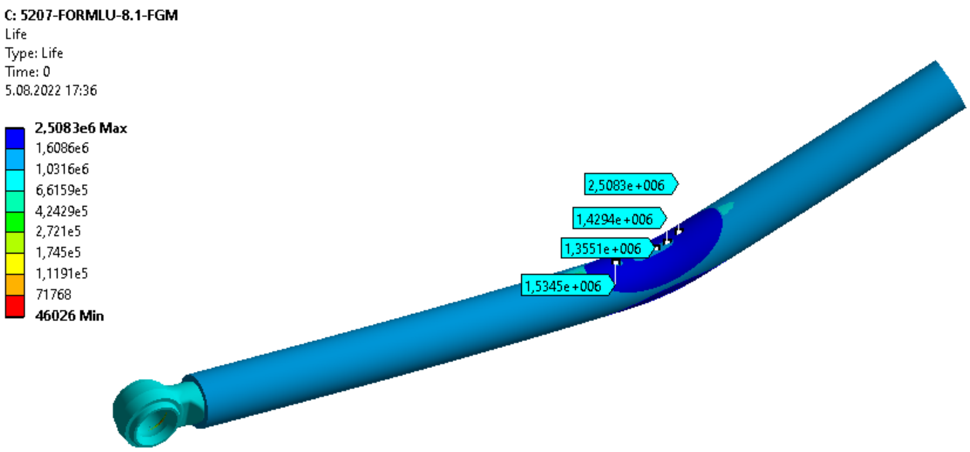

Figure 20. Cycle number distribution of drag link at 20 kN

Table 4 shows the conditions and results of the drag links fatigue analysis, which is assumed to have no pre-strain, functional graded drag link fatigue analysis with pre-strain, and the experimental drag link fatigue test. According to the results obtained, it was seen that the functional graded model, which was created by considering the pre-strain, showed better fatigue behavior and closer to the experimental results than the model without pre-strain. According to the analysis results, there is a significant difference between the fatigue behavior of the drag link model modeled as FGM and the drag link model modeled as one piece.

Table 4. FEA and experimental fatigue results according to pre-strain condition

Force (kN)	Cycle Number For No Prestrained Model (FEA)	Cycle Number For FGM Model (FEA)	Average Cycle Number (Experimental)
14	1.000.000		
16	650.520		
18			
20	98.227	1.355.100	1.000.000 (No damage)
22		512.860	
25		138.180	486.863 (Broken from the bend)

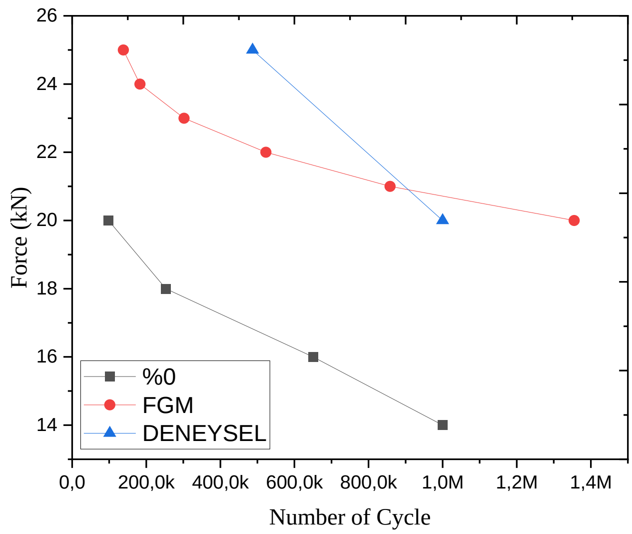

Figure 21. FEA according to the pre-strain condition and experimental test results curves

4. CONCLUSION

In this study, the effect of plastic deformation occurring during drag link bending on fatigue behavior was investigated. Tensile and fatigue tests for the drag link material and fatigue tests of the drag links were carried out. In addition, drag link bending process and fatigue tests are simulated in the finite element analysis environment. The results obtained are listed below:

- The tensile test results of E355+N pipe material and S355JR+N material in equivalent filled form were very close to each other. The differences between the results are negligible. It has been observed that S355JR+N material can be used for the fatigue behavior of the drag link pipe material.
- It was observed that specimens with pre-strain showed better fatigue behavior than specimens without pre-strain.
- According to the finite element fatigue analysis, it was observed that the functionally graded drag link showed better fatigue behavior than the drag link model modeled as a single piece without taking into account the deformation, and the functionally graded model results were closer to the experimental results. By dividing the functionally graded model into more sub-models, it is possible to obtain results closer to the real values.

SIMILARTY RATE: 6%

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