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Effect of Film Elastic Modulus on Fatigue Behaviour of DLC-Coated Wrought Magnesium Alloy AZ61

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Abstract

Plane bending fatigue tests were conducted using DLC-coated magnesium alloy AZ61 with two different film elastic moduli in order to investigate the effect of film elastic modulus on fatigue behaviour. Fatigue strength was improved by DLC film where DLC film with larger elastic modulus was more effective to improve fatigue strength. Delaminations of DLC film from base metal were observed near crack initiation sites. The number of small cracks and delaminations was larger as film elastic modulus was larger. By DLC film, stress near the boundary between base metal and DLC film is redistributed in a specimen compared with parent material without DLC film. Stress is reduced at base metal but large stress occurs at DLC film due to the difference of elastic moduli of base metal and DLC film. Stress at base metal and DLC film near the boundary is calculated by FEM (Finite Element Method) analysis. FEM analysis showed that stress decreases at base metal, stress increases at DLC film and that the difference of stresses at base metal and DLC film becomes larger when film elastic modulus is larger. It is considered that firm restraint of slip deformation in base metal by DLC film is effective to improve fatigue strength and that large stress in DLC film would not give negative effect on fatigue strength.

Keywords: Fatigue; Magnesium Alloy; DLC; Elastic Modulus.

1. Introduction

DLC (Diamond-like carbon) film is applied to materials of mechanical tools and slide components for the purpose of surface protection and functional addition since DLC film has advantageous properties in high hardness, wear resistance and low friction. Furthermore, DLC film is effective to improve corrosion resistance and fatigue strength [1] and so is also useful in application to structural materials.

In recent years, light materials have been promoted to be used in structural elements in transportation machinery to reduce fuel consumption against the environmental problems. Magnesium alloy, which is the lightest among all available metals in practical use, is expected in this usage. However, magnesium alloy is sensitive to corrosion, thus corrosion resistance is necessary to be improved for application to transportation structures. Coating with DLC film is useful in engineering usage in order to improve corrosion resistance and fatigue strength.

When magnesium alloy with DLC film is loaded, it is expected that high stress is generated near the boundary due to the difference of elastic moduli between soft magnesium alloy and rigid DLC film and affects the fatigue strength. In this study, plane bending fatigue tests were conducted using DLC-coated magnesium alloy AZ61 with

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two different kinds of film elastic modulus and stress near boundary was analyzed by FEM (finite element method). Based on experiments and FEM analysis, the effect of film elastic modulus on fatigue behaviour is discussed.

2. Experimental and analytical procedures

2.1. Material and DLC coated specimen

The Material used is extruded magnesium alloy AZ61. Tables 1 and 2 show the chemical composition and the mechanical properties of the material, respectively. The Material is mechanically-machined into a shape of specimen and polished by emery papers and buff-finished. DLC film is deposited to specimens after buff-finishing with the thickness of 13 μm by PECVD (plasma-enhanced chemical vapour deposition) method. The temperature during DLC deposition process is 150 °C. Elastic modulus of DLC film could be adjusted by the amount of hydrogen during deposition process. In this study, two different DLC films, Young's modulus of which is 50GPa and 170GPa, are deposited. Hereafter, specimens coated with each DLC film are denoted as 50DLC and 170DLC.

Table 1. Chemical composition of material (wt%)

Material	Al	Zn	Si	Cu	Ni	Fe	Mg
AZ61 magnesium alloy	5.8	0.65	0.29	0.01	0.002	0.002	Bal.

Table 2. Mechanical properties of material

Material	0.2% proof Stress, $\sigma_{0.2}$ (MPa)	Tensile strength, σ_B (MPa)	Elongation, δ (%)	Reduction of area, φ (%)	Elastic modulus, E (GPa)
AZ61 magnesium alloy	193	302	19	24	44

2.2. Experiments

Rockwell Hardness test was utilized to evaluate the adhesive strength between DLC film and base metal by comparing the extents of delamination of DLC film around the indentation of 1470 N with B scale indenter. Fatigue tests were conducted in laboratory air using resonance type plane bending fatigue testing machine with frequency f=33.3 Hz and stress ratio R=-1. All fracture surfaces were observed by SEM (Scanning Electron Microscope).

2.3. FEM stress analysis

Stress analysis was conducted by FEM (Finite Element Method) using commercial code NX Nastran in the assumption that deformation is linear elastic and that adhesion between base metal and DLC film is rigid. Material constants used are that Young's modulus of the base metal is 44GPa, that of two DLC films are 50GPa and 170GPa, respectively, and that Poisson's ratio of all materials is 0.3. Analytical region and coordinate systems are shown in Fig. 1(b). The element type is 8-node hexahedral and the numbers of node and mesh are 29172 and 27040.

3. Experimental and analytical results

3.1. Adhesive strength

Figure 1 shows the surface of a DLC-coated specimen around a Rockwell indentation where the delamination of DLC film is observed. Delamination is as same as small in both materials, indicating that the adhesive strength is as same as high. Small cracks are also observed around a delamination. The number of small cracks is larger in 50DLC material than 170DLC, thus the resistance to crack initiation is a little higher in 170DLC.

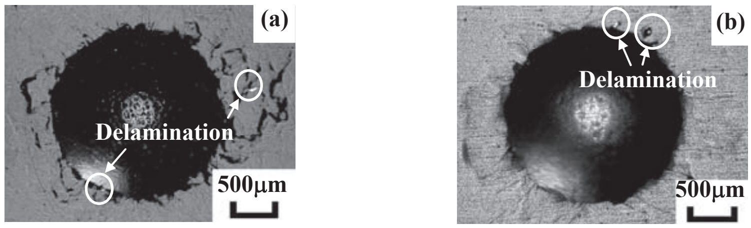

Fig. 1. Surface of DLC-coated material around Rockwell indentation: (a) 50DLC; (b) 170DLC

3.2. Fatigue test results

Figure 2 shows the *S-N* diagram. The fatigue limits of the base metal, 50DLC and 170 DLC are 60, 70, 90 MPa, respectively. Fatigue limit is improved by DLC film and fatigue limit is larger as Young's modulus of DLC film is larger. Fatigue strength in finite life region of 170DLC is higher than that of base metal and 50DLC. Figure 3 shows the SEM observations of fracture surface of (a) 50DLC and (b) 170DLC. It is considered that a crack initiated on the surface of base metal. Small cracks and delamination of DLC film are also observed near crack initiation site. Fracture surface of both materials is similar. However the extent of delamination is larger in 170DLC.

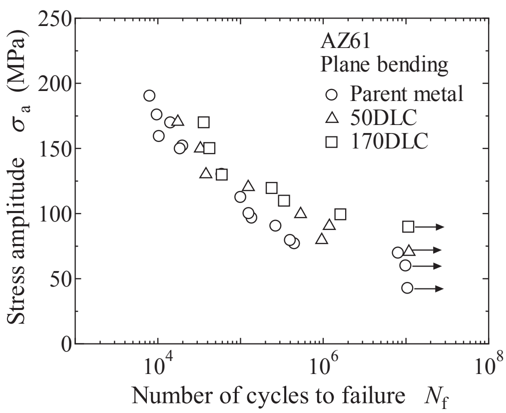

Fig. 2. *S-N* diagram

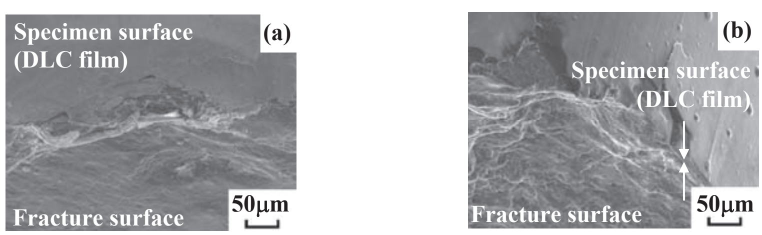

Fig. 3. SEM micrographs showing crack initiation site: (a) 50DLC (σ_a=120MPa, N_f=1.2×10^5); (b) 170DLC (σ_a=130MPa, N_f=6.0×10^4)

3.3. Stress Analysis results

Since DLC film is more rigid than base metal of magnesium alloy, stress of DLC film is higher than base metal at the boundary where deformation of DLC film and base metal is the same. From the analytical results, normal stresses along specimen axis of DLC film at the boundary of 50DLC and 170DLC are 1.1 and 3.8 times that of base metal at the boundary, thus stress of DLC film is higher in 170DLC. On the other hand, since DLC film shares load, stress at base metal is reduced. Compared with parent material without DLC coating, the stresses of 50DLC and 170DLC at base metal are 99.8% and 96.3%, thus the stress reduction ratios are only 0.2% and 3.7%.

4. Discussion

4.1. Fatigue strength improvement by DLC film

The fatigue strength of DLC-coated material was higher than that of parent material without DLC film. Improvement of fatigue limit compared with parent metal was 17% in 50DLC and 50% in 170DLC. However, the FEM stress analysis shows that the stress reductions at base metal by load share of DLC film are only 0.2% and 3.7%, thus the contribution of load share of DLC film to improvement of fatigue strength is small, which is attributed to that the rigid DLC film restrains slip deformation of base metal. The DLC film with the larger Young's modulus is also higher in hardness and strength, which restrains the deformation of base metal more rigidly, thus it is more effective to improve the fatigue strength. Stress of DLC film is larger in 170DLC than 50DLC, which does not affect the fatigue strength since the strength of DLC film is large enough and fracture does not occur from DLC film even though stress becomes large.

4.2. Delamination of DLC film at fracture surface

By Rockwell indentation, it was shown that the adhesive strengths of both materials are similar and that the resistance to crack initiation is slightly higher in 170DLC than 50DLC. However, the SEM observation of fracture surfaces showed that the extent of delaminations was larger in 170DLC by the difference of stresses between base metal and DLC film. Stresses of DLC film at the boundary of 50DLC and 170DLC are 1.1 and 3.8 times that of base metal. Since the difference is large, stress release is also large after crack is initiated and the extent of delaminations is large.

5. Conclusions

In this study, plane bending fatigue tests and FEM stress analysis were conducted using DLC-coated magnesium alloy AZ61, the Young's modulus of which is 44GPa, with two different kinds of film elastic modulus, 50GPa and 170GPa, and in order to investigate the effect of film elastic modulus on fatigue behaviour. The main conclusions can be made as follows.

1) Fatigue strength was improved by DLC film. Improvement of fatigue limit was 17% in 50DLC and 50% in 170DLC. DLC film of larger elastic modulus was more effective to improve fatigue strength.

2) Cracks initiated near the boundary of base metal and DLC film. Delaminations of DLC film were observed near crack initiation sites. The extent of delamination of DLC film was larger in 170DLC than 50DLC.

3) Stress reduction of base metal by load share of DLC film is 0.2% in 50DLC and 3.7% in 170DLC. Stress at DLC film on base metal at boundary is 1.1 times in 50DLC and 3.8 times in 170DLC as large as that of base metal on DLC film at boundary.

References

[1] Uematsu Y, Tokaji K, and Takekawa, H. Effect of Thick DLC Coating on Fatigue Behaviour of Magnesium Alloy in Laboratory Air and Demineralized Water. *Fatigue and Fracture of Engineering Materials & Structures* 2010; **33**(9): 607-616.