Numerical study on the effects of equi-biaxial residual stress on mechanical Properties of Nickel film by means of nanoindentation

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Summary In this paper, mechanical properties of Nickel film under residual stress have been systematically examined using the finite element method in nanoindentation. It was found that load-displacement curves shifted under elastic residual stress and plastic residual stress (i.e. residual stress exceeded the elastic limit stresses) for fixed indentation depth. Indentation profiles changed monotonously with compressive and tensile stresses at peak force which determinates contact area observed directly by FEM. The elastic residual stress has an effect slightly on the hardness but a remarkable effect in plastic residual stress in nickel film. The hardness increased when plastic residual stress increased under tensile and compressive stress applied to specimen. The relationship between residual stress and hardness was linear. It was found that residual stresses didn't affect elastic modulus whether elastic residual stress or plastic stress was applied to specimen.

Introduction

Residual stresses exist widely in bulk materials and films deposited on different substrates commonly due to the thermal mismatch, or mechanical and thermal processing. The mechanical properties and reliability of materials is strongly affected by their residual stress. Plastic residual stress or strain exist commonly in devices and components used in various engineering applications and machining. For example, film used for thermal protection in high temperature applications, such as gas turbines for propulsion and energy production, evolve as they are exposed to elevated temperatures and can in addition exhibit local compressive mismatch stresses as high as 4-6GPa at room temperature. Nanoindentation is a technique developed over the last two decades for probing the mechanical properties of materials. In this paper, we used the finite element method to investigate the effect of equi-biaxial elastic and plastic residual stresses on mechanical properties of nickel film.

Finite element simulation

Nickel film/substrate system with assumption of perfectly bonded of film and substrate was simulated using the axsymmetric capabilities of the ABAQUS finite element code. A rigid conical indenter with a 70.3°half-included angle gives the same area-to-depth ratio as a triangular Berkovich indenter used commonly in nanoindentation experiments. The thickness of nickel film and substrate is 2 μm and 100 μm in the simulations, respectively, and all simulations have been performed by pushing the indenter 100 nm into so as to avoid the influence from the substrate and then withdrawing. The equi-biaxial compressive or tensile stress is applied to the model by prescribing a radial displacement along the outer surface of the film/substrate system prior to the indentation. Coulomb's friction law is used between contact surfaces with a friction coefficient of 0.15 (the classical value of the friction coefficient between metal and diamond).

Result and discussion

Fig.1 displayed the effect of residual stresses on the surface profiles. There is slightly piling-up of indentation profile for virgin specimen. With the increase of tensile stress, amount of piling-up was decreasing and the surface profile converted into the sinking-in profile in Fig.1 (b). The influence of compressive stresses on surface profile is different from that of tensile stresses, which piling-up increased under compressive stress in Fig.1 (b). The contact depth under $\sigma_r / \sigma_y = \pm 2.1$ was approximately 10% higher than virgin materials by finite element analysis. Therefore, the contact area increased approximately 20% comparable to virgin material. It was also observed from Fig.1 (b) that the influence of plastic tensile stress on surface profiles was smaller than that of elastic tensile stress. The plastic compressive stresses had the same large influence as elastic compressive stresses in Fig.1 (a).

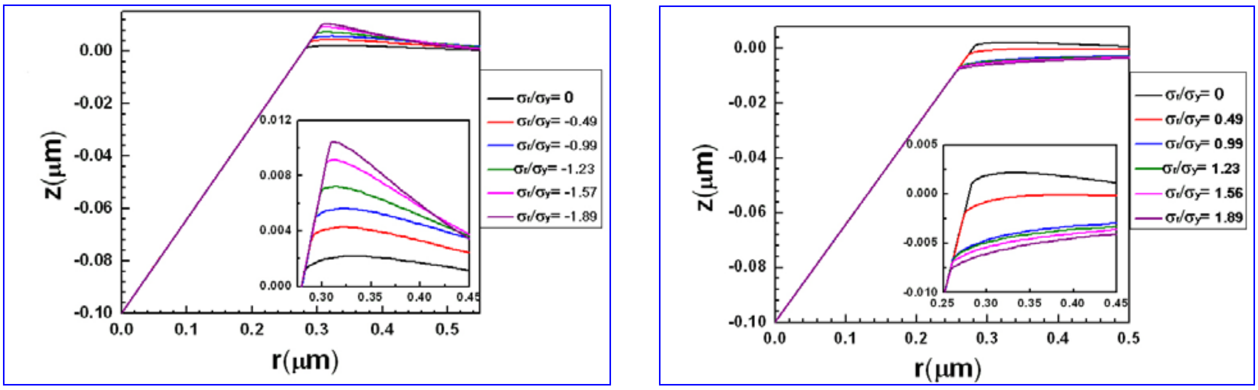

Fig.1 Indentation profiles at peak force under applied stresses. The insert shows an enlargement of surface profiles (a) under residual tensile stresses and (b) under residual compressive stresses.

The influence of residual stresses on the hardness and elastic modulus was plotted in Fig.2. Clearly, this diagram shows that elastic stresses have the small effect on hardness (within 6%) and elastic tensile stresses lead to decreasing hardness while compressive stresses lead to increasing hardness. The plastic tensile or compressive stresses lead to increasing hardness. It is also obvious that the elastic modulus is independent of the residual stresses including tensile and compressive stresses. The modulus calculated is in accordance with the input modulus for the simulations.

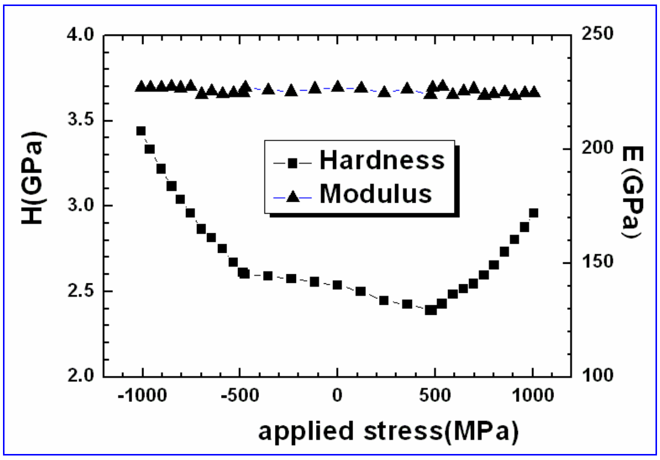

Fig.2 The stress dependence of the hardness and elastic modulus computed using the output parameter of simulations

Conclusions

A numerical investigation has been performed in order to study how residual elastic and plastic stresses affected mechanical properties of nickel film by sharp indentation tests. The following major conclusions can be drawn from the study.

(1) Residual elastic and plastic stresses affected the load-displacement curve of sharp indentation test. The influence of residual plastic compressive stress is larger than that of elastic stress and plastic tensile stress.

(2) Contact depth is sensitive to residual elastic stresses and residual plastic compressive stresses while hardly depend with the increasing plastic tensile stresses.

(3) It is found that the influence of plastic stress on hardness is larger (without 35%) than elastic stress for nickel film of strain-hardening material. And linear relation was fitted between hardness and residual stress. The elastic modulus was independent of residual stress.