Residual stress changes in Al_2O_3 induced by Nd:YAG laser irradiation

Sunmog Yeo [*], and Jae-Won Park
Korea Atomic Energy Research Institute, 150 Dukjin-Dong, Yuseong-Gu, Daejeon, Republic of Korea
[*]*Corresponding author:* sunmog@gmail.com

1. Introduction

Residual stress is remnant stress after external causes such as heat treatments, machining, and welding have been removed. It is related to crack propagation, fatigue strength, corrosion cracking, etc. In addition, it is an important factor for determining thin film quality. For example, surface layer delamination from the substrate is caused by residual compressive stress while a surface crack in films is caused by residual tensile stress [1, 2]. On the other hand, alumina (Al_2O_3) is one of the typical refractory ceramics which has a high thermal shock strength and a high resistance to corrosion and erosion. Recently, it was reported that a laser surface treatment of Al_2O_3 can reduce the permeability to corrosive species and enhance surface hardness, by eliminating pores and cracks on the surface, [3]. However, very few residual stress studies have been carried out. In this paper, by using a Q-switched Nd:YAG laser, a systematic study of the residual stress changes by means of an X-ray diffraction method is presented.

2. Methods and Results

2.1 *Residual stress measurement and analysis*

Residual stress can be evaluated by various methods, for example, X-ray diffraction, nano-indentation fracture, Raman spectroscopy, and so forth. In this experiment, the X-ray diffraction technique was used because it was non-destructive and the most frequently used method. One of the key factors for the residual stress evaluation was a choice of a proper 2θ angle. Therefore, the x-ray diffraction experiments on the Al_2O_3 plates (Sumitomo chemical Co. Ltd.) were performed up to 135^o of 2θ by a Rigaku X-ray diffractometer, showing that there was no significant impurity in the samples. For residual stress analysis, a peak should be well separated from the other Al_2O_3 polycrystalline peaks and be located at high angles so that the Cu $K_{\alpha 2}$ peak is well separated from the Cu $K_{\alpha 1}$ peak. A satisfied peak was a (1310) peak around 127.7^o. Let ψ be the tilting angle of the sample. Changing the tilting angle produced new θ–2θ data set. In this experiment, the tiling angles are 0^o, 5^o, 10^o, 15^o, and 20^o. Then, background was removed by a linear fitting and the Cu $K_{\alpha 1}$ peaks were normalized.

The $\sin^2\psi$ technique was used to evaluate the residual stresses (σ_ϕ) [4]. The Rachinger correction[5] was effective to remove the Cu $K_{\alpha 2}$ peak contributions. The empirical top 15% rule and a parabola fitting were applied to determine precise peak positions. The Bragg condition leaded the interplanar spacing (d_ψ) for every ψ, and d_ψ was plotted as a function of $\sin^2\psi$. Then, the residual stresses (σ_ϕ) can be evaluated by obtaining the slope (a) of $d_\psi(\sin^2\psi)$ with a formula,

$$\sigma_\phi = \frac{E}{d_0(1+\nu)} \cdot a \qquad (1)$$

where E (~300 GPa) and ν (~0.33) are elastic modulus and Poisson's ratio, respectively [6]. The unstressed lattice spacing (d_0) can be replaced by the lattice spacing measured at $\psi = 0$ in practice [4].

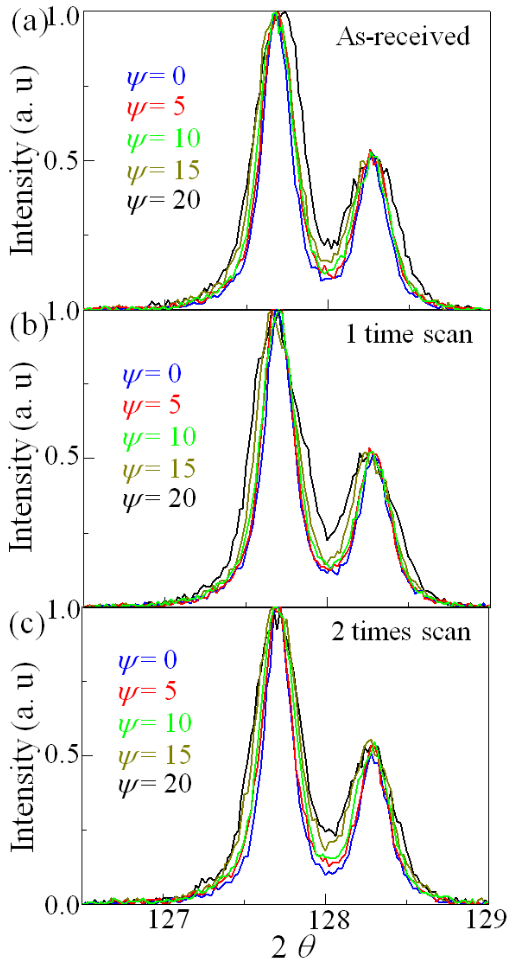

Fig. 1. X-ray diffraction patterns at different ψ's for (a) as-received sample, (b) a 1 time scan sample, and (c) a 2 time scan sample.

2.2 *Laser irradiation*

A Q-switched Nd:YAG laser (Quanta-Ray Pro-230) generated a source beam and a second harmonic generator with a nonlinear optical crystal produced a water-penetrable wave (λ = 532 nm). The source beam of λ = 532 nm irradiated on a sample in a water jacket through a window. The energy density of the irradiation beam was ~ 12.7 J/cm^2, and the spot size was about 1 mm. By scanning the irradiation beam on alumina plates, the surface treatment was performed. The scanned area is ~ 1 × 1.5 cm. The plates were enveloped by aluminum (Al) foils whose thermal conductivity was 235 W/mK.

2.3 Results

Fig. 1 (a) shows X-ray patterns at different ψ's for a as-received sample. The X-ray patterns shift to the left by increasing the tilting angle indicative of the increase in the interplanar spacing. A single scan sample displays a similar behavior to the as-received sample, as shown in Fig. 1 (b). However, for a double scan sample, X-ray patterns at different ψ's place the almost same 2θ angle. (See Fig. 1 (c)) This suggests that the interplanar spacing does not change much.

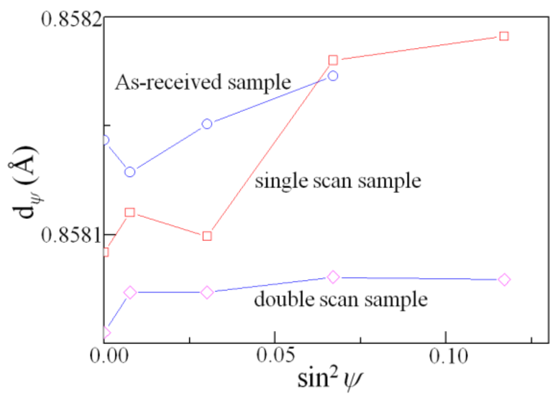

Fig. 2. Interplanar spacing versus $\sin^2\psi$ for all samples.

The interplanar spacing is plotted as a function of $\sin^2\psi$ in Fig. 2. All the slopes obtained by linear fittings are positive, suggestive of tensile residual stress for all samples. The residual stresses obtained by the formula (1) are 257, 423, and 69 MPa, for the as-received, single scan, and double scan samples, respectively. The tensile residual stress of the as-received sample originates from a manufacturing process like heat treatment. The laser surface treatment usually causes tensile residual stress as seen in the single scan sample. However, the residual stress of the double scan sample is greatly reduced compared to that of the single scan sample. This can be explained by the surface damage due to the laser irradiation. Indeed, the SEM image of the twice irradiated sample shows an explosive boiling phenomenon [7]. Like this, the laser irradiation condition affects the residual stress a lot.

3. Conclusions

The residual stress changes of the laser irradiated alumina plates were investigated. Compared to the as-received sample, the tensile residual stress of the single scan sample is enhanced. However, the tensile residual stress of the double scan sample is reduced. The residual stress is dependent of the laser irradiation condition.

Acknowledgements

This research was supported by the Development of Key Technologies for Nuclear Hydrogen, the Proton Engineering Frontier Project sponsored by the Ministry of Education, Science and Technology (MEST), and by a grant from the Fundamental R&D program from Core Technology of Materials funded by the Ministry of Knowledge Economy (MKE), Republic of Korea.

REFERENCES

[1] A. G. Evans, J. W. Hutchinson, The thermomechanical integrity of thin films and multilayers, *Acta Metall. Mater.* 1995, **43**, p 2507-2530

[2] J. W. Hutchinson, Z. Suo, Mixed mode cracking in layered materials, *Adv. Appl. Mech.* 1992, **29**, p 63-191

[3] D. Triantafyllidis, L. Li, F. H. Stott, The effects of laser-induced modification of surface roughness of Al_2O_3–based ceramics on fluid contact angle, *Mater. Sci. Eng.* A, 2005, **390**, p 271-277

[4] I. C. Noyan, J. B. Cohen, Residual Stress Measurement by Diffraction and Interpretation, Springer-Verlag New York Inc, 1987

[5] W. A. Rachinger, A correction for the α_1, α_2 doublet in the measurement of widths of x-ray diffraction lines, *J. Sci. Instrum.* 1948, **25**, p 254-255

[6] C. Meade, R. Jeanloz, Yield strength Al_2O_3 of at high pressures, *Phys. B* 1990, **42**, p 2532-2535

[7] S. Yeo, S. K. Hong, S. J. Lee, C. Lim, J. W. Park, Study of residual stress and surface morphology changes in Al_2O_3 induced by Nd:YAG laser irradiation, *J. Mat. Eng. Perf.* to be published.