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Fatigue life prediction of small notched TI-6AL-4V based on the theory of critical distance

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Ref: Nicholas(2004), 10th National Turbine Engine HCF Conference New Orleans

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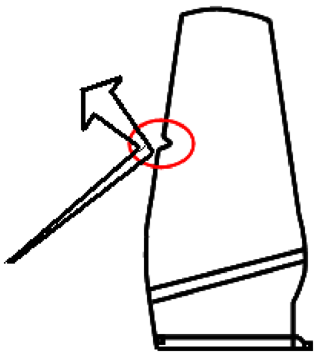
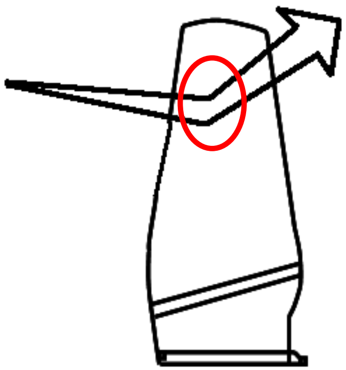
Background

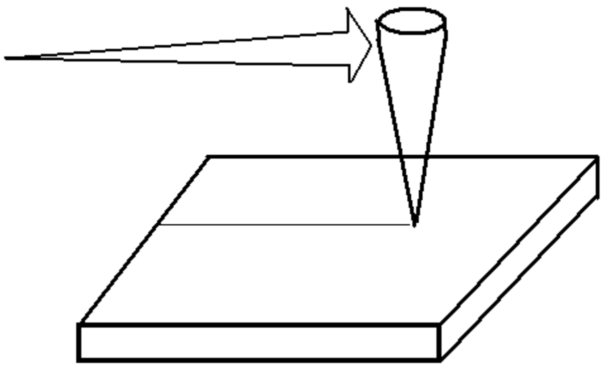
• FOD may result in “nick”, “dent” and “scratch” at the leading edges of airfoils which in turn, reduce the fatigue strength of the material.

• FOD-induced HCF is one of the significant themes in fatigue problems of aero-engine component.

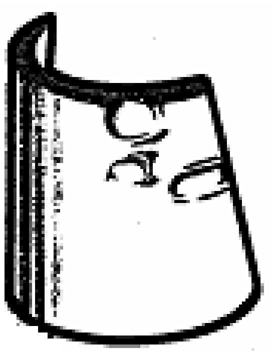
• Small notch effects on fatigue strength should be taken into account.



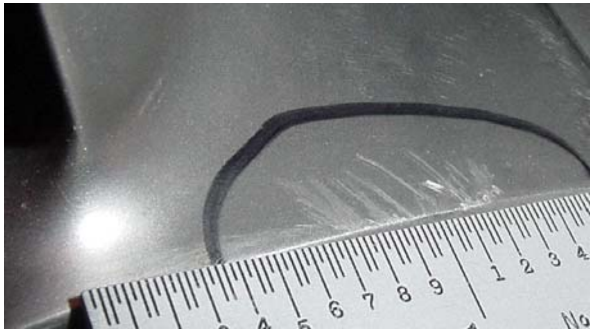




Nick



Dent

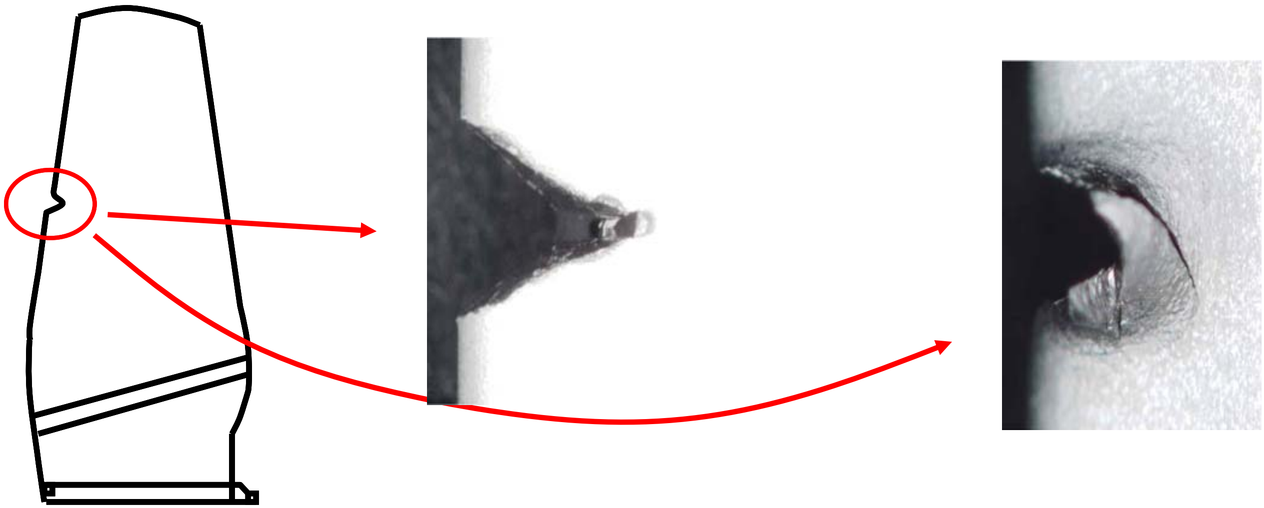


Scratch

Objective

•To investigate the method for fatigue life prediction of small notched Ti-64 specimens using the theory of the critical distance (TCD)

•To construct the appropriate method to evaluate fatigue life of Ti-64 with various notch radii and notch depths from the relationships between the critical distance stress and fatigue crack initiation life



fan balde small FOD damage

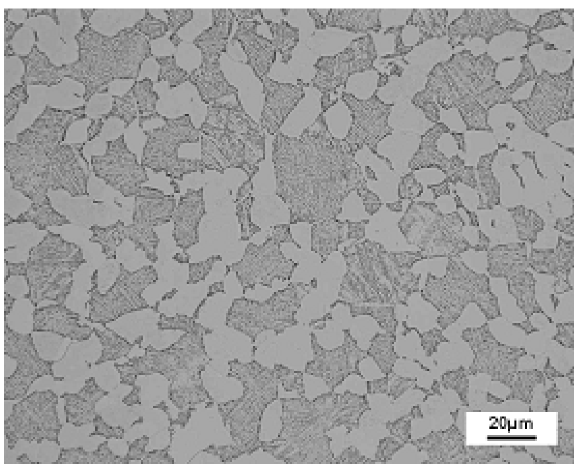
FOD damage at leading edge of airfoil

Chemical composition of Ti-64 (mass %).

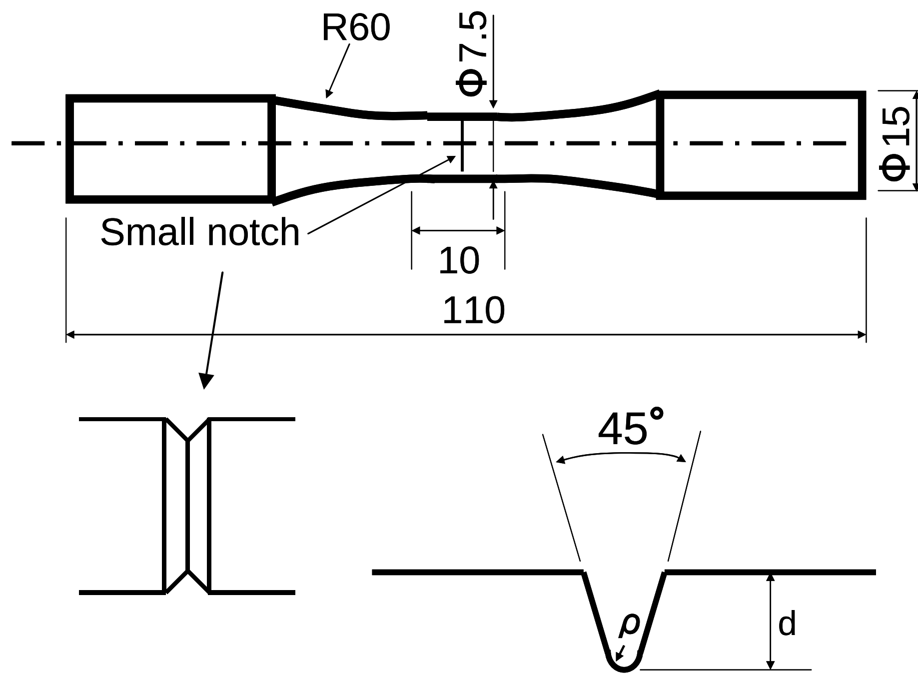
C	V	Al	Ti	N	Fe	O	H
0.002	4.16	6.3	bal.	0.004	0.16	0.2	0.0053

Mechanical properties of Ti-64.

σ_{Y0} (MPa)	σ_{uts} (MPa)	ε_f (%)	ψ (%)	E (GPa)
935	1006	18.4	44.5	110



Bimodal microstructure of Ti-64 (STOA)

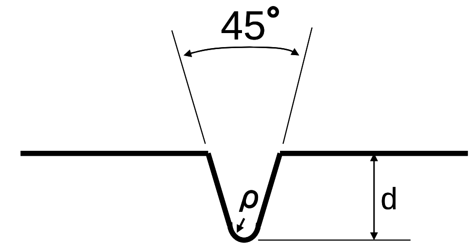


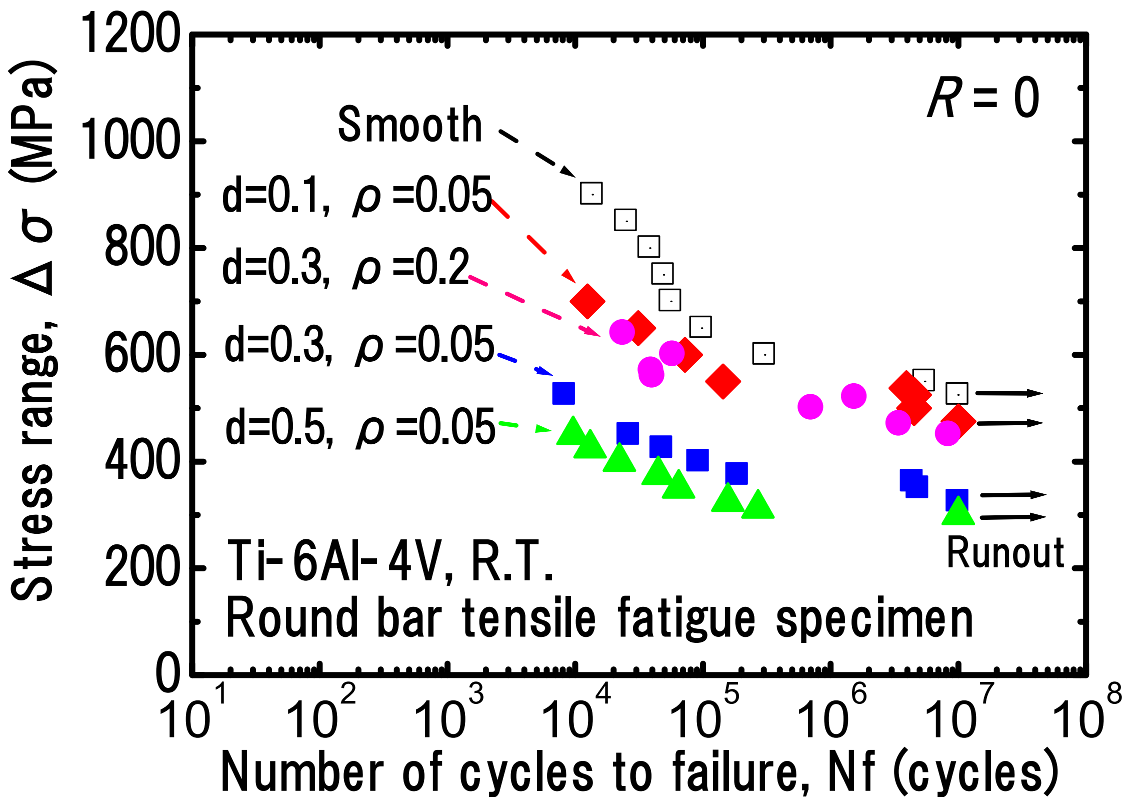
Circumferential notch

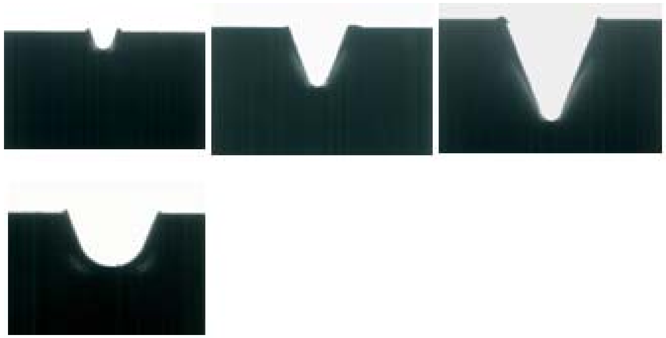
Experiment

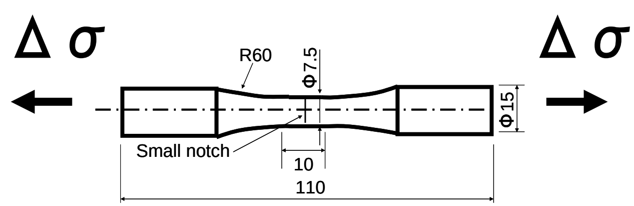
Fatigue test conditions (0-tension, R=0).

Notch depth, d (mm)	Notch root radius, ρ (mm)	Note
0	∞	Smooth specimen
0.1	0.05	Notch specimen
0.3	0.05	Notch specimen
0.5	0.05	Notch specimen
0.3	0.2	Notch specimen









Maximum peak stress approach

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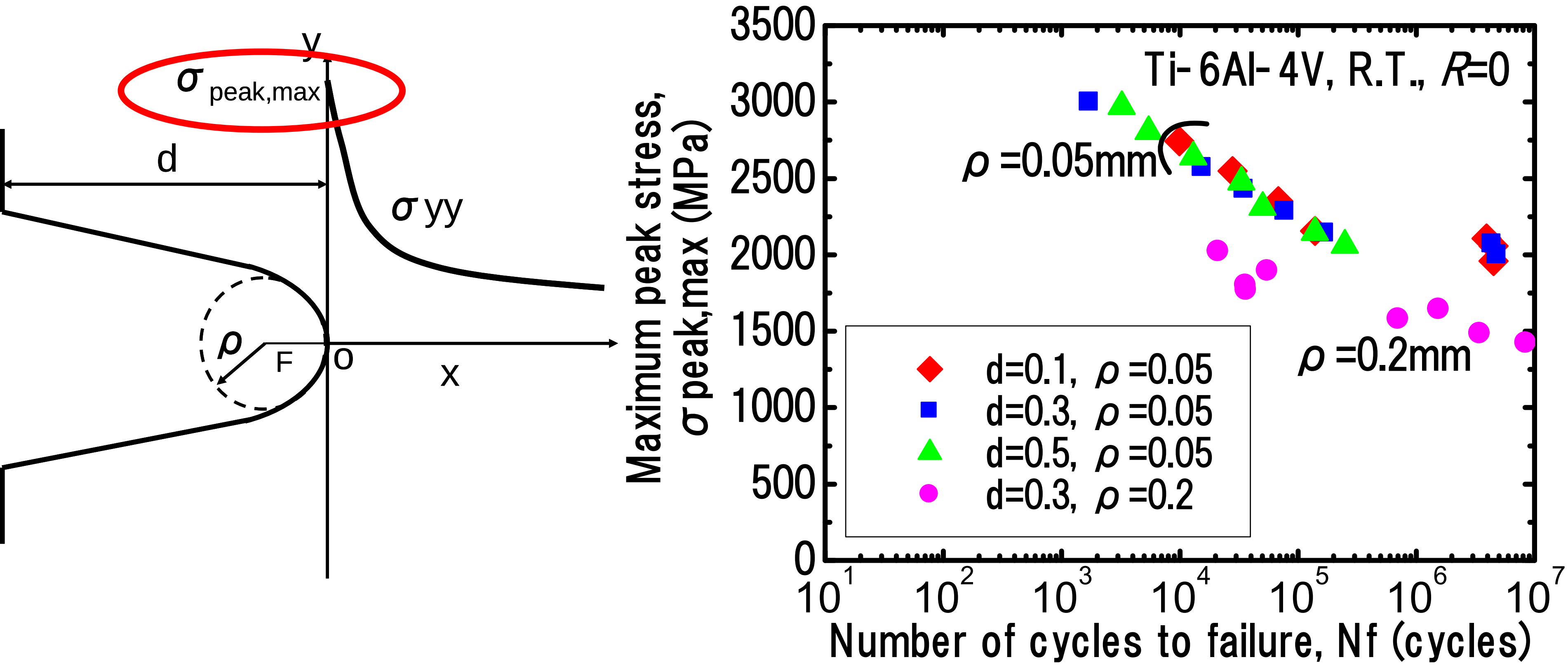
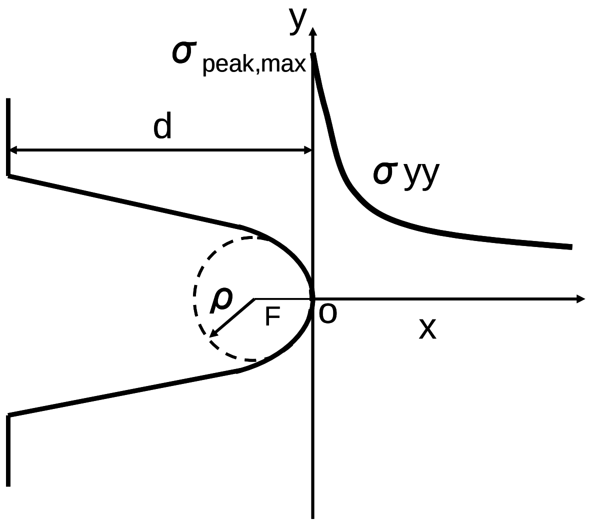
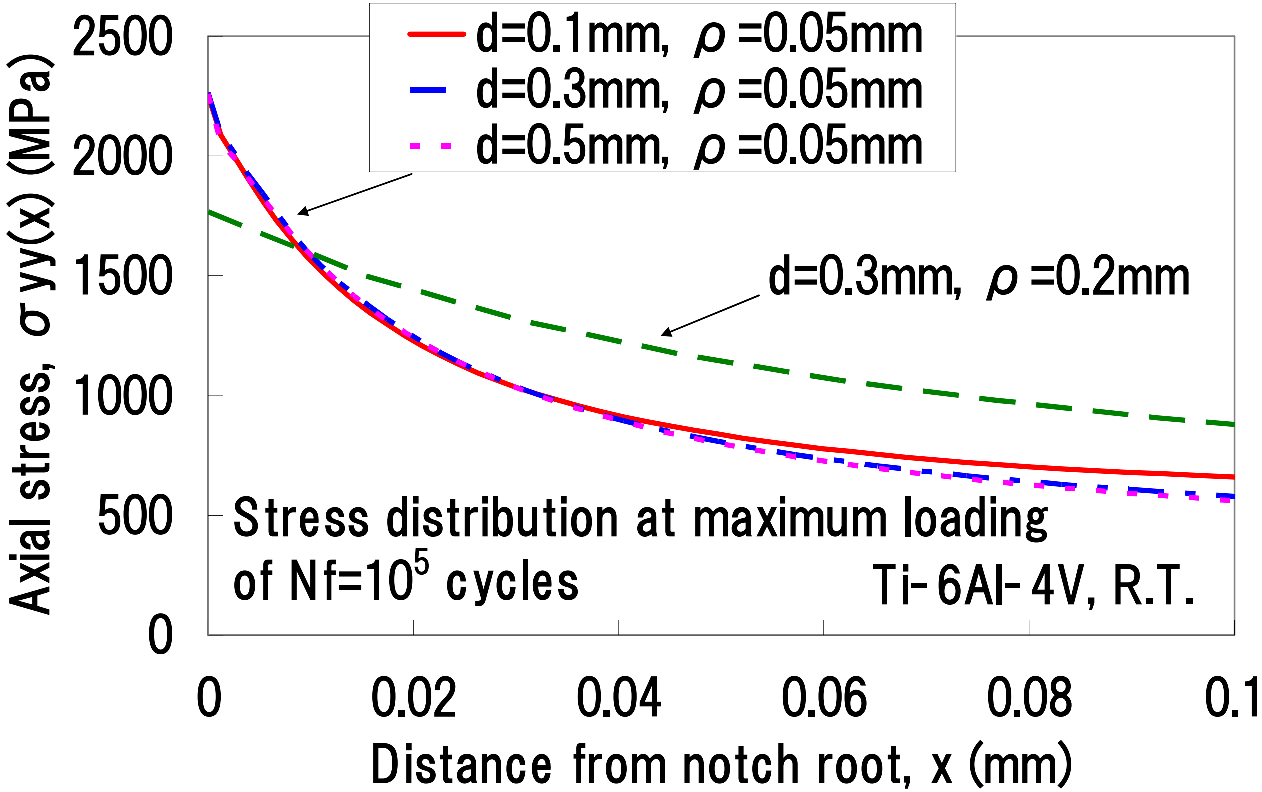


Fatigue life prediction based on maximum peak stress approach gives inaccurate results for the notch fatigue life of various notch root radii.

Stress distributions inward from notch root





Comparison at the same life of Nf=1.0×10^5 cycles

Maximum peak stress at notch root and the stress gradient have to be taken into account in fatigue life prediction for small notched specimens.

Application of conventional TCD

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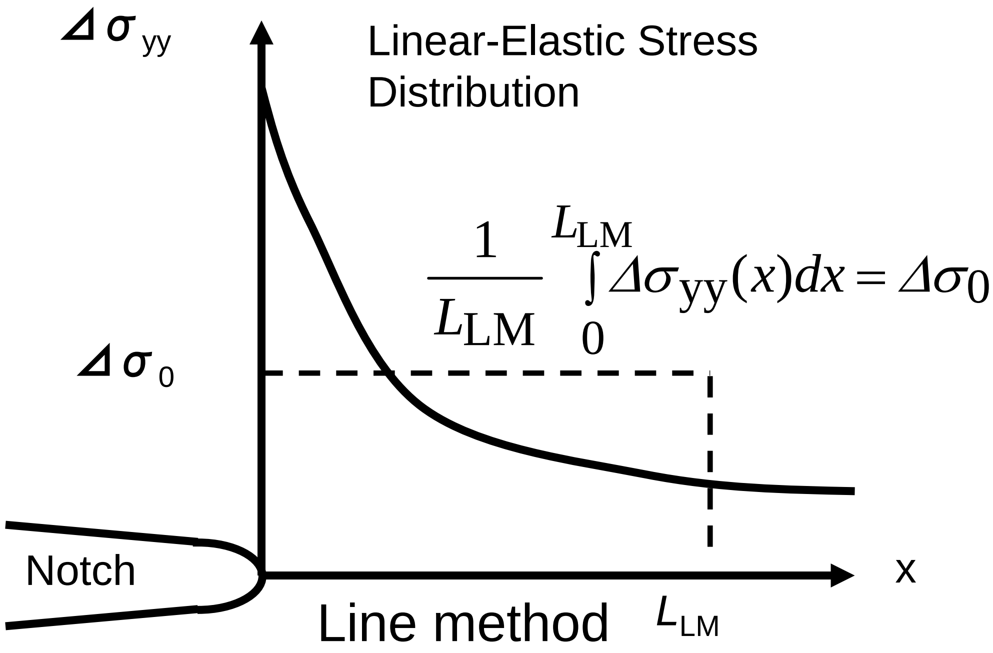

The most simple approach conventionally determines the distance inward from the notch root to the location at which the average stress range of the notched specimen is equal to the stress range of smooth specimens at the same fatigue life.

Conventional TCD was proposed by :

Neuber: (1958) [4], Peterson: (1959) [5]

Tanaka: Int. J. of Fract. (1983) [13]

Taylor: Eng. Fract. Mech. (2008) [6-8]

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_0}\right)^2$$

$$\Delta\sigma_0 = 538\text{MPa}$$

$$\Delta K_{th} = 3.86\text{MPa}\sqrt{\text{m}}$$

NASA / NASGLO

Line method $L_{LM} = 2L = 0.032\text{mm}$

Application of conventional TCD

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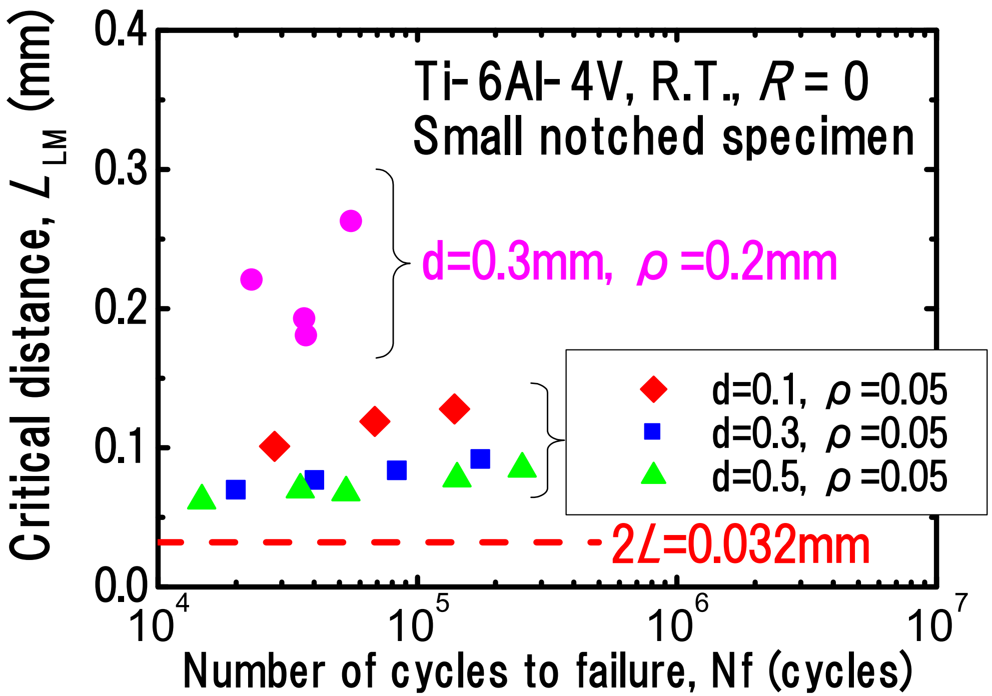

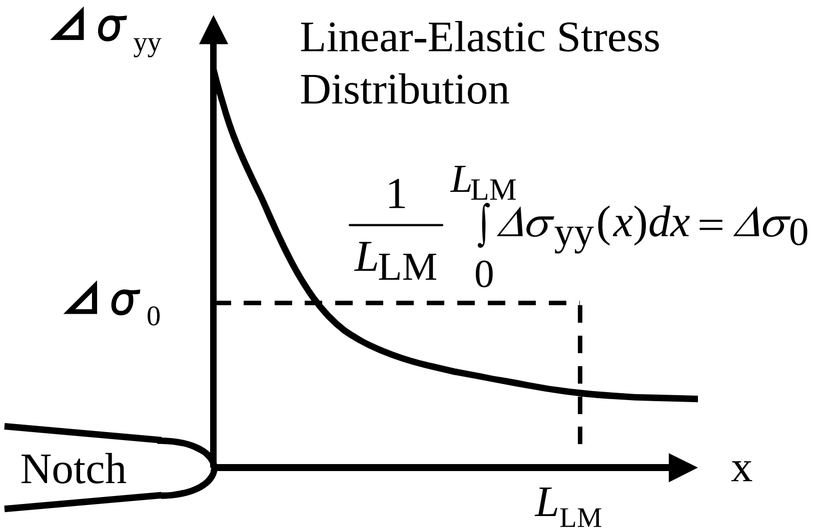

Line method

The critical distances for ρ =0.2mm are larger than those for ρ =0.05mm.

The conventional TCD approach may not give an appropriate unified value, when the notch tip radius of the notched specimens is different from each other.

L_{LM}=2L of the line method of determination of the critical distances are much smaller than the critical distances as the distance inward from the notch root to the location at which the stress range required for a fatigue failure life is equal to the stress range required for the same fatigue failure life for smooth specimens.

SEM observation

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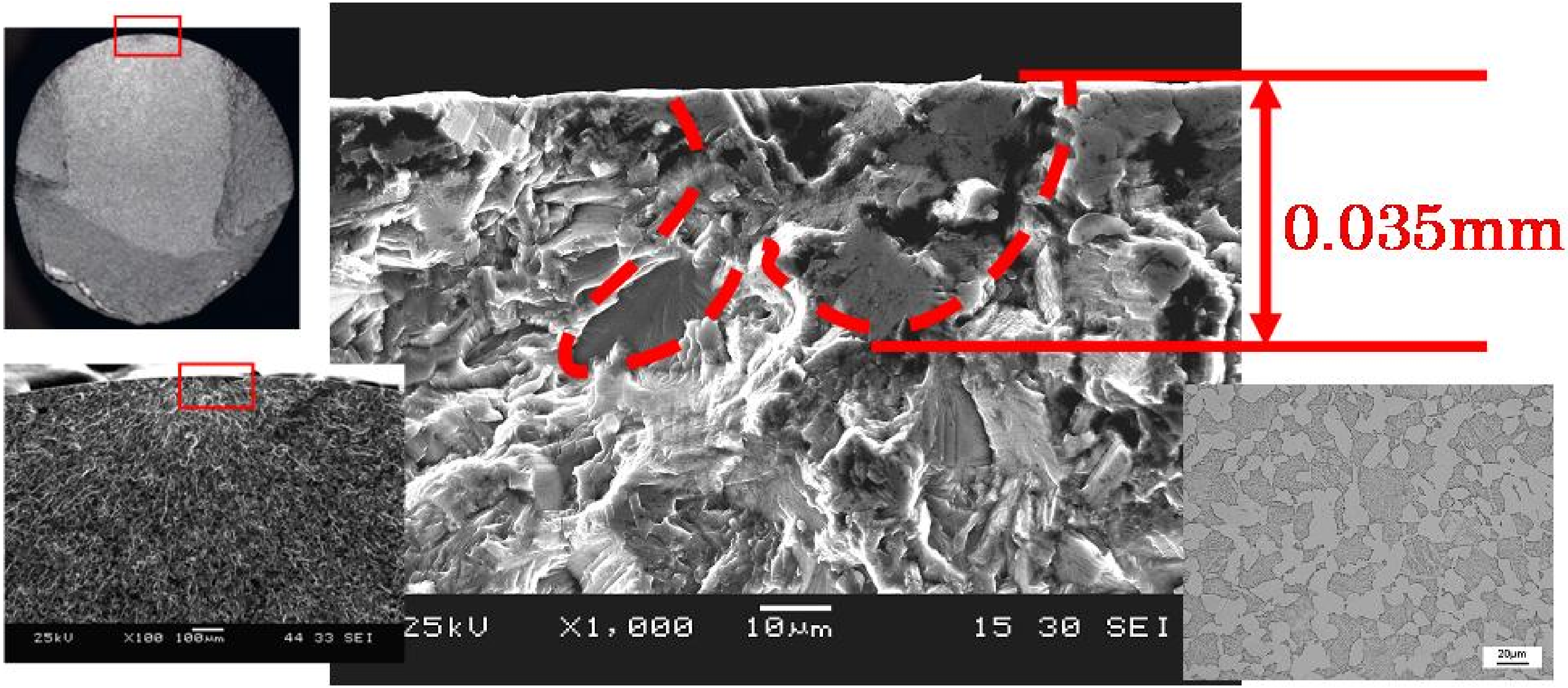

Smooth specimen of Nf=5.67×10^4

Fatigue crack initiation site

→quasi-cleavage, crystallographic facets at origin, no inclusion

The facets : α phase (A. Nozue [17], H. Oguma [18], O. Jin [19]),

approximately semi-circle, equal to average α phase size

SEM observation

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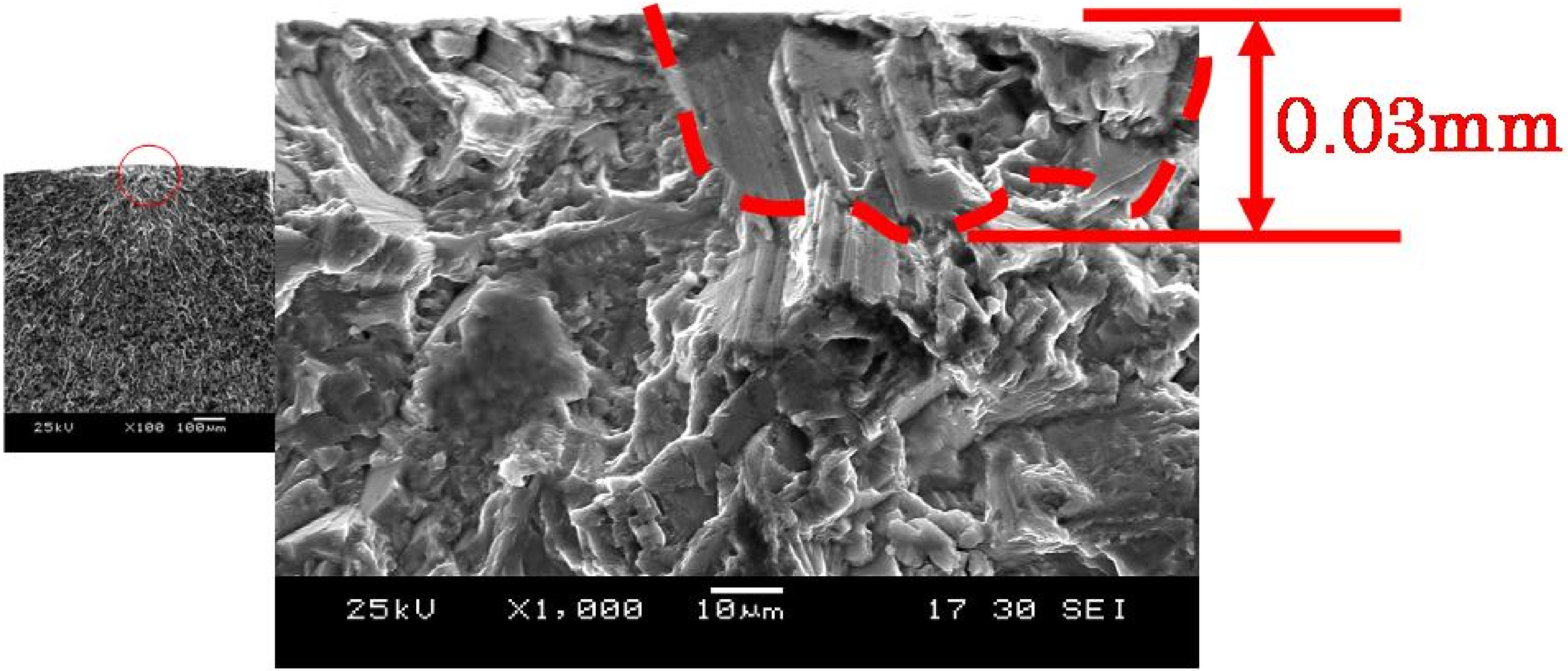
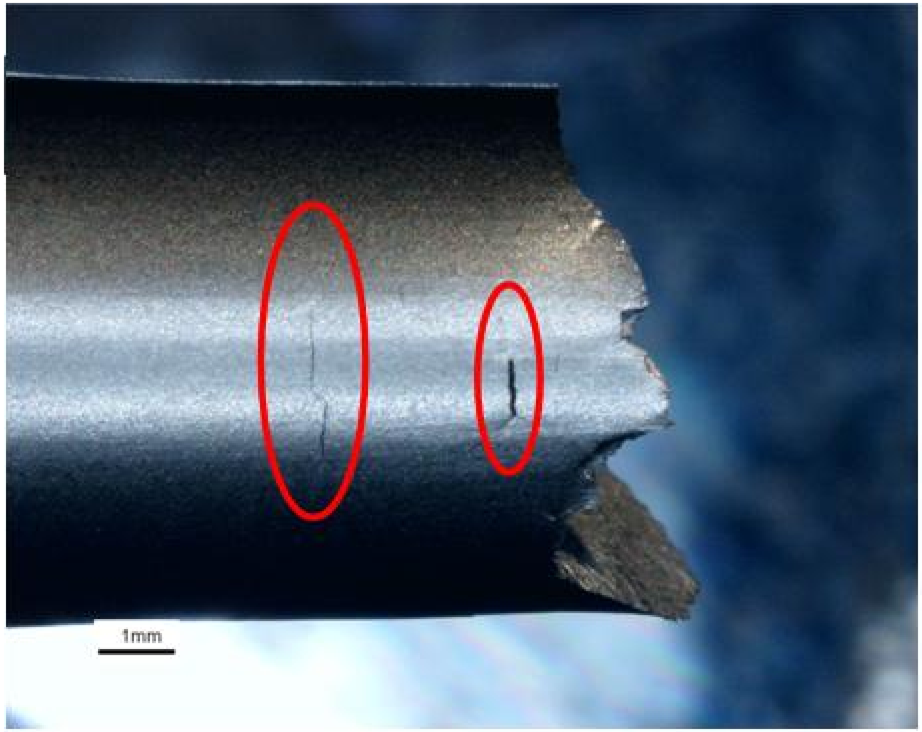
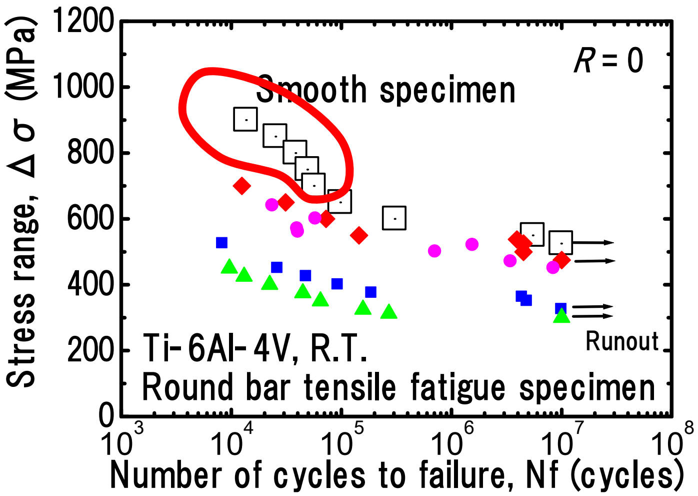


Smooth specimen of Nf=3.86×10^4

The determination procedure of the critical distance calculated from ⊿K equation of semi-circle crack is appropriate for the forged Ti-64.

Smooth specimen sub-crack





✓ The volume effects of fatigue fracture process zone extend throughout the gauge length of 10mm.

✓ Difference in volume effects between the notched and smooth specimen

✓ This is the evidence that the approach in determination of the critical distance, as the distance inward from the notch root to the location at which the stress range is equal to the stress range of smooth specimens, does not give an appropriate unified value.

Appropriate critical distance stress

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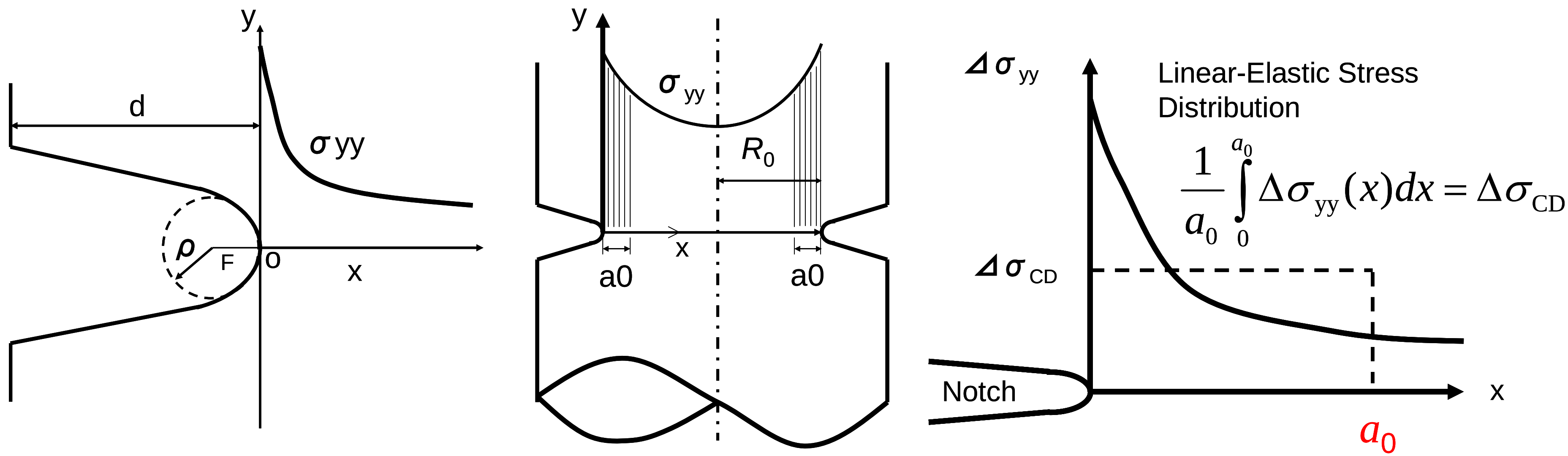

Method (1) : K eq. of through crack in infinite plate (0.016mm)

$$a_0 = (1/\pi)\cdot(\Delta K\mathrm{th}/\Delta\sigma_0)^2 \qquad \because \Delta K = \Delta\sigma\sqrt{\pi a}$$

Method (2) : K eq. of semi-circle surface crack (0.032mm)

$$a_0 = (1/\pi)\cdot(\pi\cdot\Delta K\mathrm{th}/(1.1215\times 2\times \Delta\sigma_0))^2 \qquad \because \Delta K = 1.1215\cdot(2/\pi)\cdot\Delta\sigma\sqrt{\pi a}$$

Critical distance stress : Average stress in fatigue fracture process zone

$$\sigma_{CD} = \int_0^{a_0}\sigma_{yy}(x)\cdot 2\pi\cdot(R_0 - x)\cdot dx \Bigg/ \int_0^{a_0} 2\pi\cdot(R_0 - x)\cdot dx$$

Appropriate critical distance stress

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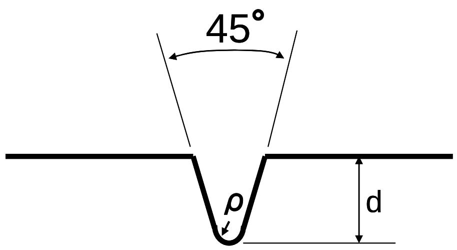
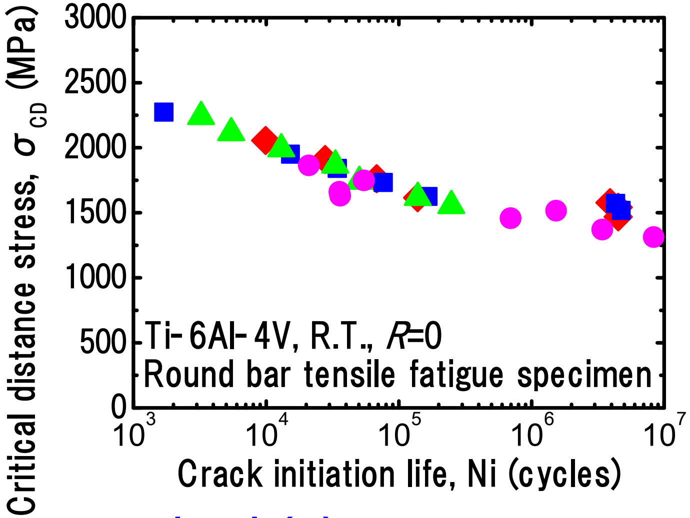
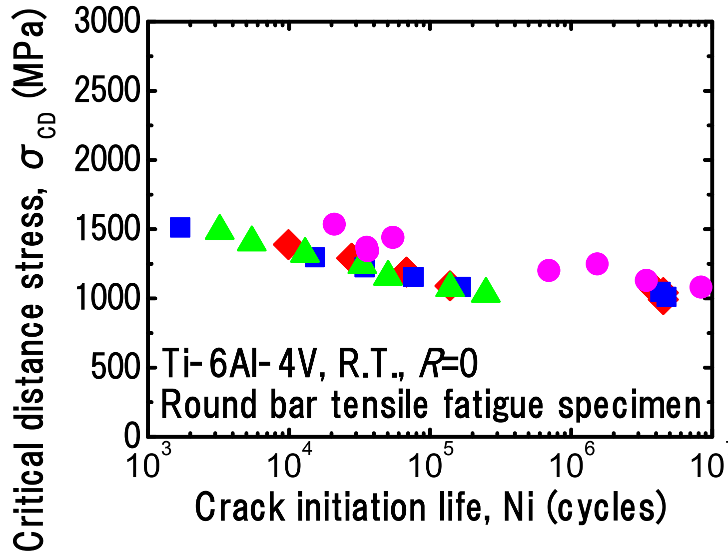
d=0.1mm, ρ =0.05mm
d=0.3mm, ρ =0.05mm
d=0.5mm, ρ =0.05mm
d=0.5mm, ρ =0.2mm



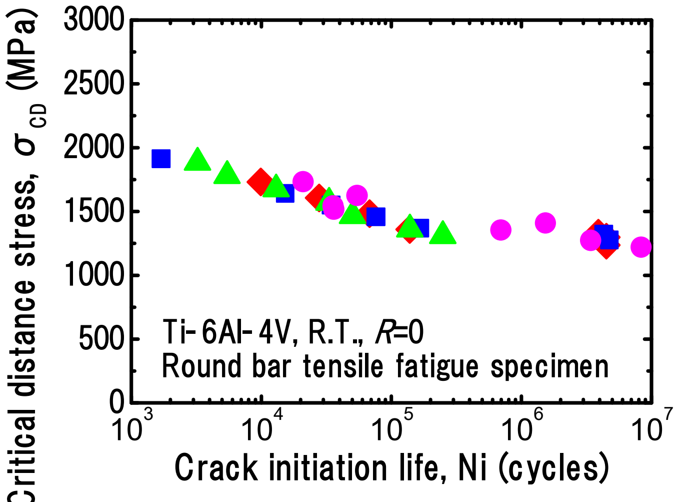


Method (1) a_0 = 0.016 mm

$$a_0 = (1/\pi)\cdot(\Delta K\mathrm{th}/\Delta\sigma_0)^2$$



(3) a_0 = 0.064mm = 0.032×2 mm



Best correlation
for all fatigue test data

Method (2) a_0 = 0.032 mm

$$a0 = (1/\pi)\cdot(\pi\cdot\Delta K\mathrm{th}/(1.1215\times 2\times\Delta\sigma_0))^2$$

Appropriate critical distance stress

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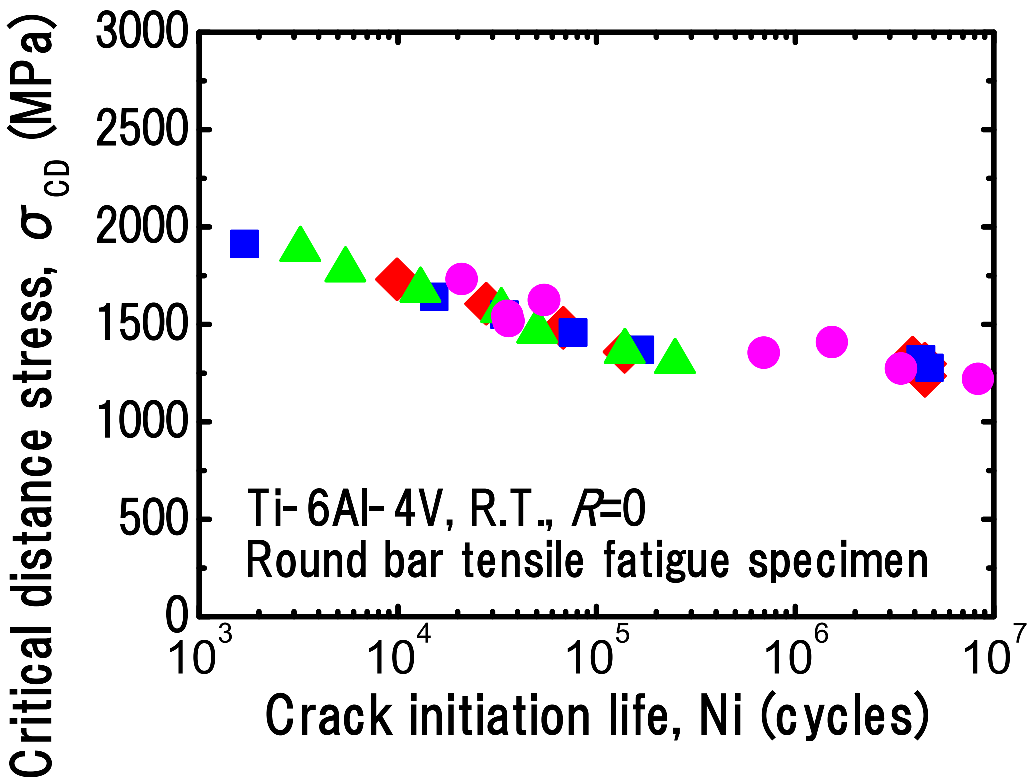

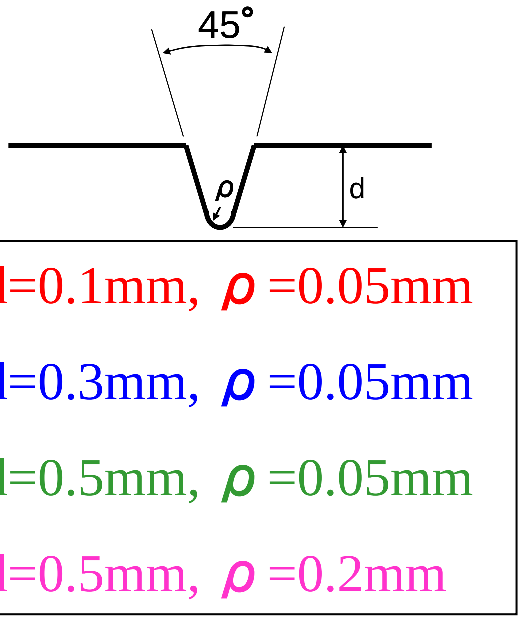

$$a0 = (1/\pi)\cdot(\pi \cdot \Delta K\mathrm{th}/(1.1215\times 2\times \Delta\sigma_0))^2$$

✓ There exists the good correlation between critical distance stress and crack initiation life of small notched specimen if the critical distance, a_0, is determined with 10^7 cycle $\Delta\sigma_0$, and ΔK_{th} using the K equation of semi-circle surface crack.

Min. fatigue strength : Effects of small notch root radius

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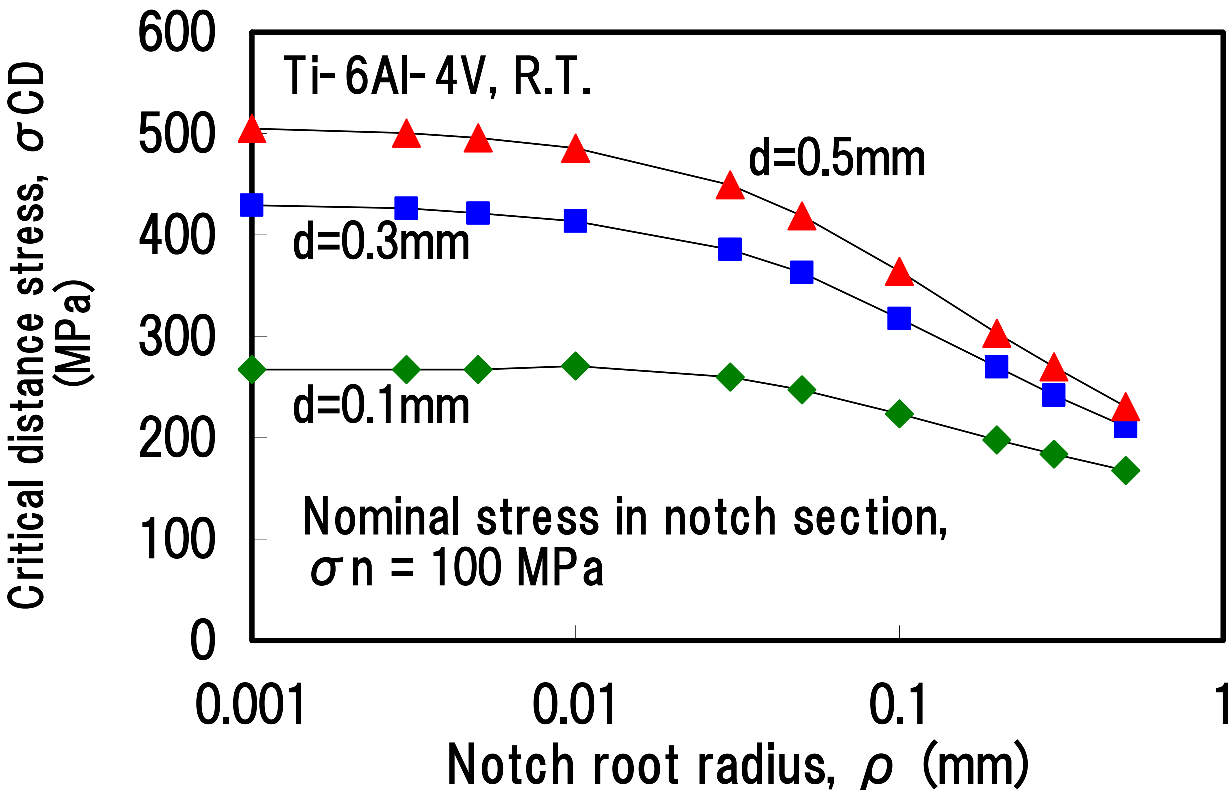


Very small notch root radius of ρ=0.001-0.01mm gives the constant critical distance stress at the same fatigue initiation life.

Minimum notch fatigue strength exists for each notch depth of d=0.1, 0.3 and 0.5mm.

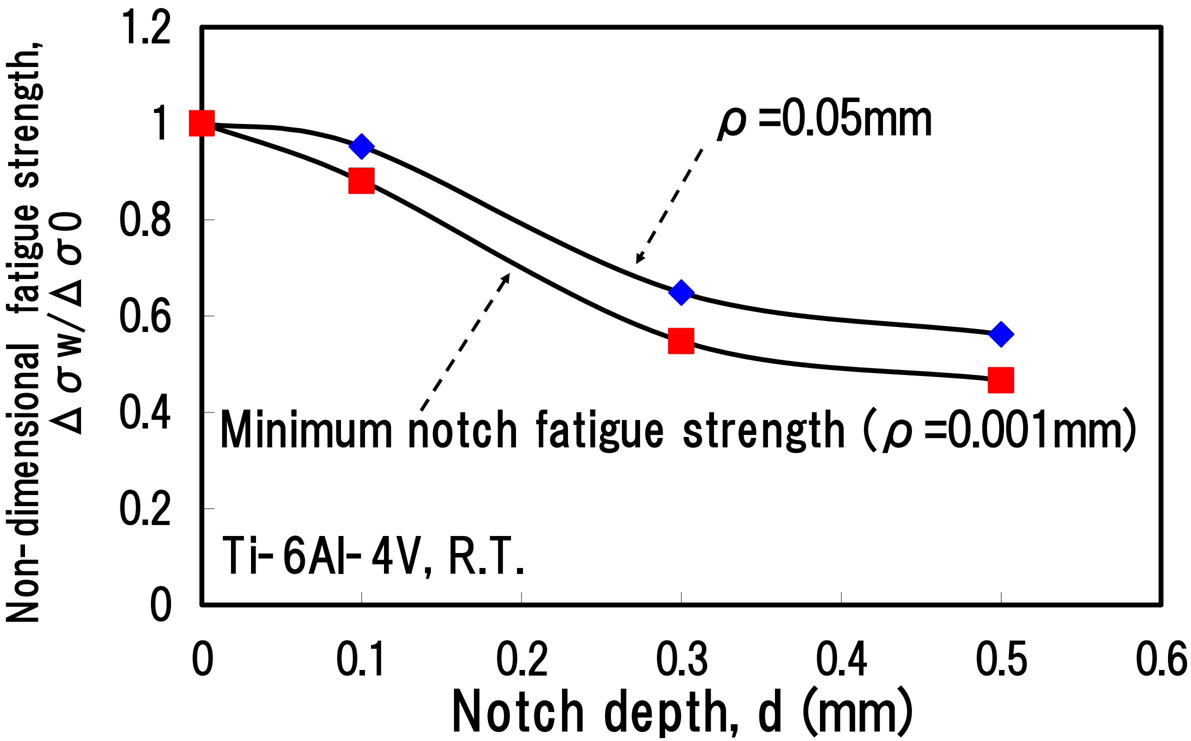
Min. fatigue strength of small notched Ti-64

$\Delta\sigma w$

: 10^7 notch fatigue strength

$\Delta\sigma 0$

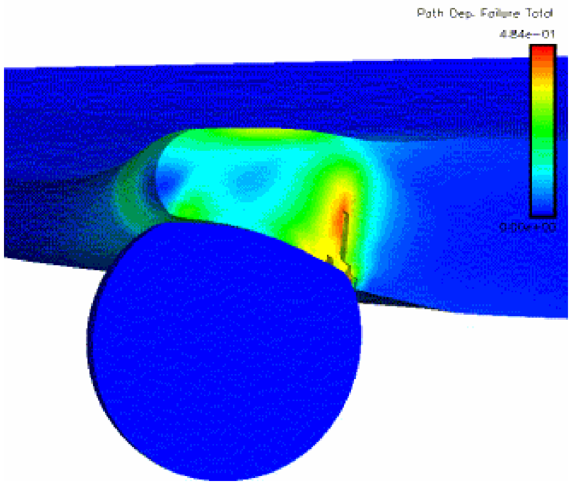
: 10^7 smooth specimen fatigue strength



■ : minimum fatigue reduction curve(ρ=0.001mm) can be determined by the appropriate critical distance stress

The design engineer can determine the minimum fatigue strength of the airfoils with nicks, dents and scratches in fatigue strength design of the airfoils.

Example residual stress simulation due to FOD



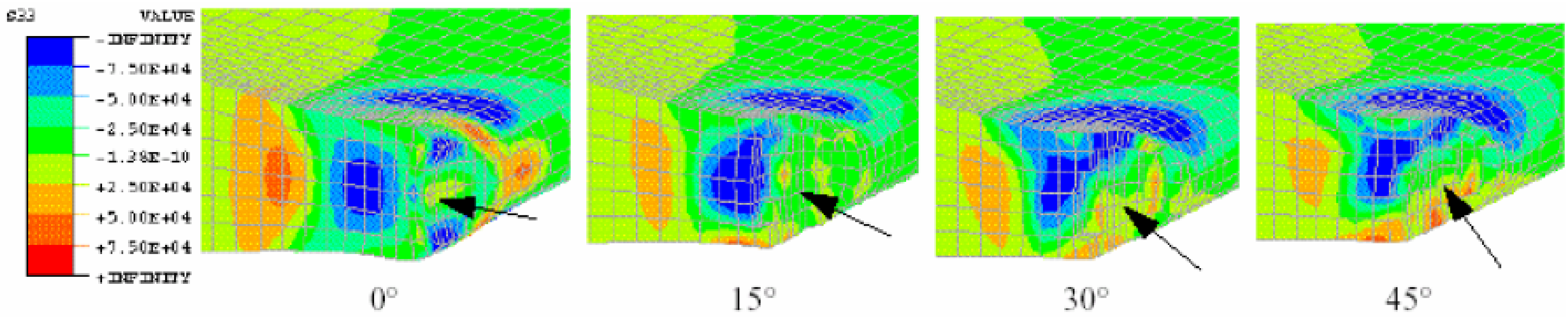
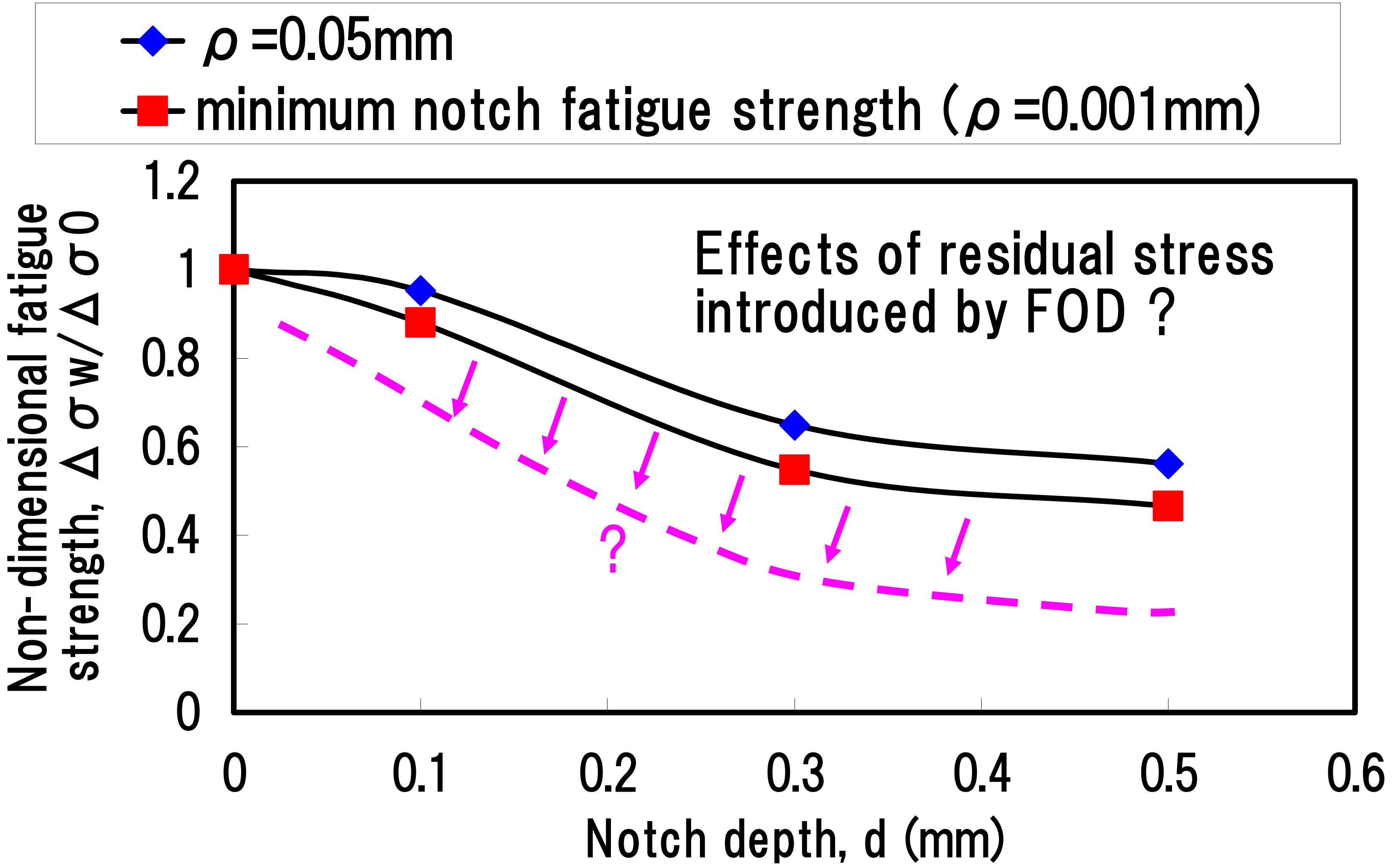


Figure 36: Comparison of Residual Stress Fields for Different Impact Angles.

Example of FOD simulation

Ref. The Research and Technology Organisation (RTO) of NATO, RTO technical report, TR-AVT-094 (2007) 78-84.

Discussion : Residual stress effects on FOD induced HCF



✓ Residual stress effects may be needed to take into account to evaluate the FOD-induced HCF.

Conclusions

Small notched fatigue strength based on the appropriate TCD for Ti-64

✓ There exists the good correlation between critical distance stress and crack initiation life when the critical distance, a_0, was determined with plain fatigue limit, $\Delta\sigma_0$, and ΔK_{th} using the K equation of semi-circle surface crack.

✓ The critical distance approach is powerful engineering tool to determine the small notched minimum fatigue strength under a required fatigue life in design if it is appropriately applied.

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ACKNOWLEDGEMENTS

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Thank You for Attention.

