가스터빈 부품 단조 기술

Hot Forging of Gas Turbine Components

한국 기계 연구원 (KIMM)
박노광, 염종택, 나영상, 김인수

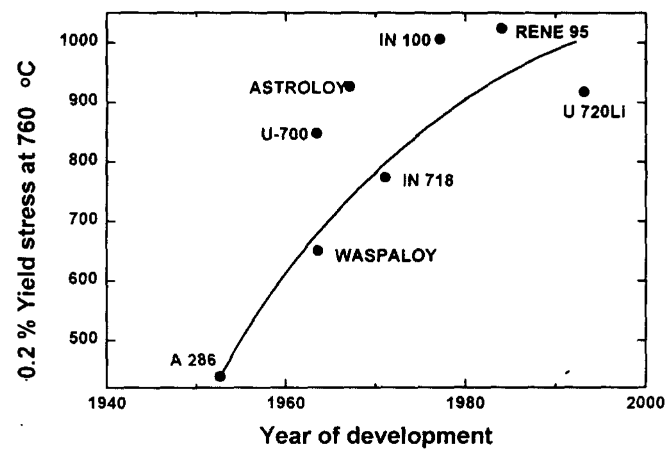
◆ 항공기 가스터빈 재료

- Constraint: High temperature strength, Density, Safety, Cost

↓

- 압축기용 재료 (α+β Ti 합금, α Ti 합금 : Ti-64, Ti-6246, IMI834, Ni 합금: Alloy 718)
- 터빈디스크 재료 (단조용 Ni합금: Alloy 718, Waspaloy, U720/U720Li, Astroloy, IN 100, Rene 95)
- 터빈블레이드 재료 (다결정, 일방향응고, 단결정재료)
- 노즐가이드 베인 재료 (다결정, 일방향응고 재료)

◇ 단조용 초내열합금의 변천



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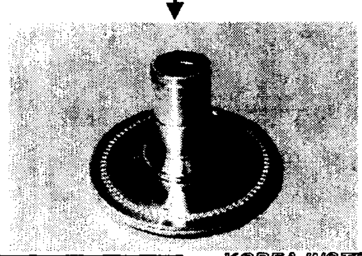
◇ 터빈 디스크 제조기술

- VIM + Precision Casting + HIP'ing
- VIM + (ESR) + VAR + Forging
- P/M + HIP'ing (or Extrude) + (Forging)

↓

- Post Treat: Welding , HT , SP, Machining

↓



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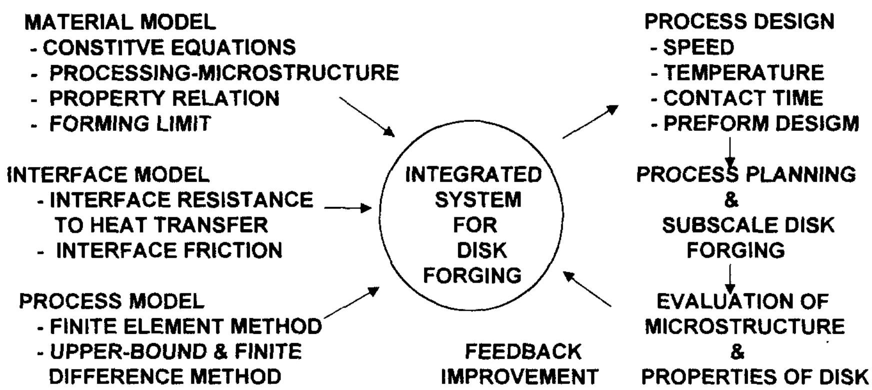
◆ Program Approach for Tailored Disk



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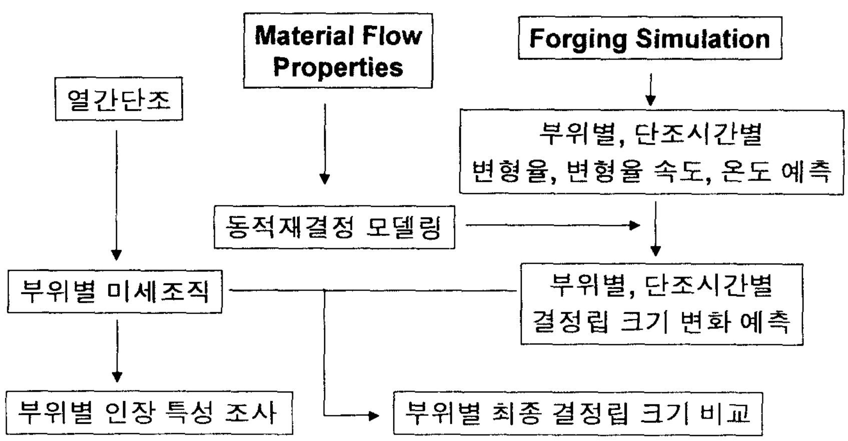
◆ 단조품 특성 시뮬레이션



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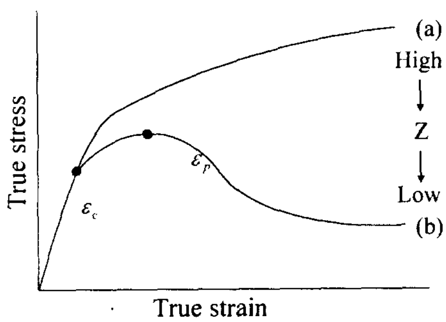
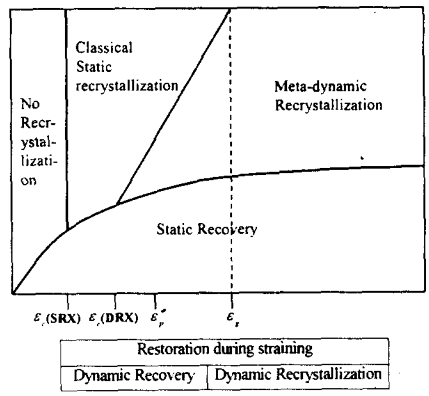
◆ 소성변형중 조직변화

Effects of Z



Evolution of Microstructure



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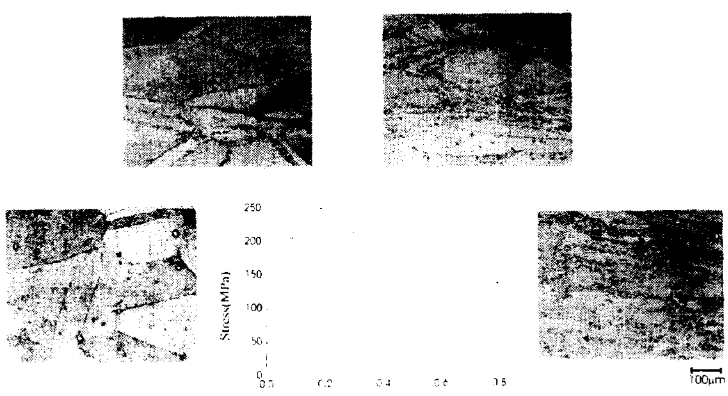
◆ 동적재결정의 진행/Alloy718



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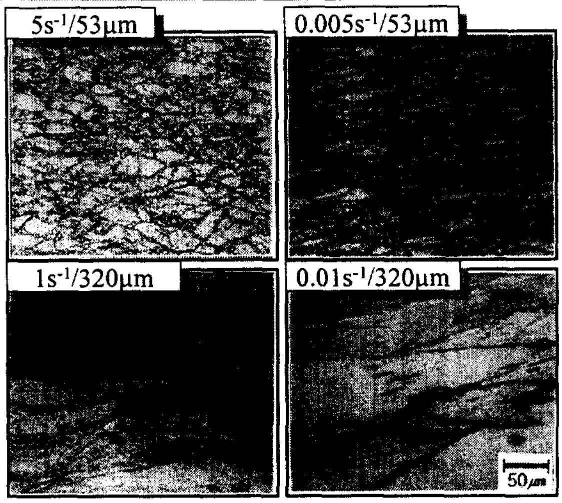
◆ 석출물 고용온도 이하(982°C)/ Alloy718



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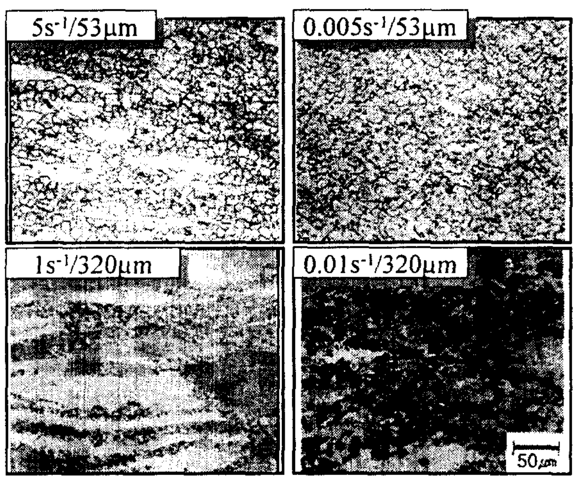
◆ 석출물 고용온도 이상(1066°C)/ Alloy718



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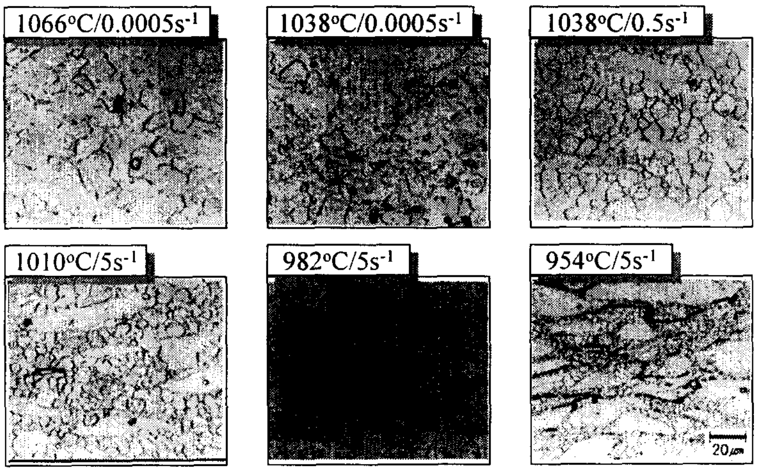
◆ 변형속도와 온도의 영향/Alloy718



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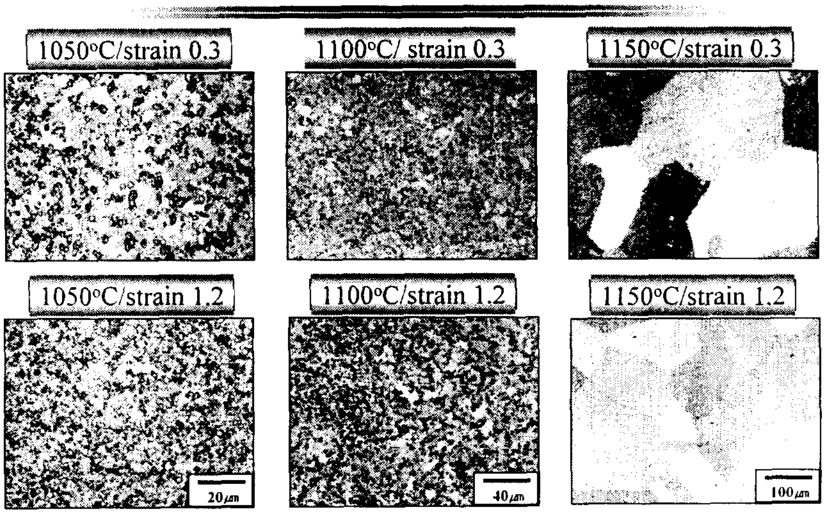
◆ 항온단조시 온도와 변형률의 영향/ Udimet 720Li



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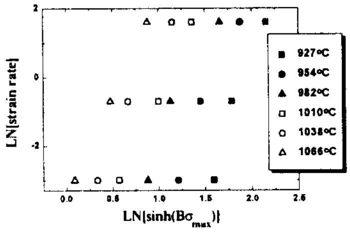
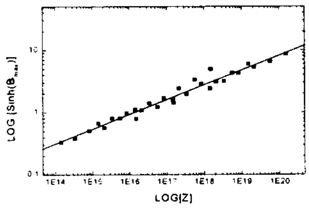
◆ 변형 활성에너지

$$\dot{\varepsilon} = A[\sinh(B\sigma_{max})]^{n}\exp(-Q/RT)$$

$$ln\dot{\varepsilon} = \ln A + n\,ln\sinh(B\sigma_{max}) - Q/RT$$



Alloy	Q (kJ/mol)	n	A	B(MPa^{-1})
Alloy718	448	4.07	1.83×10^{16}	0.0049
Ti64($\alpha+\beta$)	894	5.70	1.38×10^{40}	0.0053
Ti64(β)	332	3.84	1.45×10^{12}	0.0282



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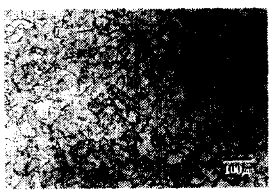
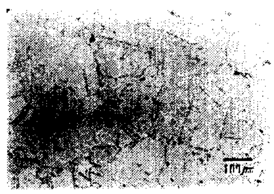
◆ 단조 조건

- Microstructure of Alloy 718 Billet





Forging Conditions

Specimen	1st Forging			2nd Forging		
	Ratio (%)	Temp. (°C)	Cooling	Ratio (%)	Temp. (°C)	Cooling
A	52	1010	FAC	24	982	FAC
B	44	1010	〃	40	982	〃
C	25	1010	〃	54	982	〃
D	52	1038	〃	24	1010	〃
E	44	1038	〃	40	1010	〃
F	25	1038	〃	54	1010	〃

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◆ FEM 해석 조건

- The Non-Isothermal Rigid-Plastic FE code (DEFORM-2)
- Axi-symmetric Forging
- Forging Conditions

Billet		
Material		Alloy 718
Preform dimension (H × D)		6 × 5.5 in
Initial Temperature (℃)	First Forging	1010
	Second Forging	982
Final Dimension	First Forging	3.9 in
	Second Forging	2.1 in
Die		
Material		H-13
Dimension(H × D)	Top Die	10 × 24 in
	Bottom Die	6 × 12 in
Inter Object Data		
Forging Machine		Screw Press
Friction Factor		0.3
Interface Heat Transfer Coefficient		0.02 Btu/s/in ^{2}/F

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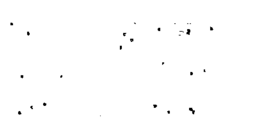
◆ 변형률과 온도분포

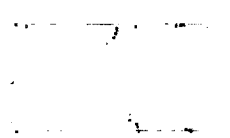
D condition



D condition

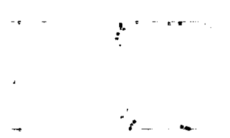
E condition

E condition



F condition

F condition



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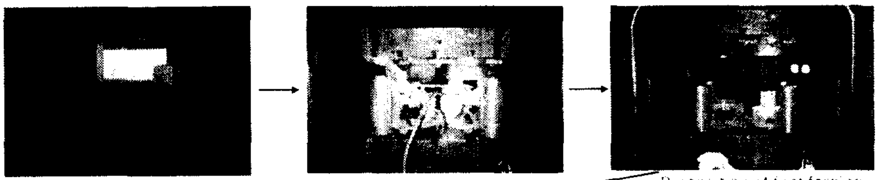
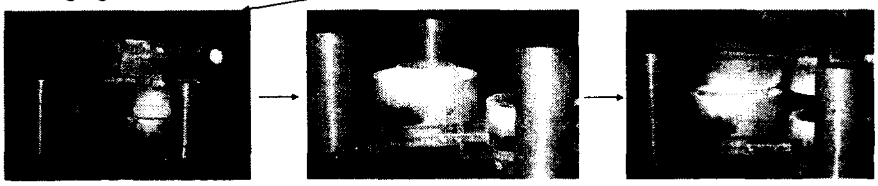
◆ 터빈 디스크 부품의 열간 단조

❑ Preliminary Process



Billet Heating → Die Heating → Preparation of first forging

❑ Forging Process



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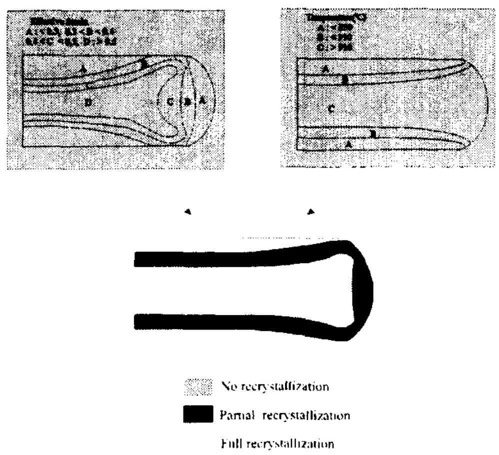
◆ 재결정 PATTERN



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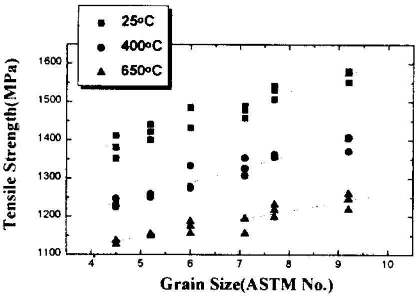
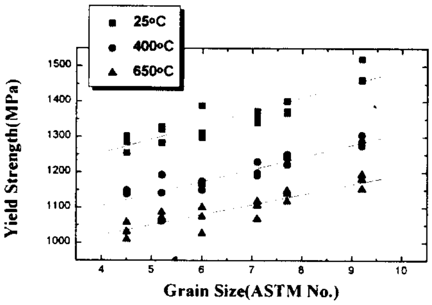
◆ 인장강도 vs 결정립크기/ Alloy718

❑ 인장강도



❑ 항복강도



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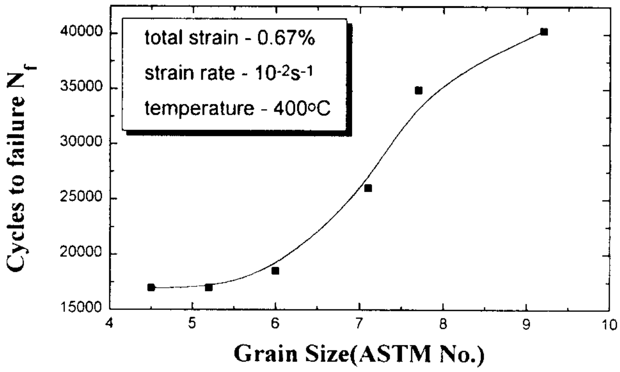
◆ 피로특성 (LCF) vs 결정립크기/Alloy718



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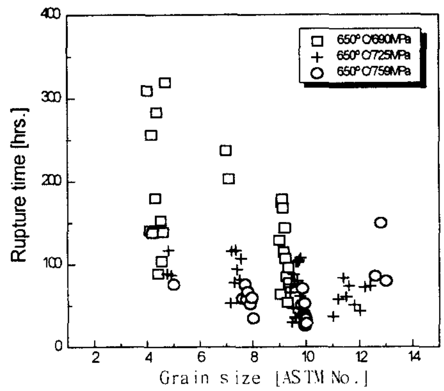
◆ SR Life vs 결정립크기/ Alloy718



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◆ 요 약

- ❑ 가스터빈에 사용되는 소재는 여타 금속소재에 비하여 고온 기계적 특성은 우수한 반면 상대적으로 단조성이 떨어지기 때문에, 금속소재의 단조성에 대한 이해와 단조 공정별 장단점을 파악하여 단조공정 설계에 반영하여야 한다.
- ❑ 가스터빈용 Ni 합금의 경우 고온기계적 성질은 결정립 크기에 크게 의존한다.
- ❑ 결정립 크기는 기계적 성질에 직접적으로 영향을 미치는 데, 동적재결정의 경우 초기 결정립크기, 변형률, 변형속도, 온도 뿐만 아니라 결정립계에 석출된 제2상에 의해서 크게 영향을 받기 때문에 이들 상의 고용온도를 파악하여 단조공정 설계에 반영하여야 한다.
- ❑ 유한요소법으로 변형률과 온도분포를 해석 함으로써 단조품 내의 결정립 분포를 효과적으로 예측할 수 있다.
- ❑ 다단계 단조 경우, 최종 단조품의 결정립 크기는 단계별 단조 온도 및 변형률 배분 등에 따라 변하므로 이를 고려하여야 한다.

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