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Instrumented Single Particle Impact Tests Using Production Shot: The Role of Velocity, Incidence Angle and Shot Size on Impact Response, Induced Plastic Strain and Life Behavior.

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Abstract

Shot peening is widely used in the aircraft industry for fatigue life enhancement derived from compressive residual stresses. Traditionally, Almen strips are used to measure the shot peening intensity, which is directly related to the resulting residual stress profile induced. These profiles do not appear to be sensitive to shot size or velocity. However, peening also induces plastic strains which are potentially detrimental. This effect appears to be very sensitive to shot size and velocity, and not dependent on intensity.

In order to develop a better understanding of the peening process and its impact on life capability, single particle impact tests using production shot were conducted at the University of Dayton Research Institute Impact Physics Laboratory. Incident and recoil velocity were measured, along with shot mass and diameter before and after impact. The coefficient of restitution (kinetic energy out / kinetic energy in) was found to decrease significantly with increasing velocity. Metallurgical evaluation was conducted on the impact dimples and on production peened samples. The temperature rise at impact was also successfully measured for two conditions. This led to the development of a "damage layer" hypothesis and the use of fracture mechanics methods to estimate the resulting life capability of a peened test specimen.

This paper describes the data from the single particle impact tests and trends in impact response due to changes in shot size, velocity and incidence angle. These results are used to interpret observed trends in life behavior, microstructure development and material behavior.

Single Particle Impact Tests

- Production shot (ccw14, ccw31, ccw52)
- Nickel-base superalloy, R88DT
- Metallurgical Evaluation of Dimples
- Material Behavior at High Strain Rates

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Background

- Shot Peen DOE results [1] - *LCF "damage" identified*
- Light Peening Study - *limited benefit for FM*
- Thompson Relation [2]: $d = 1.28(Y/\rho)^{1/4}(V_n)^{1/2}D$
  - Assumes spherical shot and dimples
  - Assumes constant coefficient of restitution (e=ΔKE,out/ΔKE,in)
- Bailey rule of thumb [3]: *intensity ~ dimple diameter*
- Popp/Thompson damage parameter [4]: $e_p = d^2/(8D^2)$
  - plastic strain due to indentation of a spherical dimple
- TEM work [5]– *shows evidence of recrystallization*

➠ There appears to be a change in mechanism at work. Existing approaches didn't provide adequate correlation.

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Benchmarking with Erosion Studies

- Velocity calculations made using Thompson's reln.
- Strain rate estimates made using $\dot{\varepsilon} \approx V / R$ [6]
  - ROM Δ observed for different shot sizes at same intensity

8A: CCW14=>5E+05, CCW31=>4E+04

- Timothy & Hutchings observed onset of adiabatic shear for d/D > 0.6 (d=dimple dia., D=shot dia.) [7]
- Using Thompson's reln., d/D=0.6 for V=81 m/s
  - equivalent intensities estimated to achieve d/D=0.6

Shot type	Diameter	Predicted Intensity *	Strain Rate 1/sec
CCW14	.356 mm (.014")	9A (.009" A)	5 E+5
CCW31	.787 mm(.031")	20A (.020" A)	2 E+5
CCW52	1.32 mm(.052")	34A (.034" A)	1 E+5

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Initial Assessment

- High strain rates involved - "normal" experience fails
  - 1100-0 Aluminum shows sharp knee around $\dot{\gamma} \approx 10^5$ [8]
  - From Meyers [8], stress response depends on mean dislocation velocity; regimes change as **velocity ⇒ shear wave velocity**:

    thermal activation ⇒ phonon drag ⇒ relativistic effects
- Even though velocities are low (for impact dynamics) strain rates are of "HYPER-VELOCITY" impact regime [8]
- Finnie's erosion work [9] noted a potential SIZE effect - microparticle impact considerations
- From available evidence, basic assumptions used in Hertzian analysis, Thompson relation, probably invalid at high strain rates

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Energy Equation

- Impact Process is transfer of shot kinetic energy to workpiece stored energy

  $KE_{,in} - KE_{,out} = \Delta E_{,rev.} + \Delta E_{,irrev.}$

- Coefficient of Restitution, $e = \Delta KE_{,out} / \Delta KE_{,in}$
- Define fraction of dissipative processes to elastic energy storage processes, $f = \Delta E_{,irrev} / \Delta E_{,rev.}$

  $(1-e) \bullet KE_{,in} = (1+f)\, \Delta E_{,rev}$

- Now, study trends of e, f as function of velocity, strain rate, etc.

  ⇒ minimize f

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Strategy

- Conduct single particle impact tests
  - production shot
  - try for Design of Experiment (DoE) approach
  - cover range of shot size, velocity, strain rate and incidence angle conditions
  - capture single impact event of an actual peening process as closely as possible (air environment, shot, target)
  - conduct metallurgical evaluation of impact dimples
- Concurrently, conduct metallurgical evaluation of production peened specimens as benchmark
- Compare and evaluate responses

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Single Particle Impact Test Effort

- Production shot (ccw14, ccw31, ccw52) and Low-Stress-Grind R88DT targets used
- Incident angle and velocity measured
- Recoil velocities obtained from high-speed photos
- Temperature measurements at impact (3 cond.)
- Resulting DIMPLES measured w/ profilometer
- Precision sections taken through selected dimples
- SEM/EDAX and Auger analysis of selected cond.
- Shot weighed and measured before & after impact

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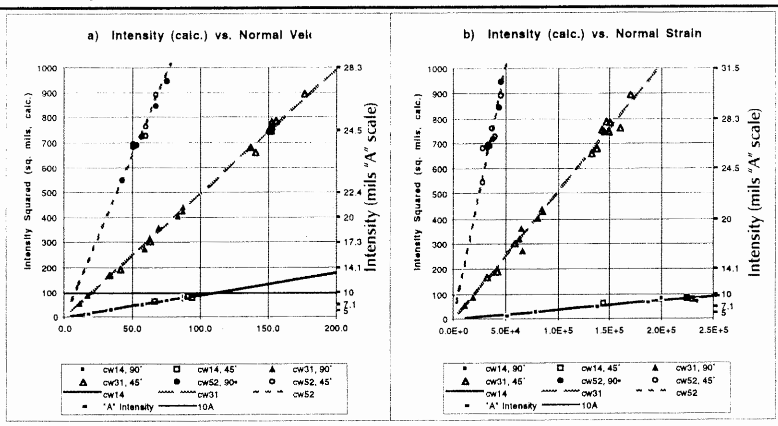
Intensity / Velocity & Intensity / Strain Rate Maps



- Thompson's relation used to calculate Intensity vs. normal velocity

@ 10A Intensity	ccw14	ccw31	ccw52
Velocity m/s	136	24	9
Strain Rate	6.5E+5	4.7E+4	1.2E+4

- Actual intensities may vary with coefficient of restitution, incidence angle

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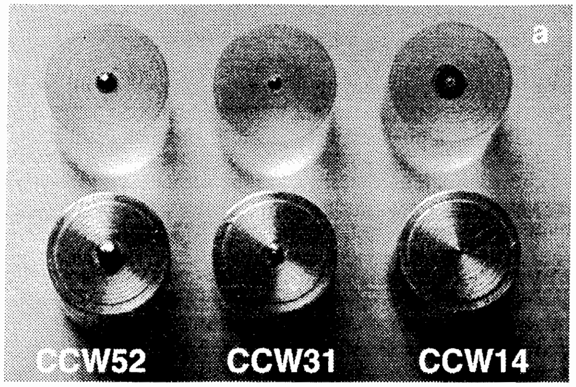
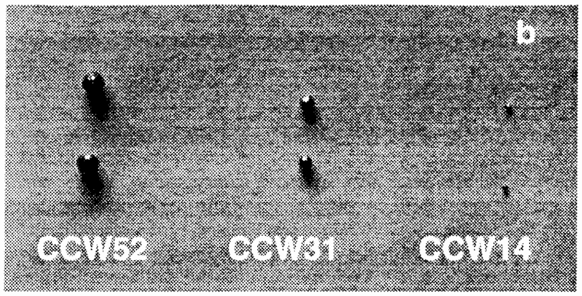
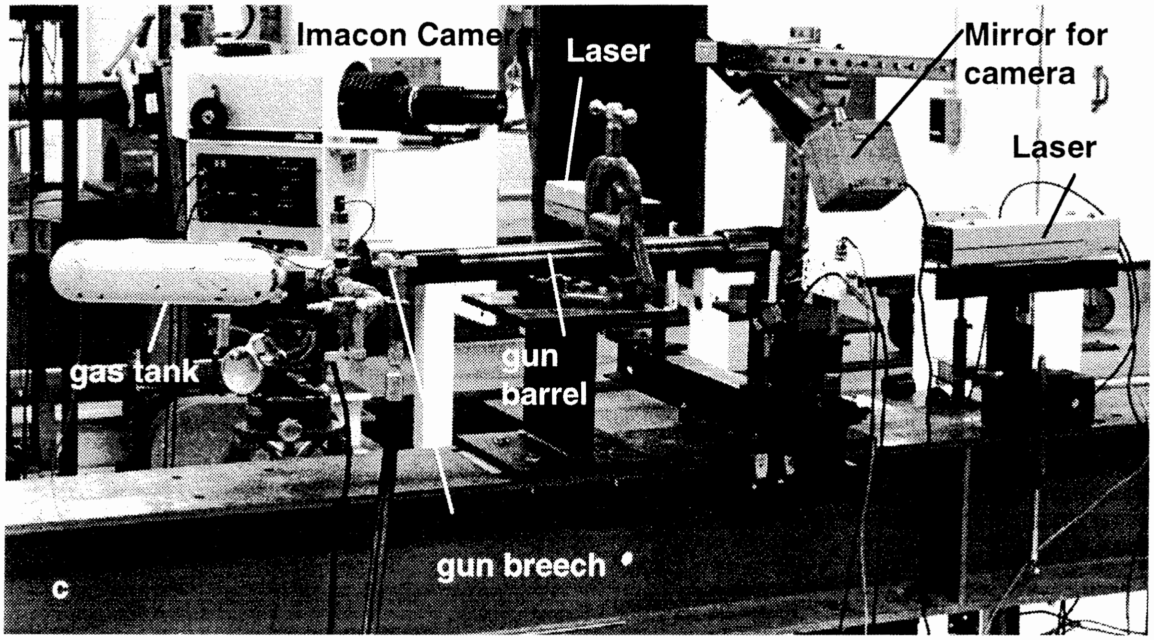
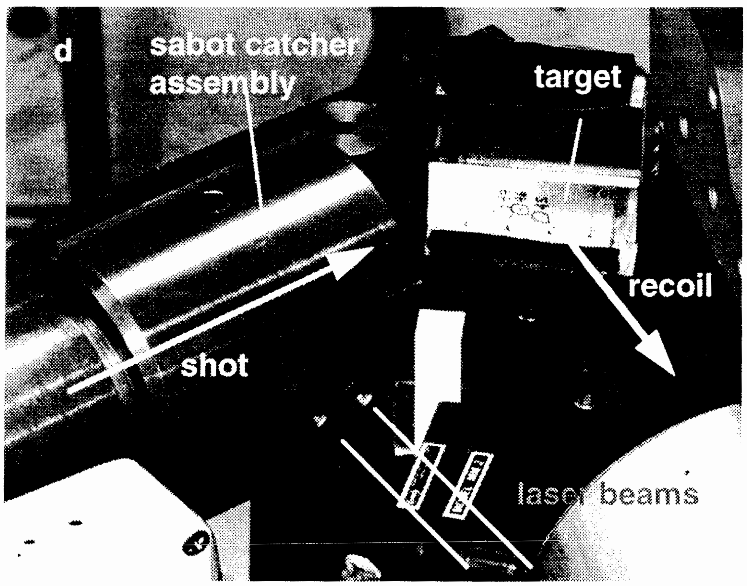
Figure 1: Single Particle Impact Test Setup





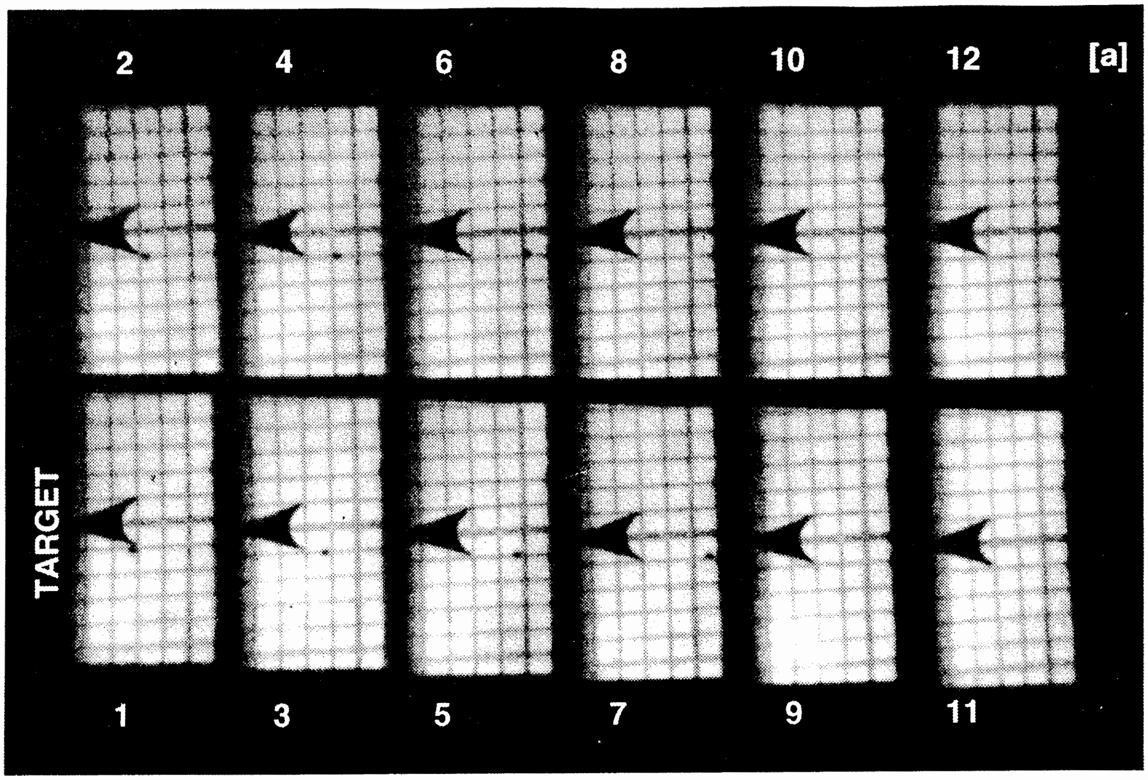
a) shot in plastic and brass sabots
b) shot samples showing three sizes



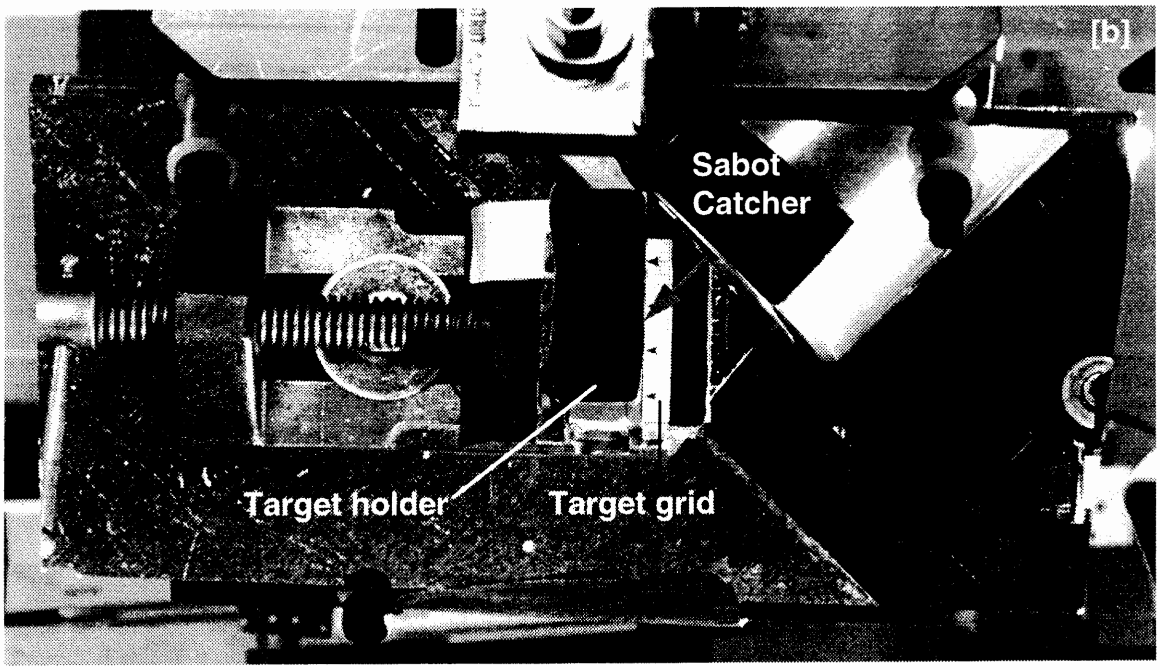


Single shot (**b**) is loaded into a plastic or brass sabot (**a**) and loaded into the breech of the gun (**c**). A helium gas tank is attached to the breech and the selected lpressure is set. When the gas is released into the breech, the sabot and shot are propelled down the barrel and into the sabot catcher (**d**), at which point the first laser beam is triggered, and the shot is released from the sabot.. The shot breaks the second laser beam on its way to the target.

Figure 2: Impact Photo



a) Impact photo from Imacon Camera. 12 frames, 10 μsec between frames, 1 mm grid. Target is at left side of grid. Photo shows recoil of CCW14 shot (~.014" / .356 mm dia. - flea dirt size), fired at 88 m/s onto a René 88 target. Test 3-015, 11/30/95, conducted at UDRI Impact Physics Laboratory, Dayton, Ohio.



b) Camera's view of impact site as seen through overhead mirror. Black felt is attached to the top of the sabot catcher assembly, target & target holder to isolate the frames on the impact photo.

Significant Observations - Production Peening

- 8 production peened conditions were evaluated
  (microstructures, SEM/EDAX, Auger spect. on selected specimens, hardness, surface roughness, erosion measurements)
- Factors correlating with "damage" state (not necessarily causative relation)
  - EROSION (mass loss per unit surface area)
  - IRON TRANSFER from shot
  - Presence of HEAVY slip bands, possibly ADIABATIC SHEAR BANDS ?
  - Surface roughness
  - Peening PERPENDICULAR to grind texture is more damaging than parallel to grind texture; also more severe for thermal exposure.
  - Recrystallized surface layer indicating significant temperature rise at impact observed from prior TEM work [x]

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Significant Observations - Single Impact Tests

- Factors correlating with deviation from "Thompson relation" Hertzian-type behavior
  - Presence of HEAVY slip bands, possibly ADIABATIC SHEAR BANDS ?
  - EROSION (mass loss) observed
  - IRON TRANSFER from shot for velocities > 58 m/s
  - Dimple shapes better approximated by elliptic parabaloids, not spheres
  - Lip formation and dimple aspect ratio likely due to local melting and deformation by plastic Rayleigh wave
  - Incidence angles directed PERPENDICULAR to grind texture is more damaging than parallel to grind texture
  - Significant temperature rise of 350°C (°F) and duration of 20-300 μsec successfully measured for 3 tests
    - » Demonstrates significant heat generated even at strain rates below the most severe observed.

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Precision Sections through Impact Dimples

- Selected Impact Dimples sectioned and etched to reveal microstructure beneath dimple
- Significant slip noticed with increasing velocity
  - Heavy shear bands noted for some dimples
  - Almost no slip noticed for low velocity impacts
- Depth of slip region correlates with shot mass, velocity and diameter
- This observation led to the hypothesis of treating the slip layer depth as an initial crack size for fracture mechanics calculation

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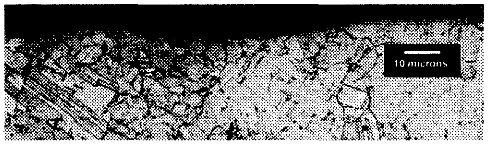
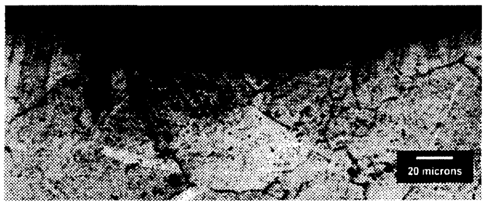
Precision Sections - CCW31 shot

a) 3-023, ccw31-13, R88-09 ═
17.5 m/s in
8/7 m/s out
90° incidence



b) 3-009, ccw31-09, R88-05 ═
58.9 m/s in
35.4 m/s out
90° incidence



c) ccw31-27, R88-16 ||
88.7 m/s in total (62.7 m/s normal)
60 m/s out total (14.5 m/s normal)
45° incidence

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Fracture Mechanics Calculations

- Using SEM microstructures of production peened coupons(750X), measured depth of cold worked zone
  - used this depth as crack radius for FM calculations
  - plotted individual DOE results on curves generated over a range of crack sizes
  - Life correlates reasonably well with FM for "damaged" conditions
  - "Undamaged" conditions also appear to hug FM curve (near threshold region of modified Kth curves)
  - No attempt made to adjust peening profiles to represent specific 6A or 10A profiles initially
  - Refined calculations using custom residual stress profiles, Kt gradients [1] provide reasonable lower bound life estimate

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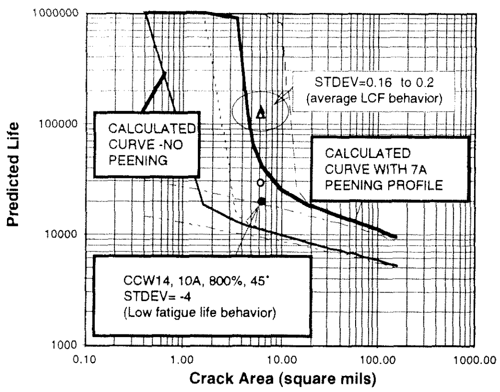
Preliminary FM calcs using Shot Peen DOE LCF data

René 88DT Shot Peen DoE Preliminary Fracture Mechanics Correlation from Estimated Slip Depth



- Slip depth estimated from microstructures
- Data appears to hug threshold region of modified Kth sigmoidal curve.
- This tends to suggest that peening pre-cracks the surface, and residual stress suppresses crack growth.
- Suggests that slip layer depth is right in region of fracture toughness threshold
  - small depths should predict no crack growth (low cycle fatigue domain)
  - larger depths would transition to FM domain

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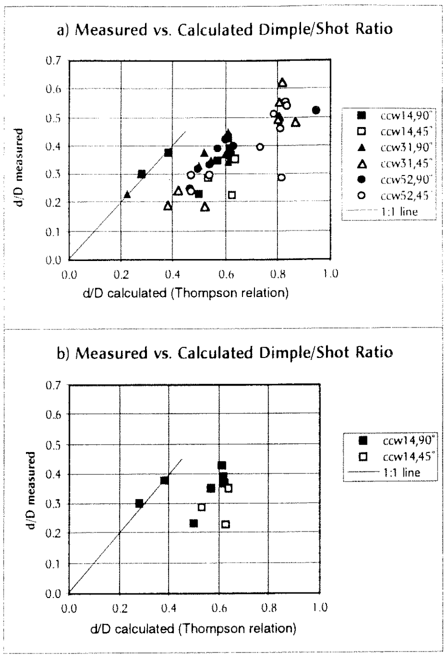

d/D - meas. vs. calc.

CCW14

- V ≤ 34 m/s - Thompson ✔
- V ≥ 58 m/s - Thompson ×.

CCW31

- V ≤ 18 m/s - Thompson ✔
- V ≥ 59 m/s - Thompson ×

Deviation from line (Thompson's relation) correlates with observation of significant plastic slip in the microstructure.

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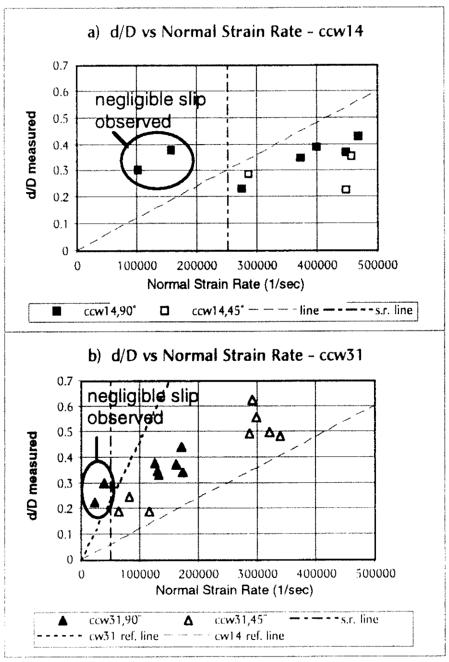

d/D vs Strain Rate $\dot{\varepsilon}$

CCW14

- strain rate ≤ 1.6E+5
  - Thompson ✔
- strain rate ≥ 2.8E+5
  - Thompson ×

CCW31

- strain rate ≤ 3.8E+4
  - Thompson ✔
- strain rate ≥ 1.3E+5
  - Thompson ×

Onset of slip occurs earlier:
As D⇑, YS ⇓ and $\dot{\varepsilon}$ ⇓
May be a shot hardness effect.

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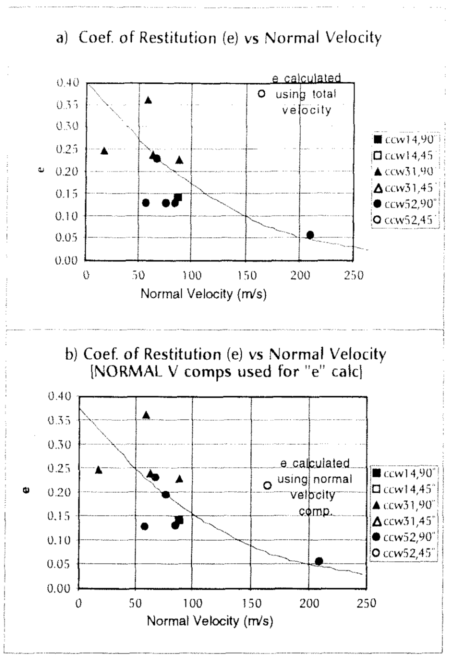

Coefficient of Restitution $e = \Delta KE_{,out} / \Delta KE_{,in}$

- Impact tests show clear drop in e as velocity increases
- 45° impacts showed higher e's when compared with 90°
  - 45° e's approached 90° e's when normal velocity comps. used for ΔKE calc.
- This phenomena is probably responsible for deviation from Thompson relation behavior.
- Suggests increased fraction of ΔKE transferred goes to dissipative processes
  - plastic strain
  - heat

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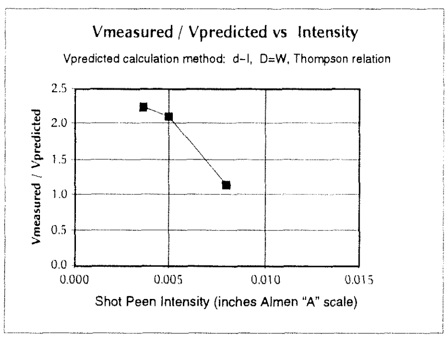
Velocity Data - Predicted vs. Observed



- Based on limited data, Thompson's relation holds for ccw14, 8A intensity
- At lower intensities, observed velocity is higher than predicted
- This effect is probably due to change in coefficient of restitution
  - As V ⇑, e ⇑,
  - ΔKE transferred ⇓
  - higher velocities ⇑ needed to get intensity

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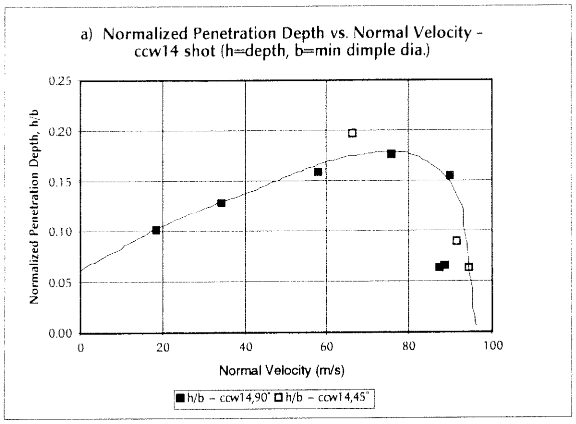
Normalized Penetration Depth Trend



- Drop in normalized penetration depth may indicate to "HYPER-VELOCITY" impact conditions
  - projectile breakup
  - adiabatic heating
- Clearly indicates increased % of ΔKE transferred into dissipative processes
  - i.e. higher %plastic strain vs. elastic residual stress

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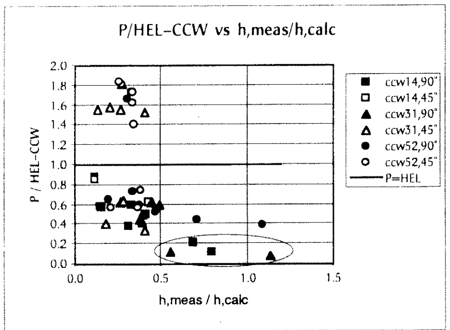

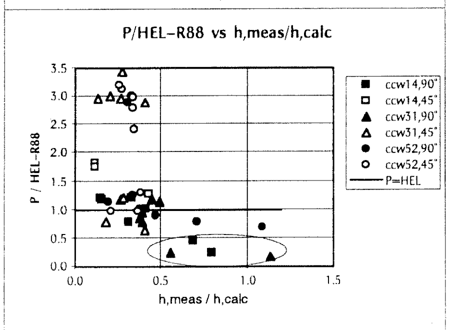

Penetration Depth (meas./calc.) vs Normalized Impact Stress

- Impact Stress (P) calculated & normalized by Hugoniot Elastic Limit (HEL) of shot and of target material
- For P/HEL,target
  - slip depth ⇑ as P/HEL ⇑
- HEL is a function of:
  - Bulk Modulus, K
  - Shear Modulus, G
  - Poisson's Ratio
  - Yield Strength
  - Density
- Could be used to predict relative sensitivity of alloys to intensity

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Additional Observations

- Dimple profilometry evaluated
  - d/D behavior fits Thompson's reln. at low velocities, strain rates
  - normalized penetration depth increases to a max, then decreases with increasing velocity
  - similar to "HYPER-VELOCITY" impact behavior (could correspond to projectile break-up, or adiabatic heating)
- Significant temperature increases ~350°C (660°F) and 20-300 μs duration observed for 3 tests
  - could not observe small shot at high strain rate conditions, but suggests significant ΔT to cause dynamic recrystallization
  - Depth calcs. suggest frictional heating (~.0004" deep only)
- Depth of "microstructural slip" correlates as a function of shot mass, VELOCITY, and diameter.

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Conclusions

- Microstructural observations suggest slip depth could be used to define initial crack size for fracture mechanics calculations
  - This led to development of fracture mechanics method [1] which is proving very useful so far
- Material behavior changes as V ⇑
  - ∴ Hertzian "elastic impact" type assumptions invalid
  - ∴ Heat generated could cause recrystallization as strain rate ⇑
- Velocity data for production peening conditions needed
  - permit correlation with slip depth
  - provide more complete characterization of peening conditions

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References

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Attachments / Supporting Data

- Precision Sections through selected Impact Dimples
  - reveals microstructure beneath dimple
  - significant slip observed as velocity increases
- Microstructures of 2 Production Peened Coupons
- Profilometry / Contour Plots of selected Dimples
  - shows that deviation from spherical dimples occurs often
  - "W" or throwback observed on many profiles

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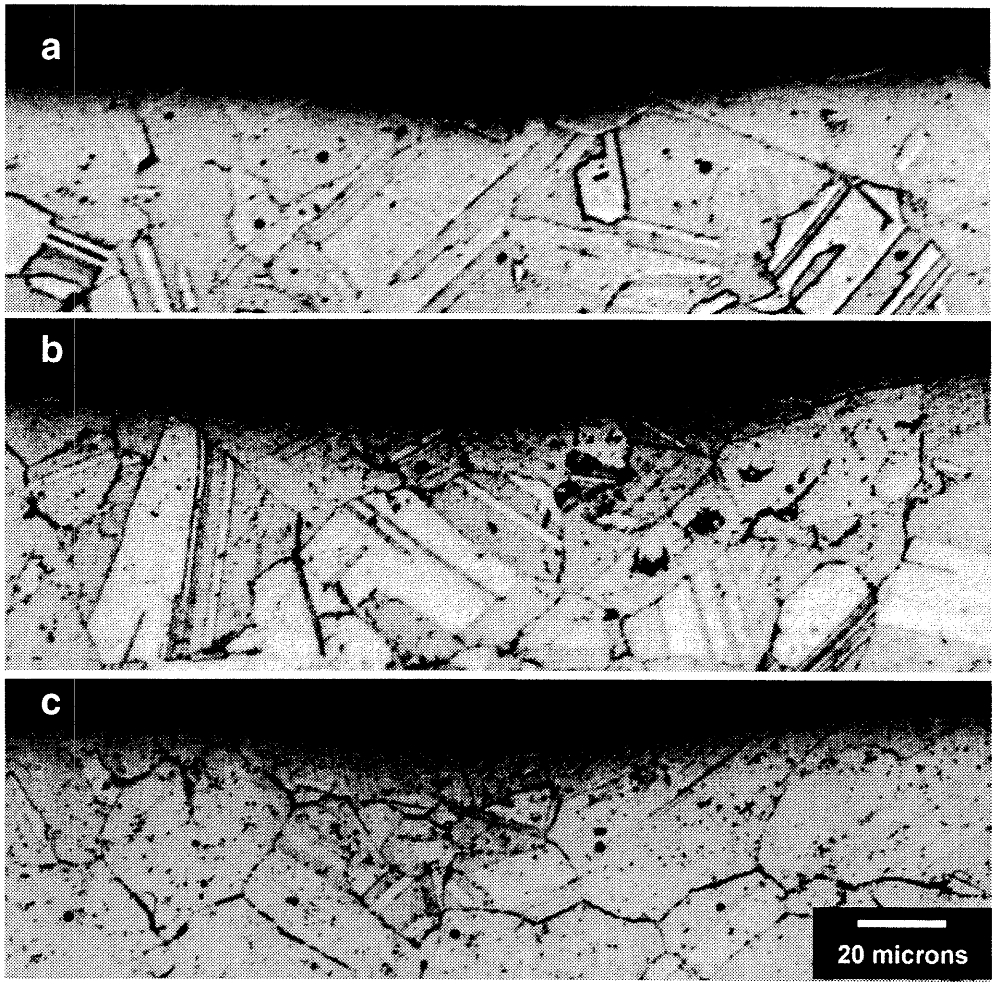
Precision Sections – CCW14 Shot

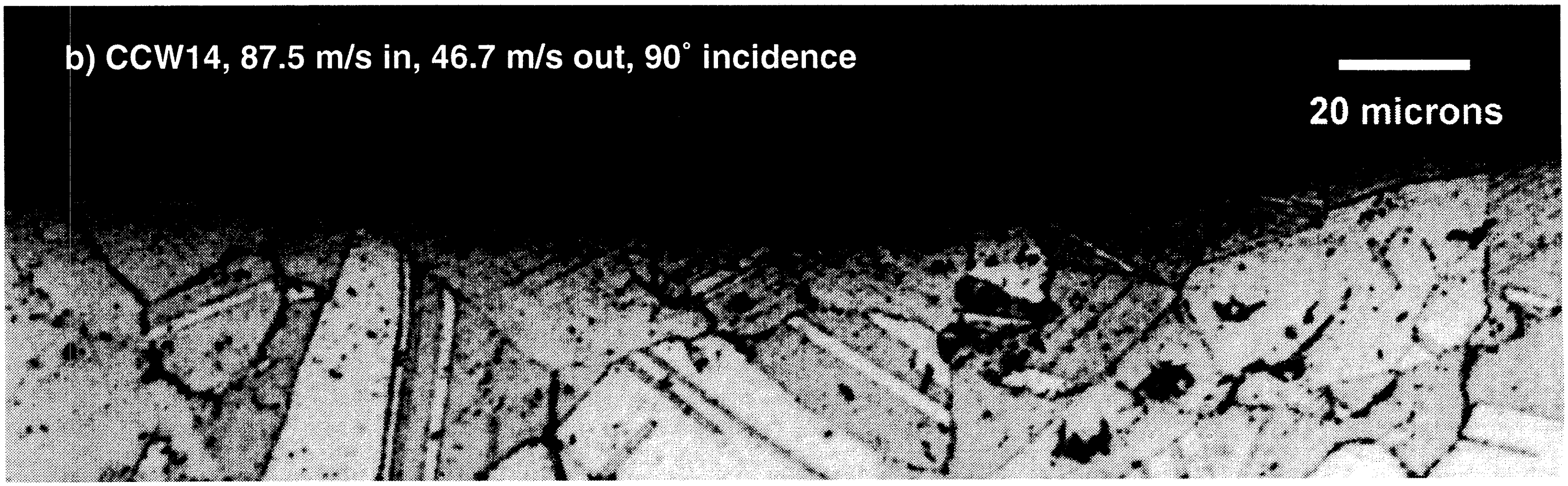


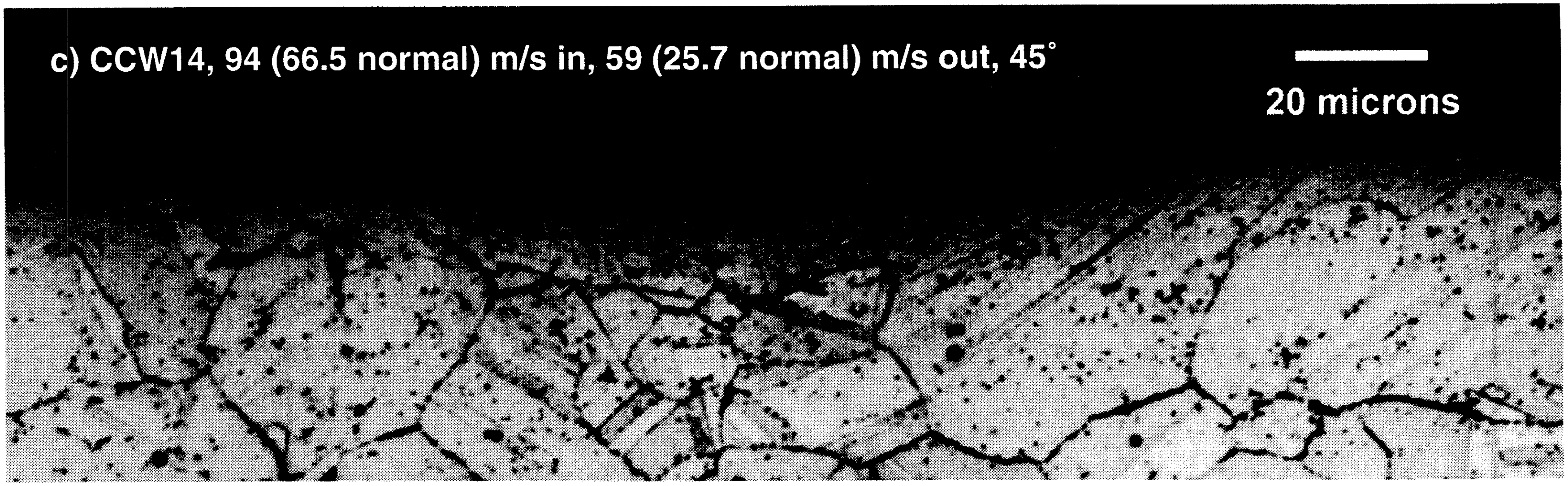
a) 3-027, ccw14-06, R88-09 ═
34.3 m/s in
recoil velocity unknown
90° incidence

b) 3-017, ccw1404, R88-04 ||
87.5 m/s in
46.7 m/s out
90° incidence

c) ccw14-08, R88-16 ═|
94 m/s in total (66.5 m/s normal)
59 m/s out total (25.7 m/s normal)
45° incidence

Enlargement: 90° vs 45° microstructures





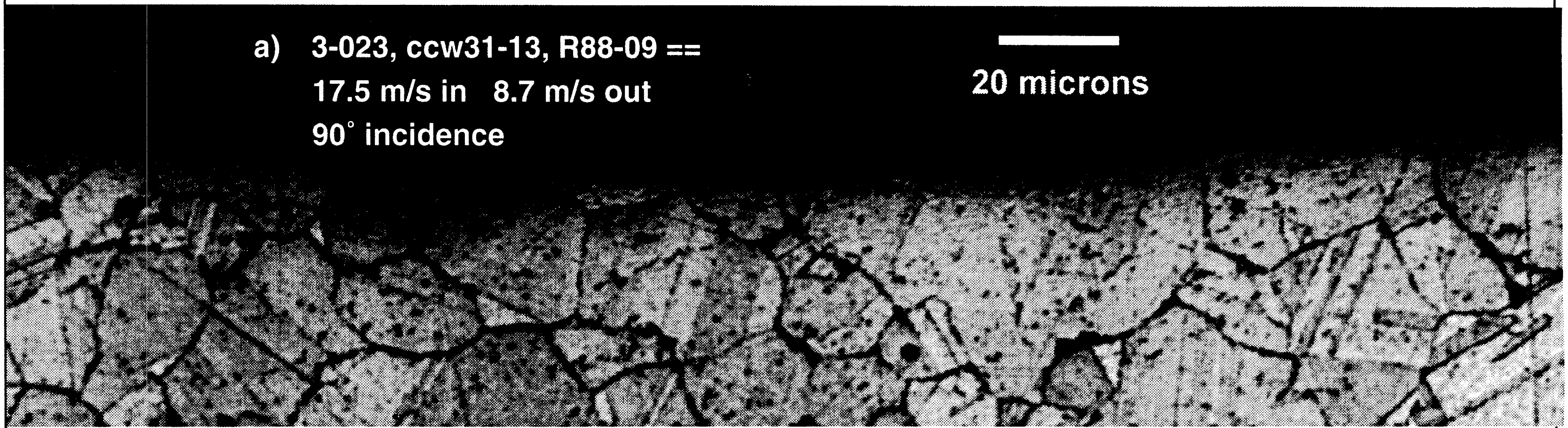
Precision Sections – CCW31 shot

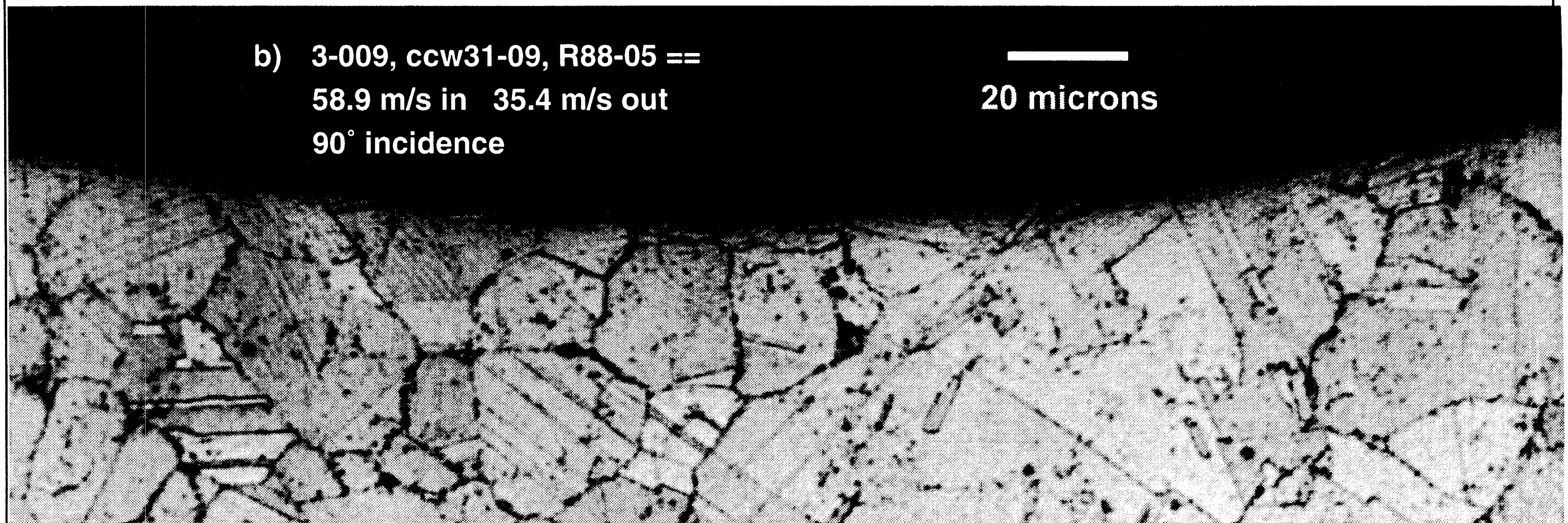
a) 3-023, ccw31-13, R88-09 ═
17.5 m/s in
8.7 m/s out
90° incidence

b) 3-009, ccw31-09, R88-05 ═
58.9 m/s in
35.4 m/s out
90° incidence

c) ccw31-27, R88-16 ||
88.7 m/s in total (62.7 m/s normal)
60 m/s out total (14.5 m/s normal)
45° incidence

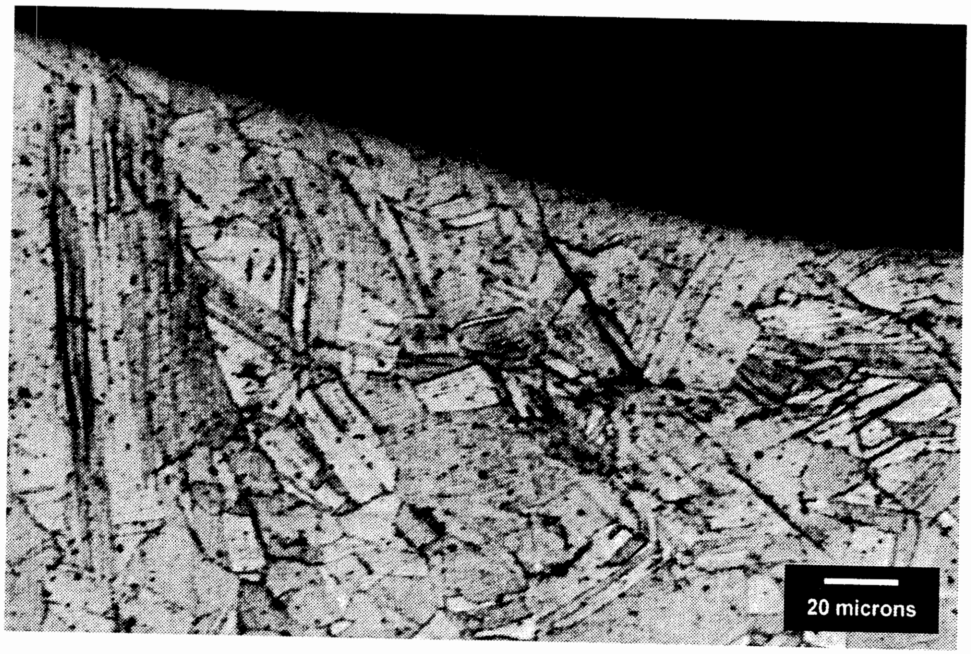
CCW31 shot - low velocity transition





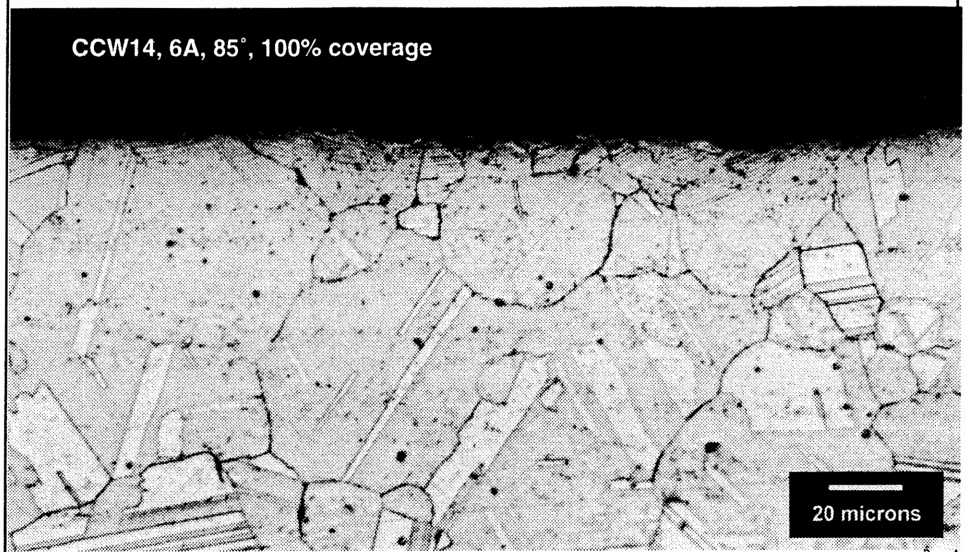
CCW52 closeup of impact site

Impact direction



- 3-066 ==
  - ccw52
  - 228 m/s in
  - (161 m/s normal)
  - 45° incidence angle
  - close-up of shear bands near initial impact site

Microstructure – Low Plastic Strain / Good Life



Microstructure – High Plastic Strain / Low Life