Effect of Surface Hardening Technique and Case Depth on Rolling Contact Fatigue Behavior of Alloy Steels

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Introduction

Two-stroke outboard engine components used in rolling contact fatigue (RCF)

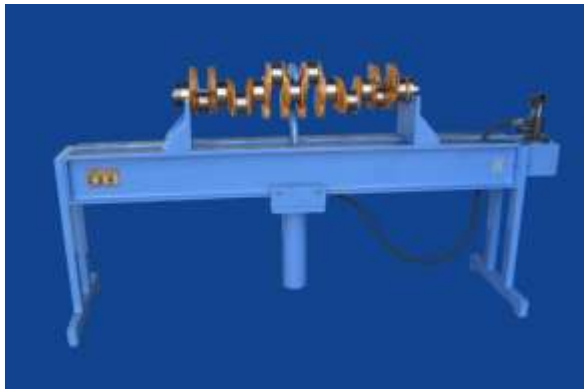
- ✓ Crankshafts
- ✓ Connecting rods
- ✓ Driveshafts
- ✓ Propeller shafts
- ✓ Gears
- ✓ Bearings
- ✓ etc.

Typical manufacturing process

Forging →

Rough machining →

Heat treatment



Straightening →

Grinding

Surface hardening processes

Atmosphere carburizing

Induction hardening

Vacuum carburizing
(with or without high-pressure gas quenching)

Carburizing vs. induction hardening

Townshend et al (1995):

✓ Straight spur gears

✓ Induction hardened AISI 1552 had longer RCF life than atmosphere carburized AISI 9310

✓ Carburized gears were ground after heat treatment; induction hardened gears were not

Jones et al (2010):

✓ Spiral bevel gears

✓ Induction hardened AISI 4340 had lower distortion

✓ Atmosphere carburized AISI 9310 had higher strength

Atmosphere vs. vacuum carburizing

Lindell et al (2002):

✓ Helical spur gears

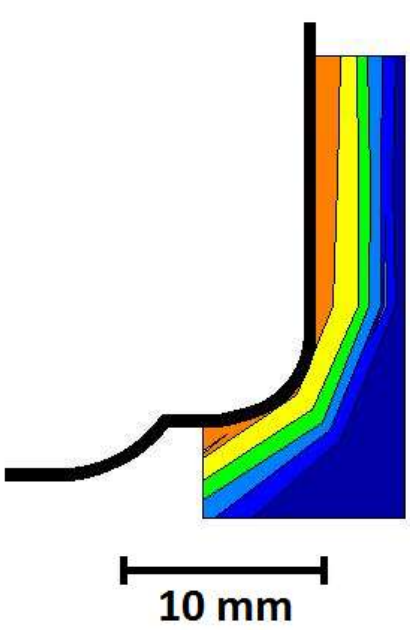
✓Atmosphere carburizing (with oil quench) vs. vacuum carburizing (with gas quench) for AISI 8620

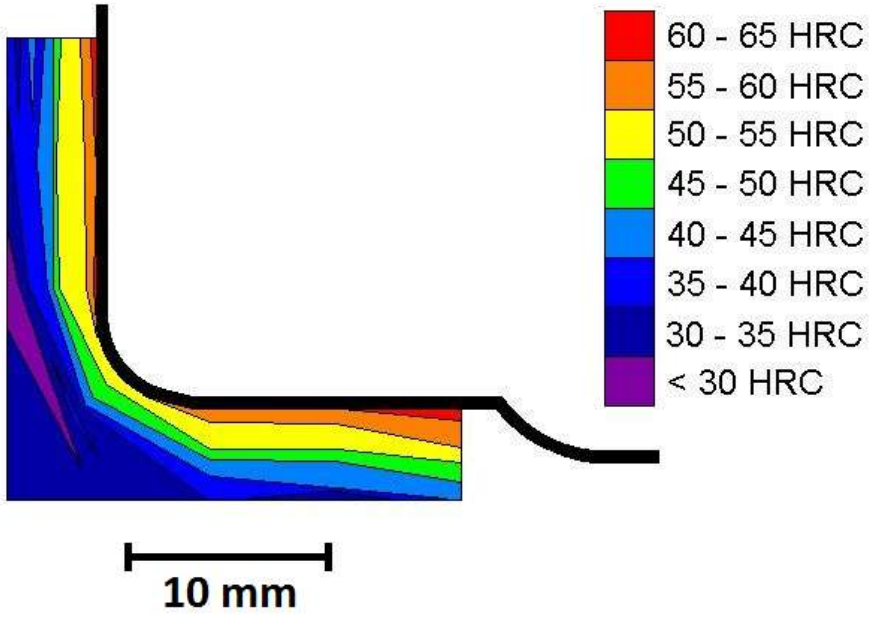
✓ Vacuum carburized AISI 8620 had:

- ✓ Higher surface hardness
- ✓ Higher surface compressive residual stress
- ✓ Greater depth of high hardness (>58 HRC) at same case depth

Case depth

- ✓ Traditionally measured as depth to 50 HRC (513 HV)
- ✓ May vary due to non-uniform heating, non-uniform carbon pickup, and/or non-uniform stock removal during grinding



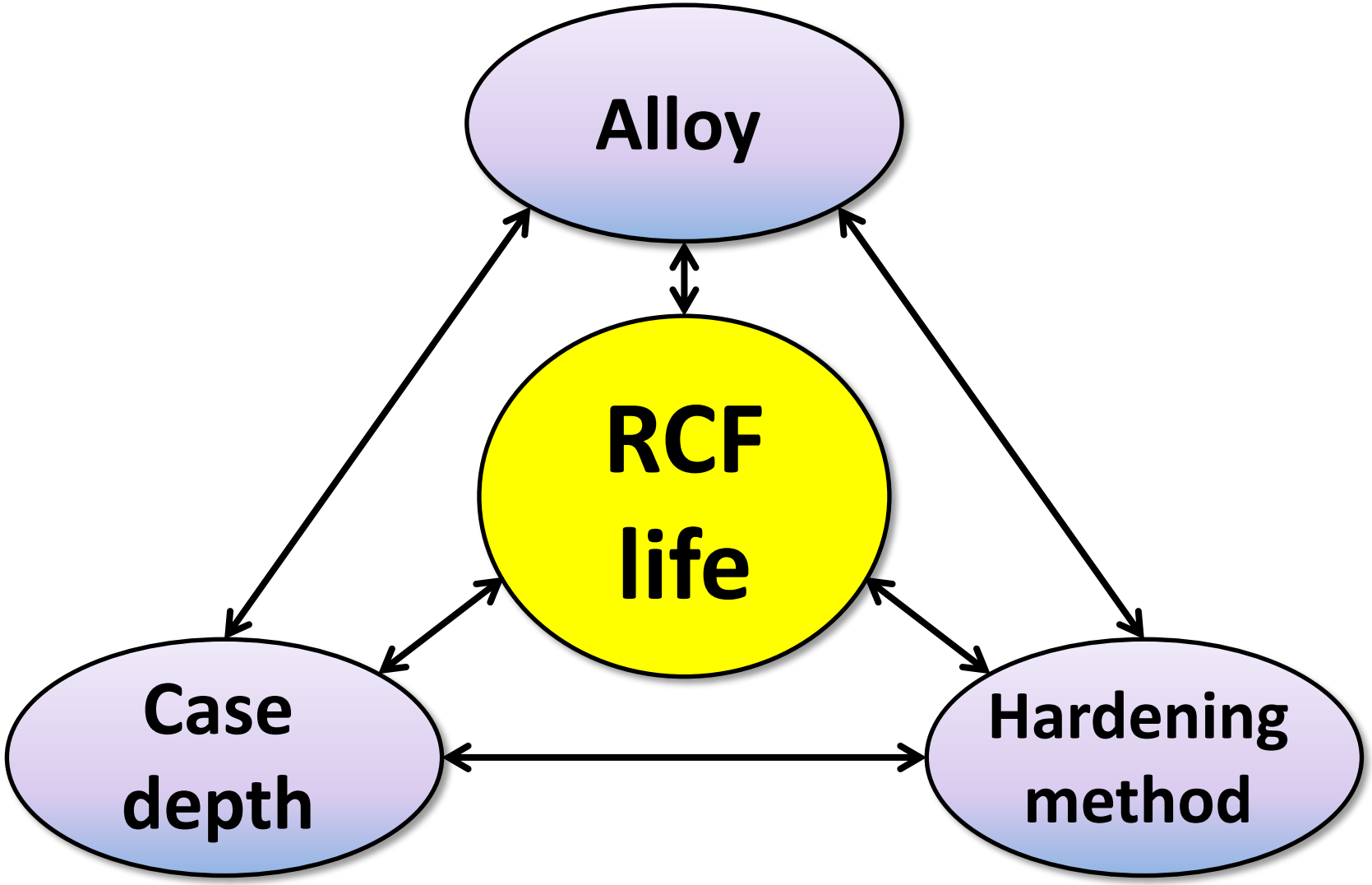


Problems

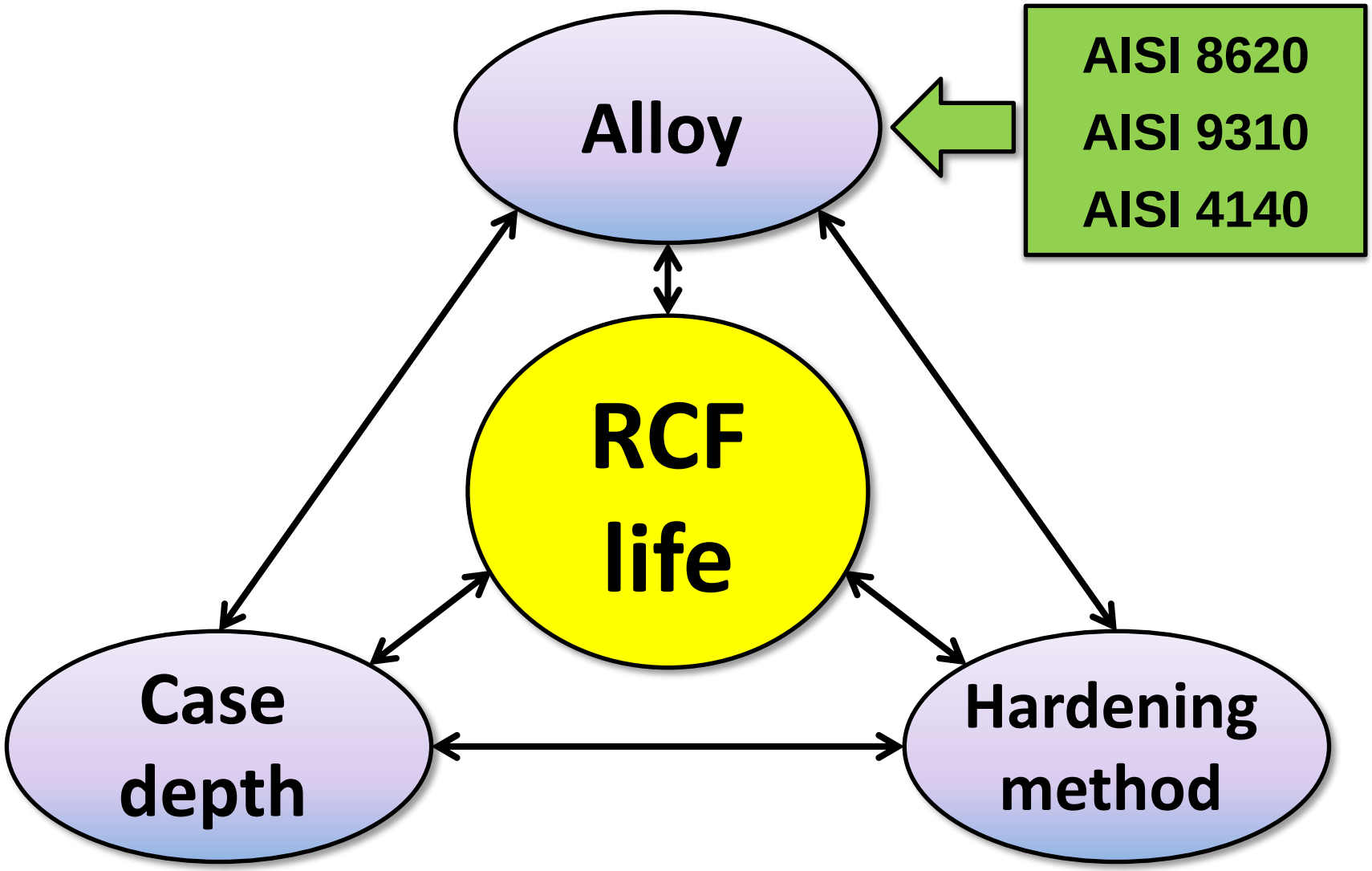
- ✓ How do different surface hardening methods affect RCF life?
  - ✓ Atmosphere carburizing with oil quenching
  - ✓ Vacuum carburizing with oil quenching
  - ✓ Vacuum carburizing with gas quenching
  - ✓ Induction hardening
- ✓ What is the effect of case depth on RCF life?
- ✓ How to account for case non-uniformity?

Experimental Design and Procedure

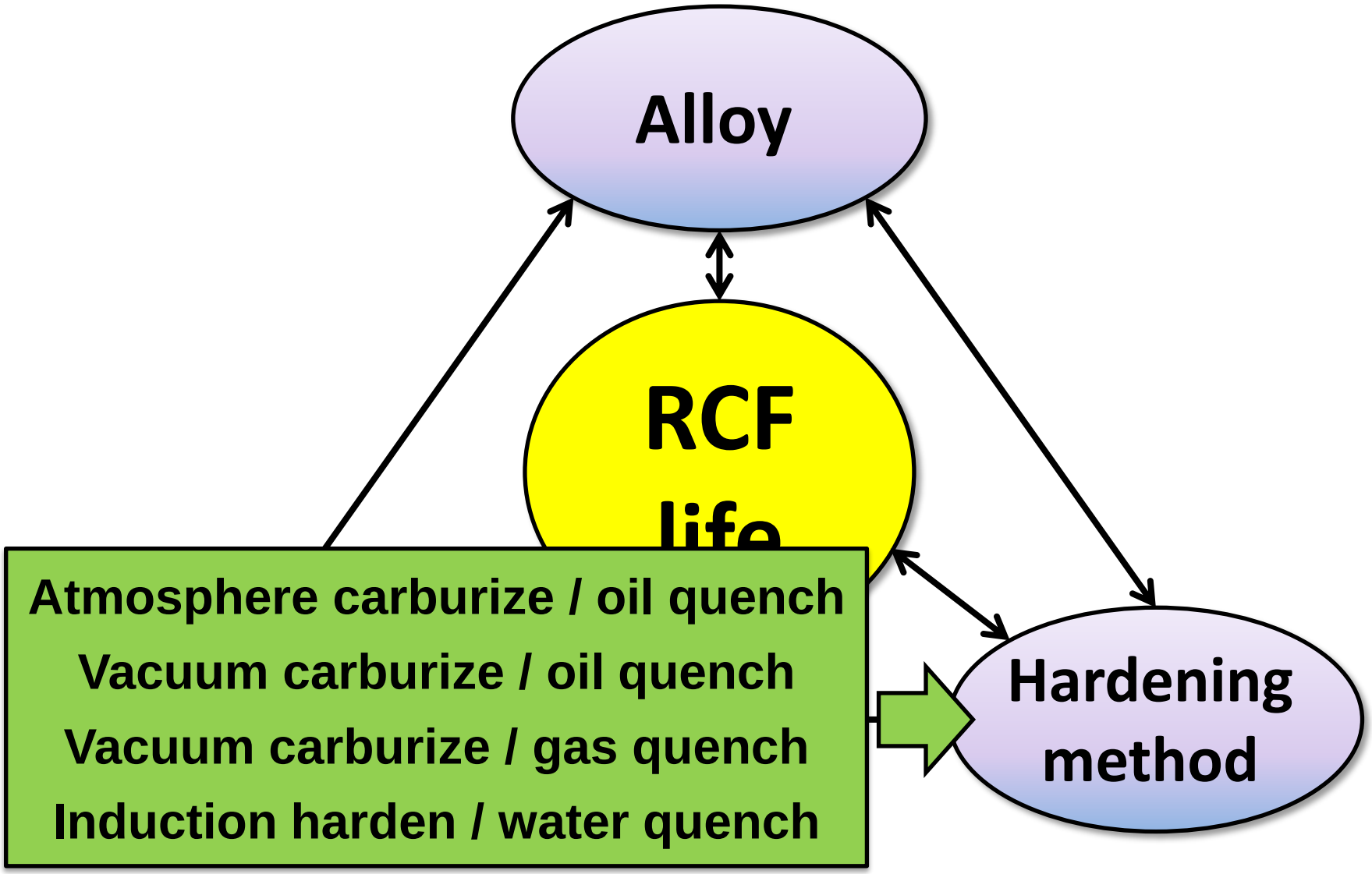
Experimental Design



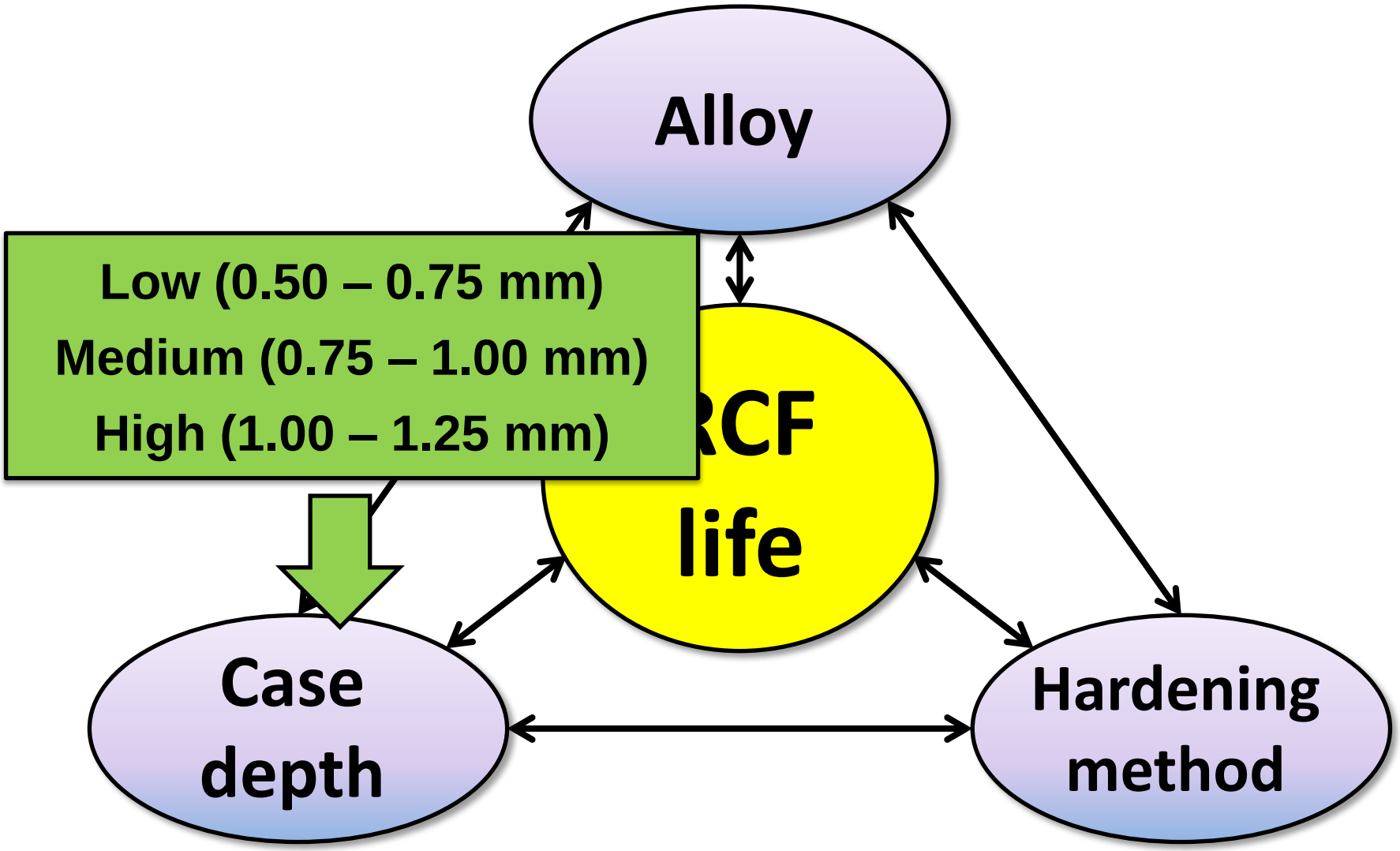
Experimental Design



Experimental Design



Experimental Design



Procedure

Rough machining

Heat treatment

Centerless grinding

RCF testing (ball-on-rod)

Microhardness / case depth

Metallography

Scanning electron microscopy

White light interferometry

Materials

AISI 8620, 9310, 4140

Vacuum degassed

Certified AQ per SAE AMS 2301

Material	C	Mn	Si	Ni	Cr	Mo	Cu	P	S	Al	Fe
8620	0.21	0.83	0.24	0.48	0.54	0.21	0.12	0.008	0.010	0.031	Balance
9310	0.11	0.62	0.26	3.06	1.16	0.10	0.15	0.007	0.020	0.033	Balance
4140	0.41	0.90	0.25	0.06	0.99	0.22	0.07	0.007	0.019	0.030	Balance

Length: 3.00 ± .05” (76.2 ± 1.3 mm)

Diameter: 0.400 ± .005” (10.16 ± 0.13 mm) – ***before grind***

Diameter: 0.3750 ± .0001” (9.525 ± 0.002 mm) – ***after grind***

Surface finish: 2 – 4 µin. (0.05 – 0.10 µm)

Heat treatment

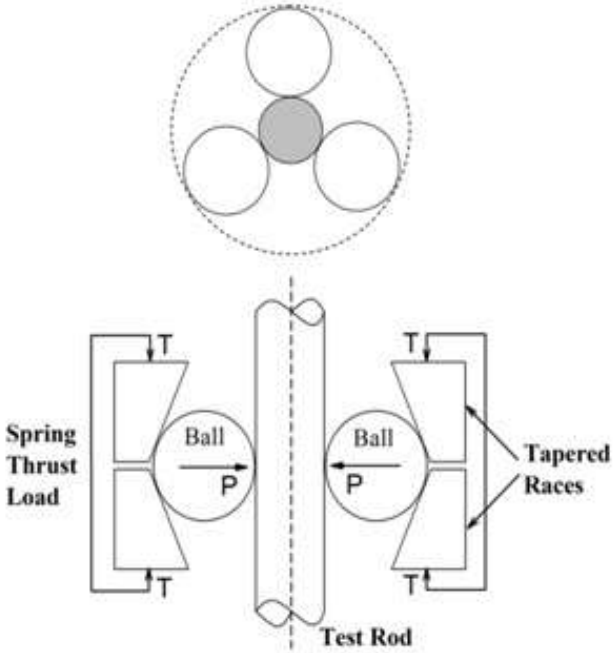
AISI 8620

	Carburizing Temp. (°C)	Hold Temp. (°C)	Hold Time (min.)	Quench Temp (°C)	Tempering Temp. (°C)	Tempering Time (hours)
Atmosphere	954	815	20	80	177	3
Vacuum	940	815	20	80	177	3

AISI 9310

	Carburizing Temp. (°C)	Hold Temp. (°C)	Hold Time (min.)	Quench Pressure (kPa)	Tempering Temp. (°C)	Tempering Time (hours)
Vacuum	940	815	20	1500	177	3

RCF testing



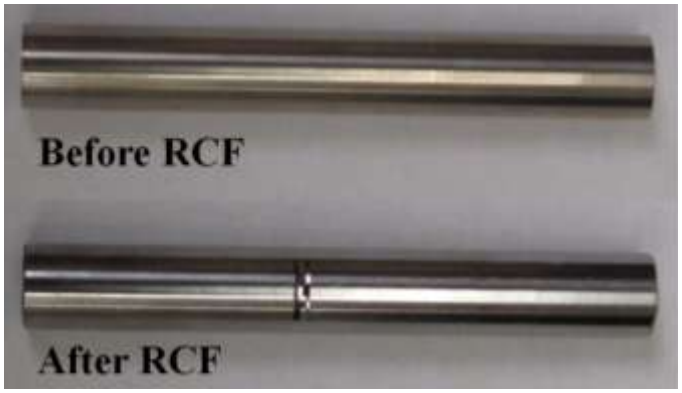
Maximum contact stress: 6 GPa

Rotation speed: 3600 rpm

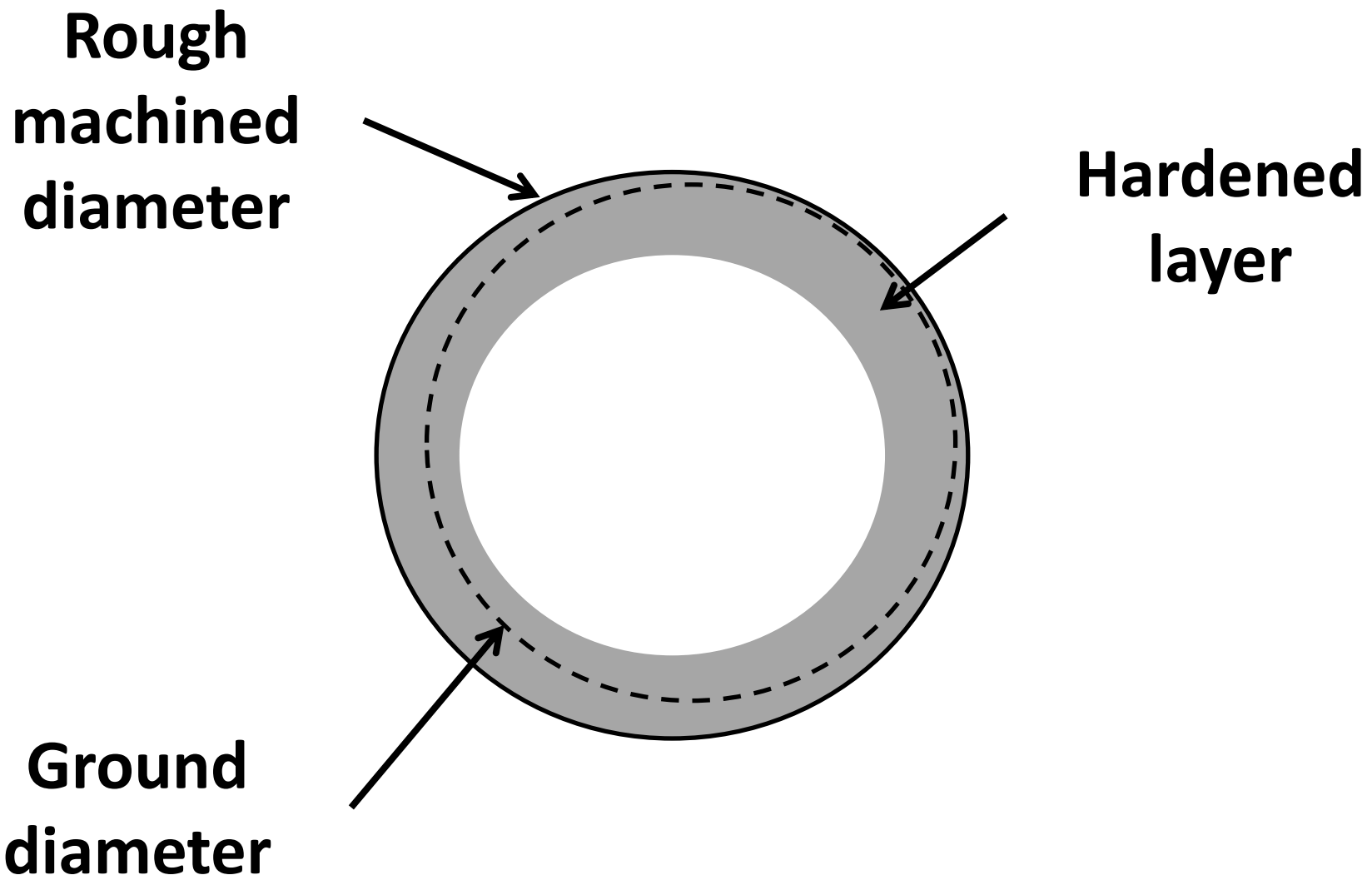
Lubrication: 0.3 mL/min TC-W3

Ball diameter: 0.500 in. (12.7 mm)

Ball material: AISI 52100



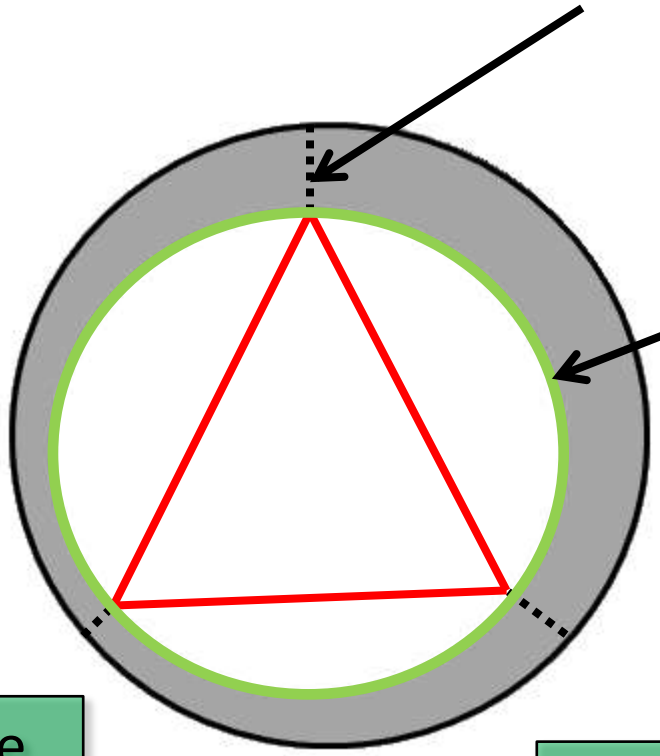
Case depth measurement



Case depth measurement

Vickers scale (500 g load)

Measurements made every .005” (.127 mm) beginning from surface



Eccentricity = distance from specimen axis to center of circumscribed circle

Average case depth = specimen radius – radius of circumscribed circle

Other measurements

Scanning electron microscopy

Hitachi S-3400

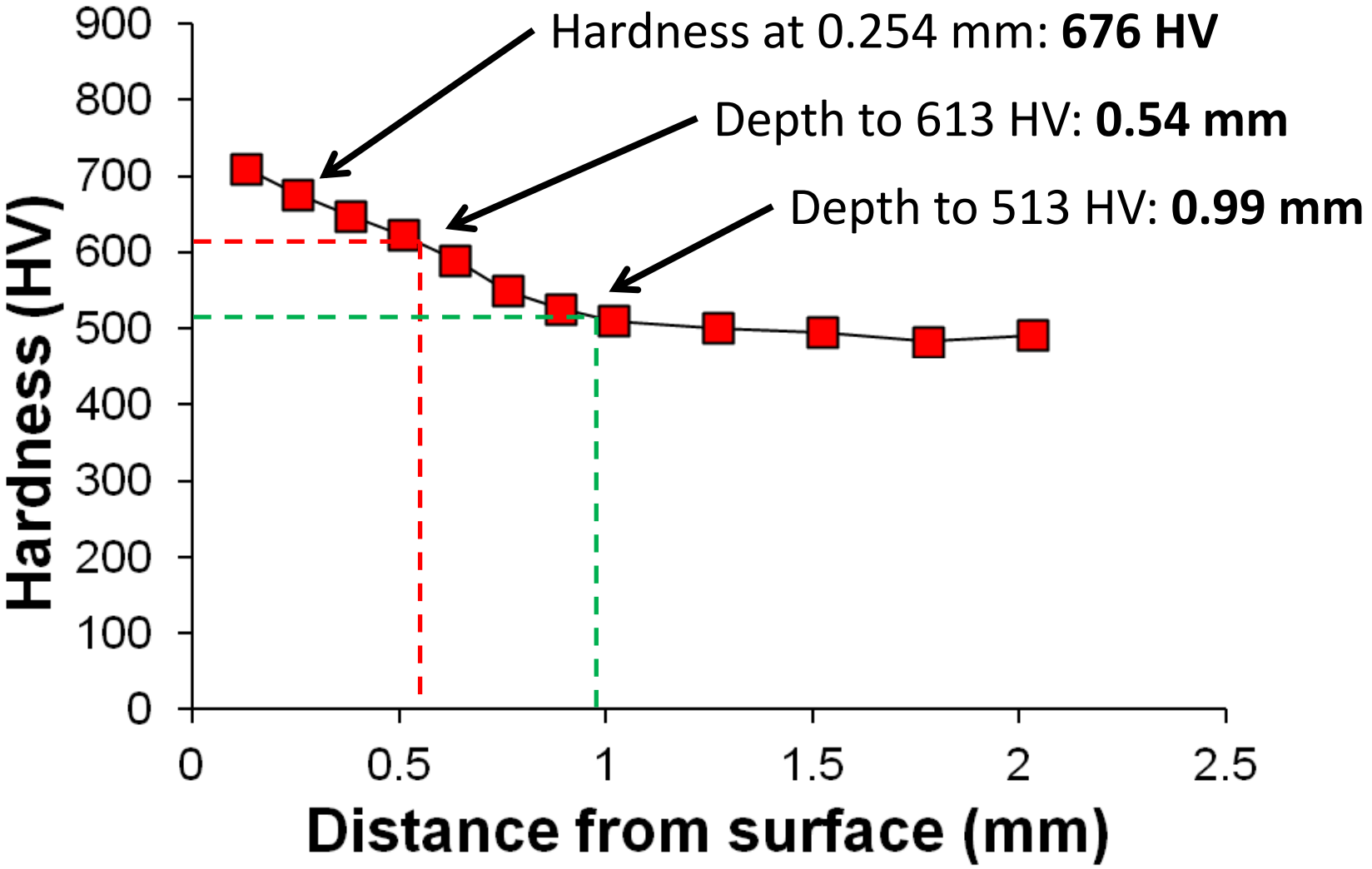
White light interferometry

ADE Phase Shift MicroXAM-100

Results and Discussion

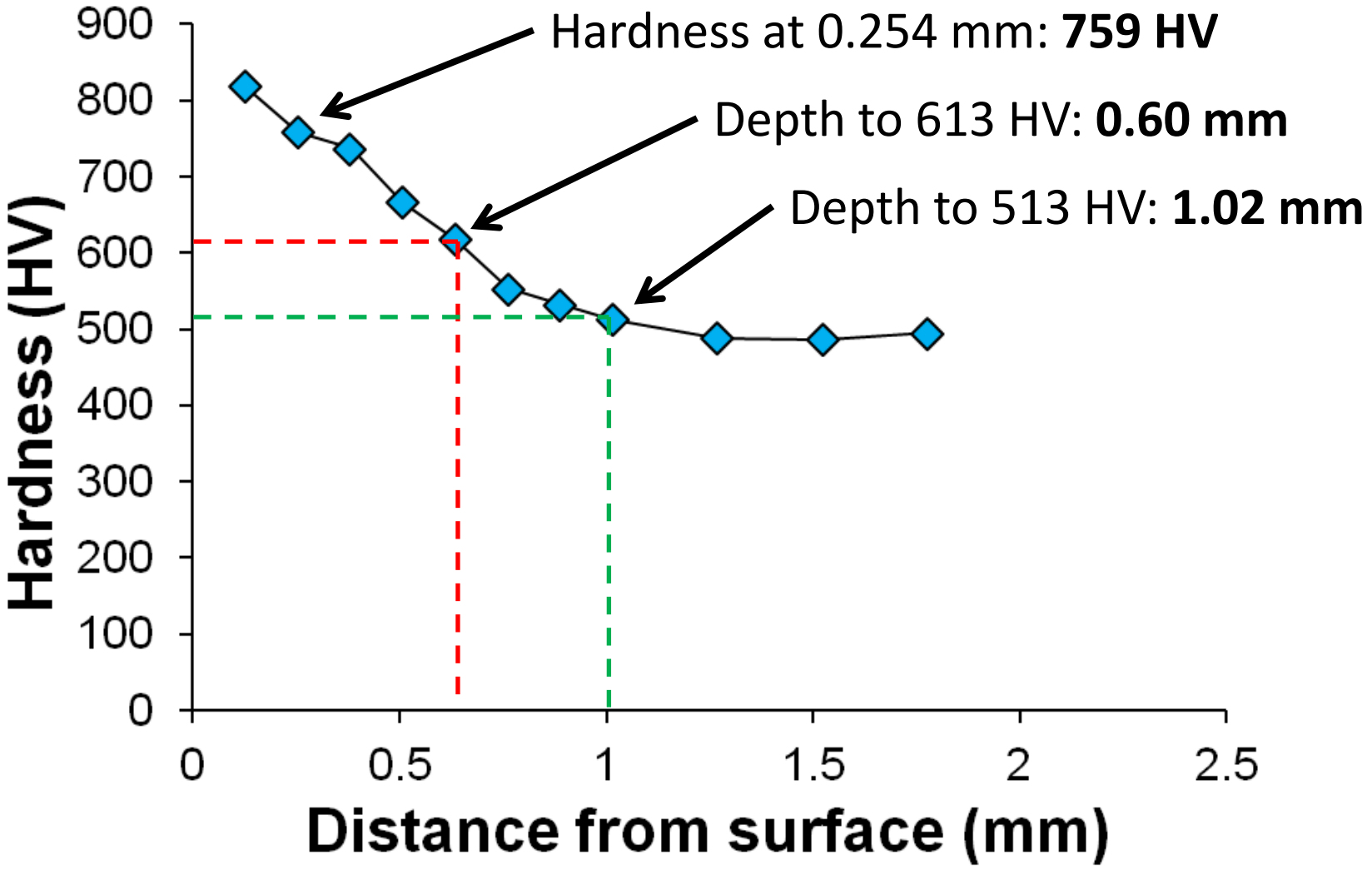
Microhardness profiles

AISI 8620 – Atmosphere carburized



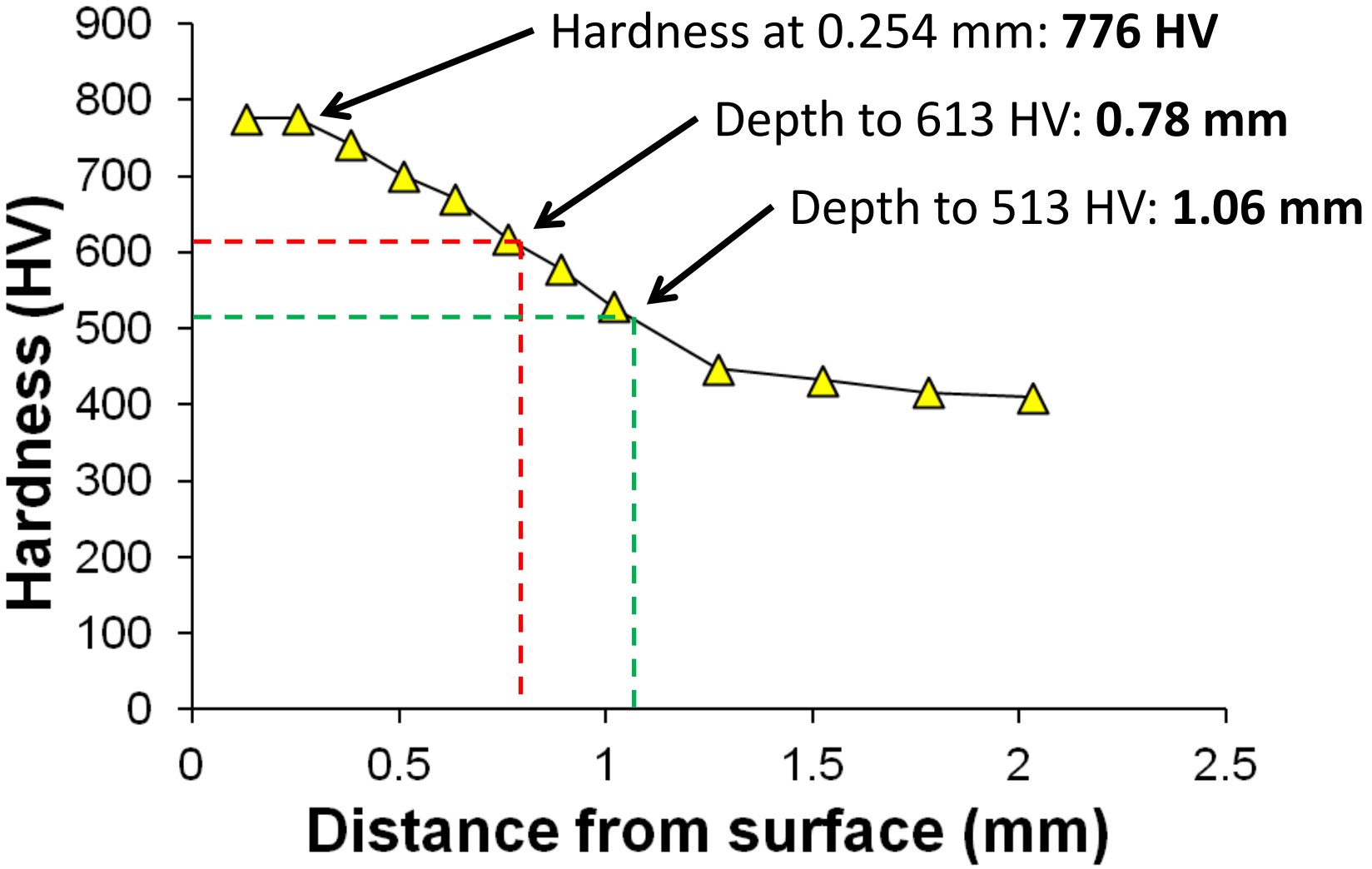
Microhardness profiles

AISI 8620 – Vacuum carburized



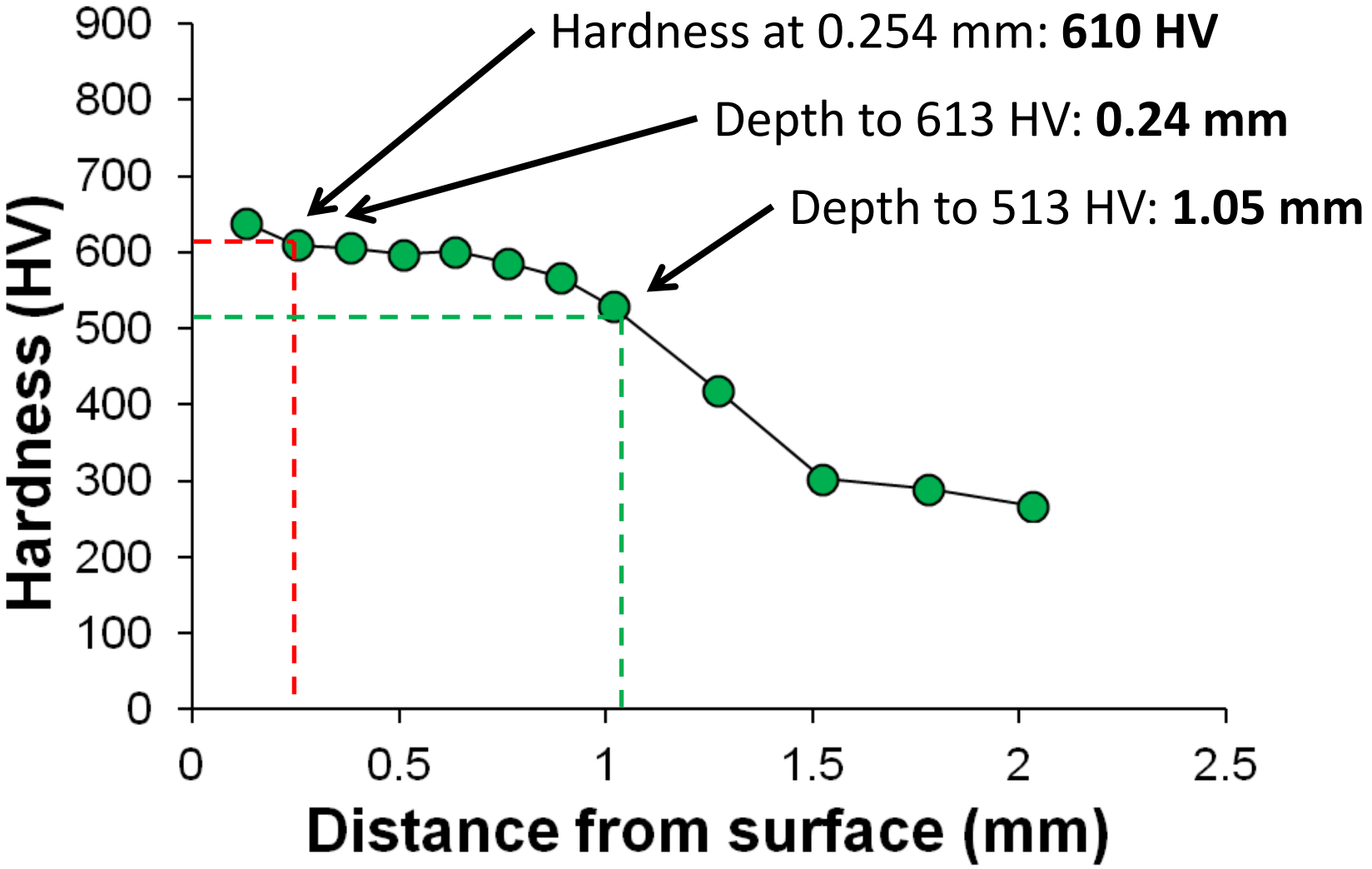
Microhardness profiles

AISI 9310 – Vacuum carburized

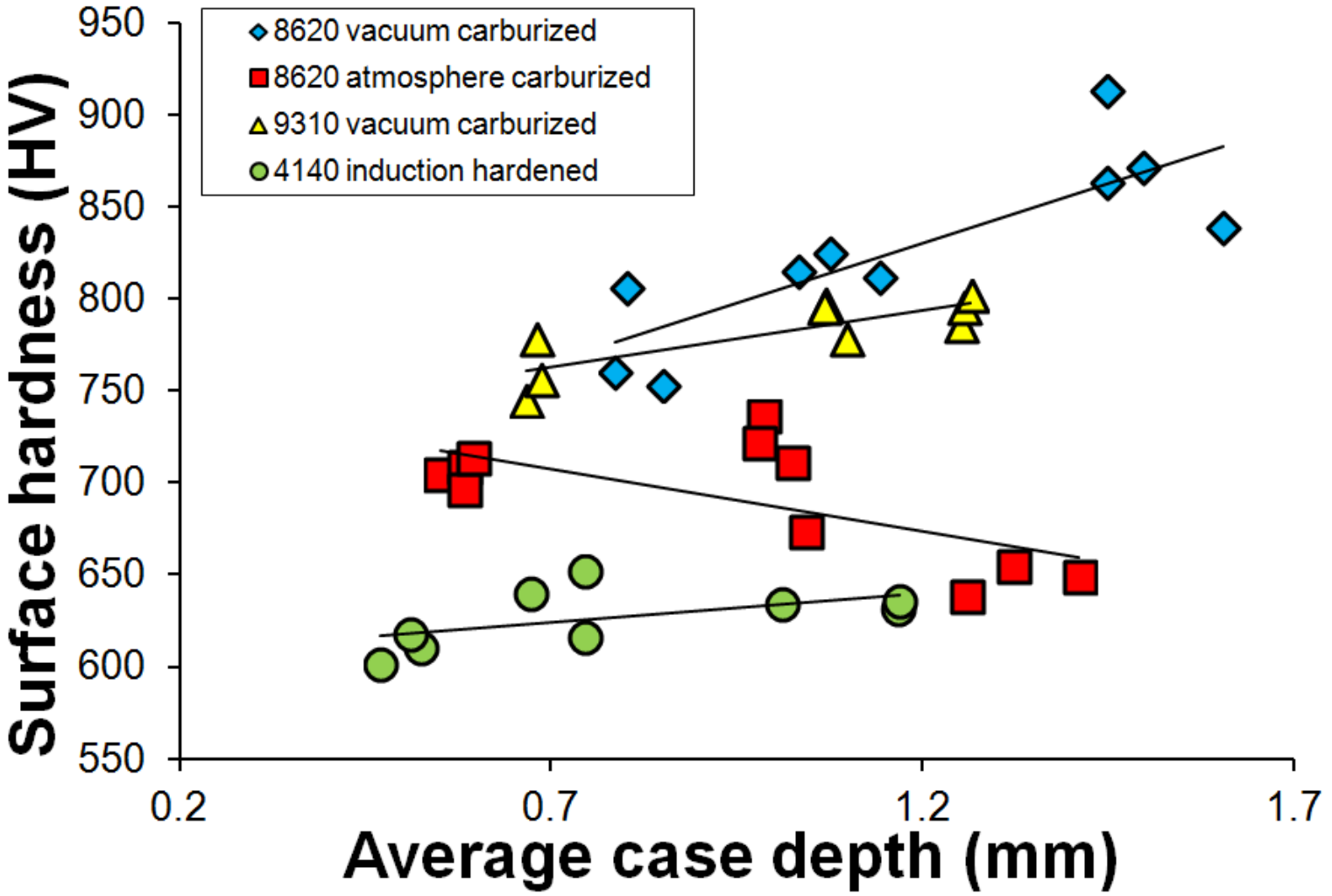


Microhardness profiles

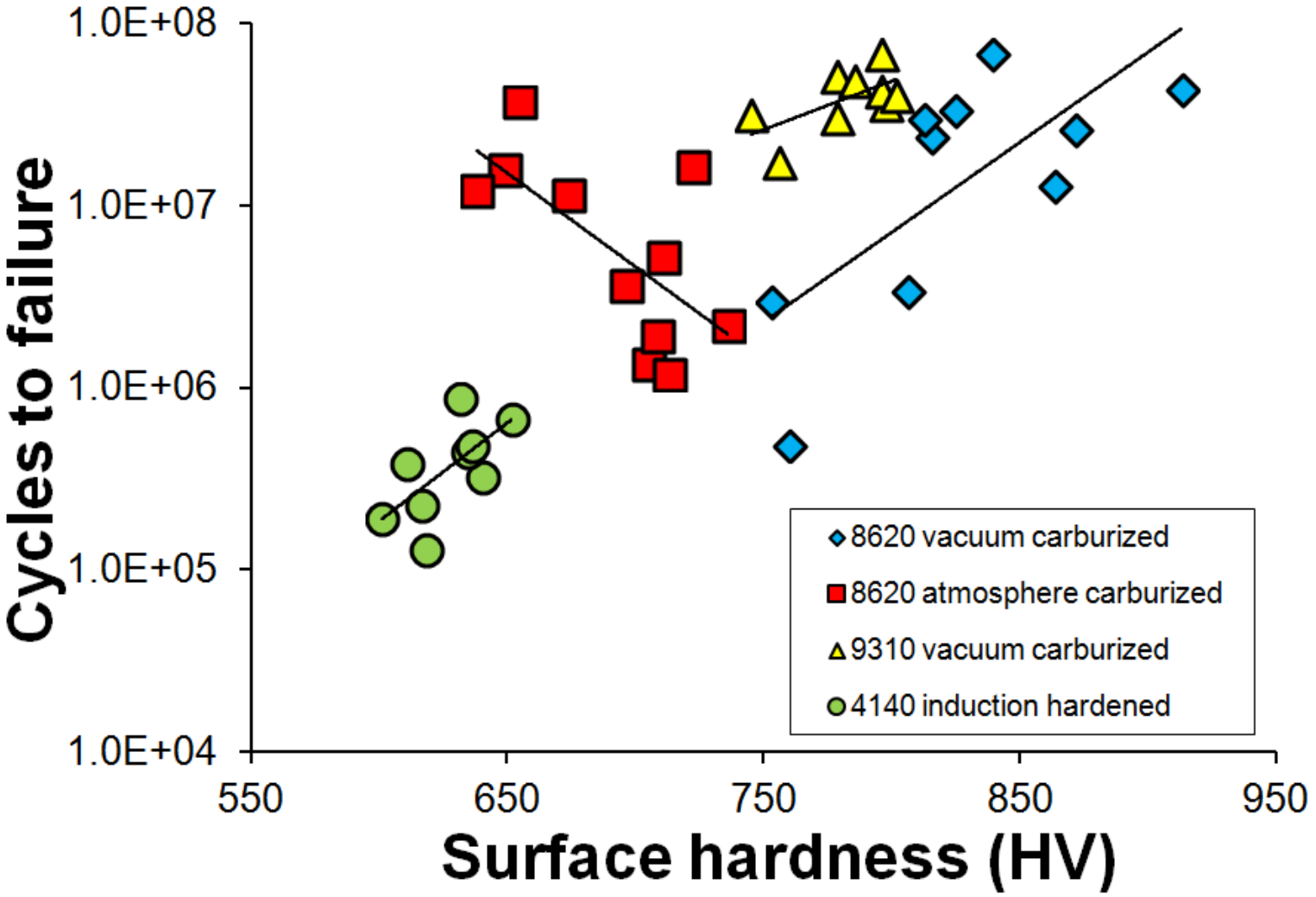
AISI 4140 – Induction hardened



Surface hardness vs. case depth

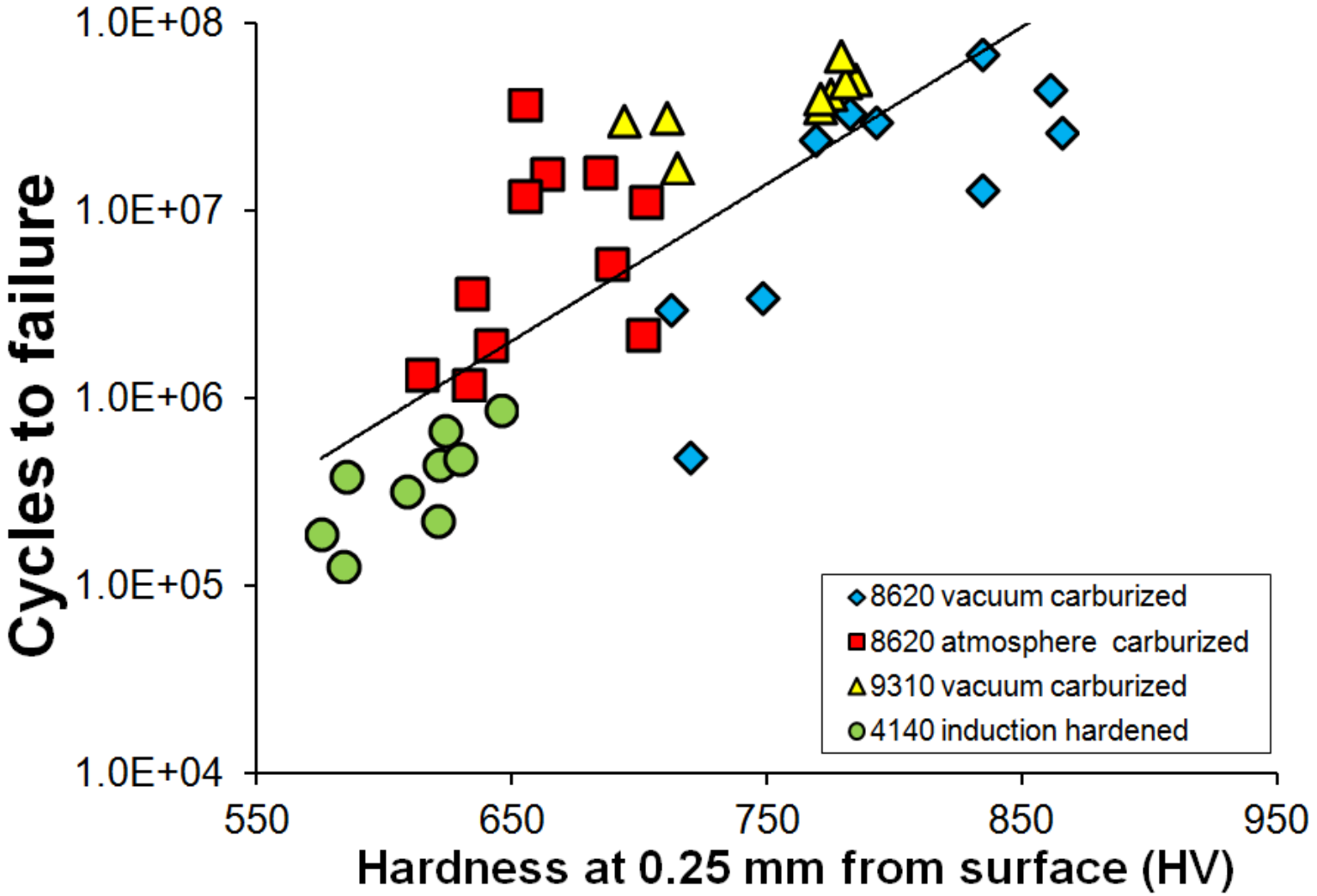


Cycles to failure vs. surface hardness

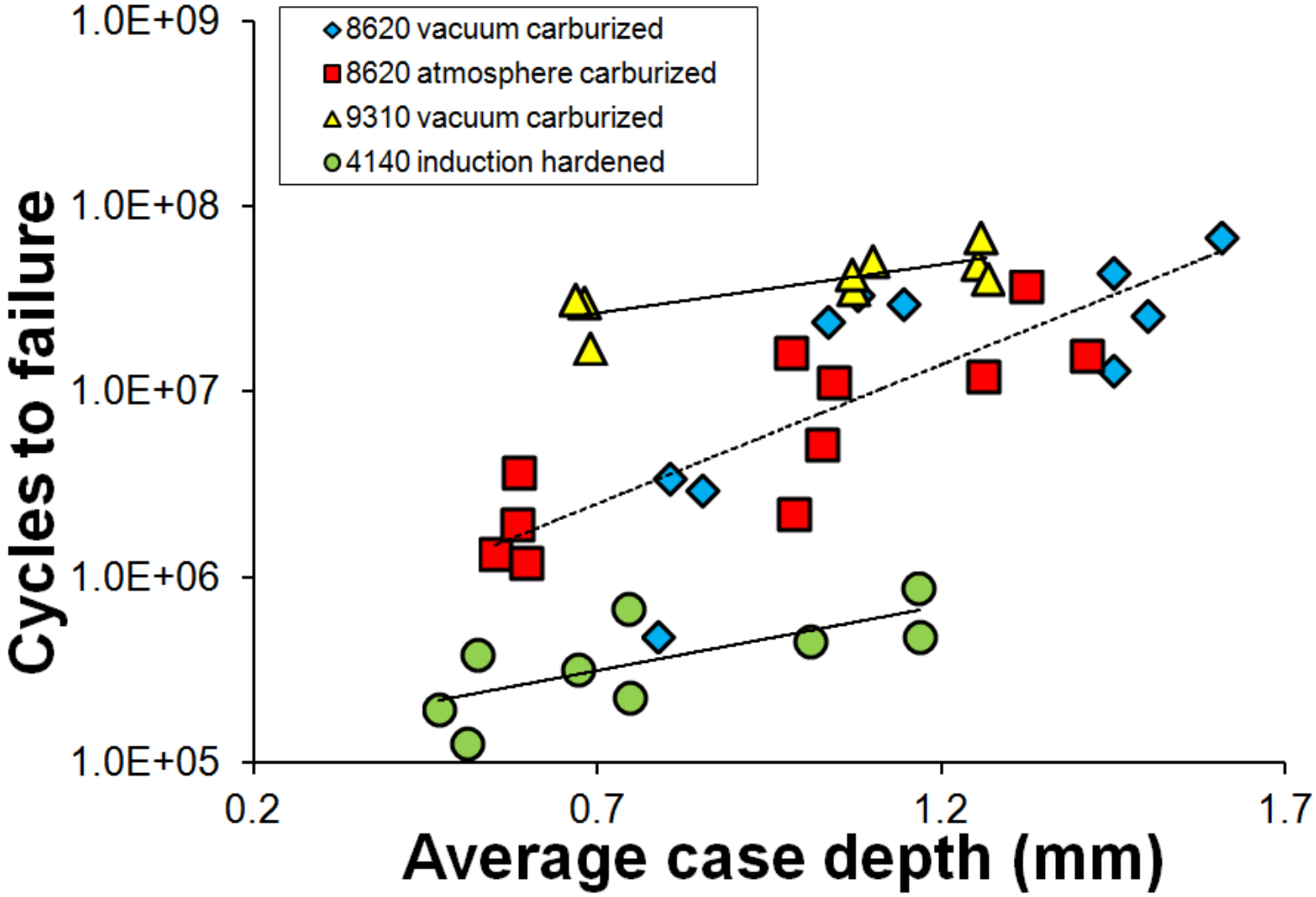


Surface hardness

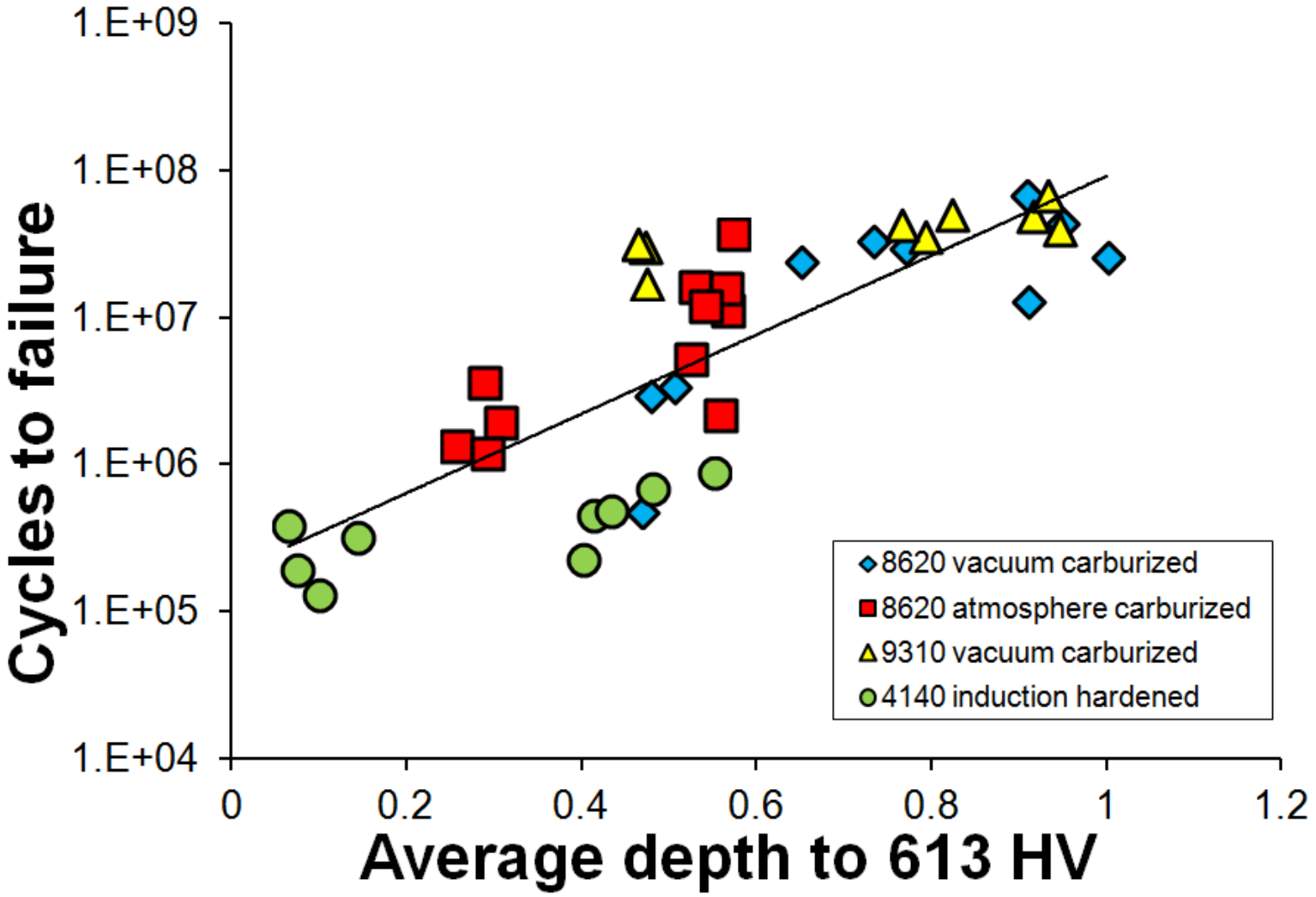
Cycles to failure vs. hardness at 0.254 mm



Cycles to failure vs. case depth



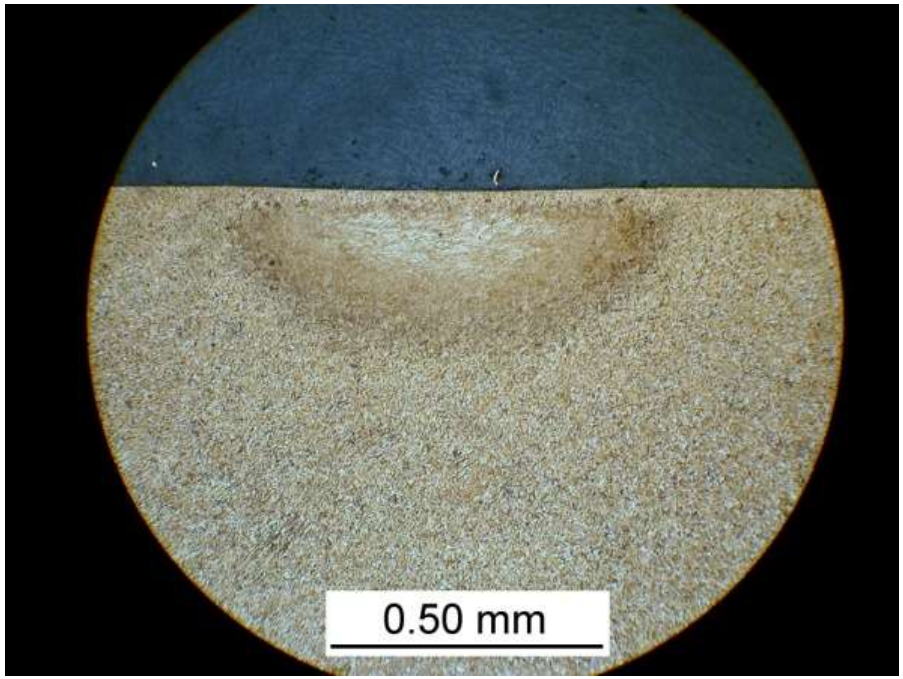
Cycles to failure vs. depth to 613 HV

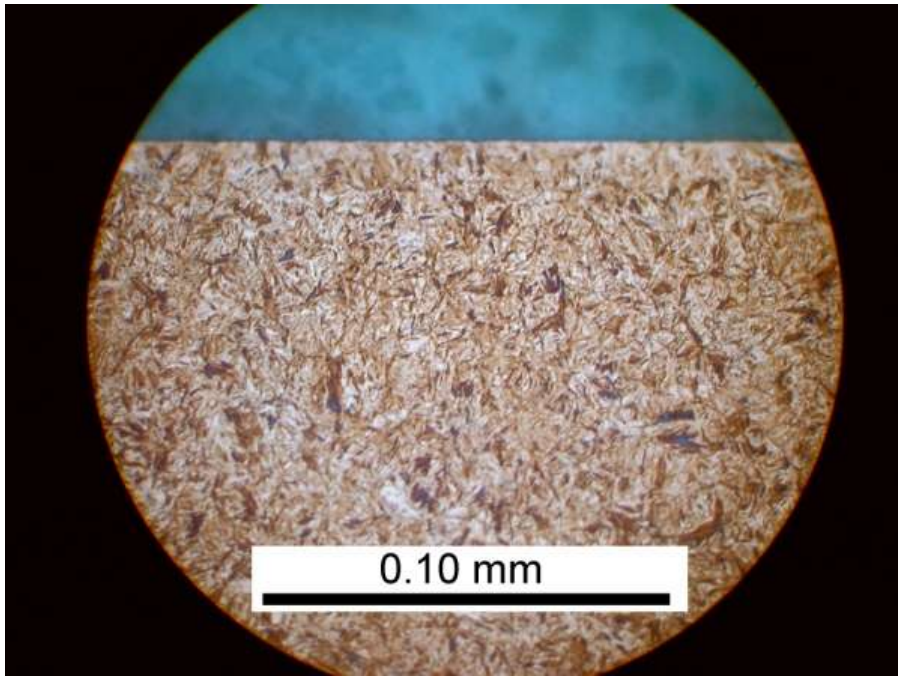


Average cycles to failure

Material	Surface treatment	Average life (cycles)	Average case depth (mm)	Eccentricity (mm)	Depth to 613 HV (mm)	Hardness at 0.254 mm (HV)
8620	vacuum	2,300,400	0.813	0.066	0.484	727
8620	vacuum	29,095,200	1.083	0.075	0.718	781
8620	vacuum	37,778,400	1.500	0.066	0.942	849
8620	atmosphere	2,049,300	0.578	0.067	0.287	630
8620	atmosphere	8,812,800	1.009	0.093	0.545	694
8620	atmosphere	21,772,800	1.332	0.141	0.560	657
9310	vacuum	26,568,000	0.677	0.030	0.470	706
9310	vacuum	43,372,800	1.078	0.033	0.793	776
9310	vacuum	52,401,600	1.257	0.027	0.931	776
4140	induction	237,600	0.502	0.041	0.080	581
4140	induction	410,400	0.720	0.060	0.342	618
4140	induction	604,800	1.115	0.086	0.465	632

AISI 8620 atmosphere carburized



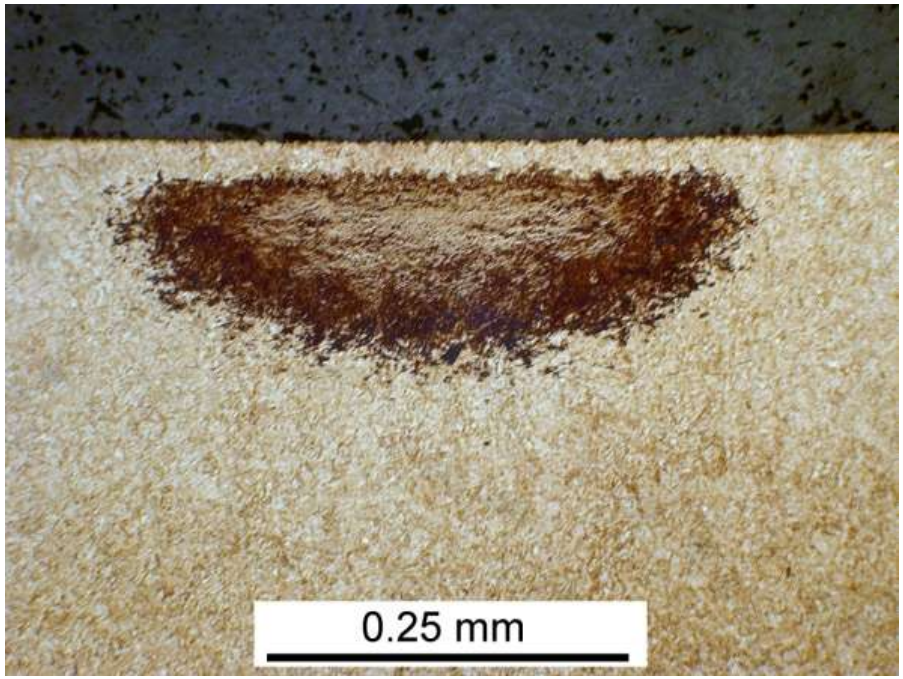


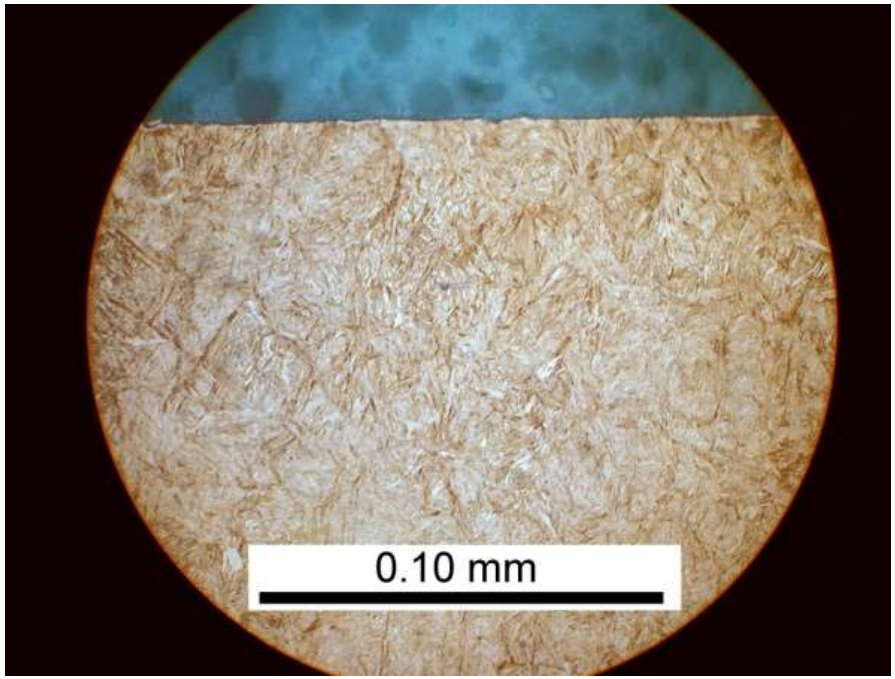
Case depth: **1.03 mm**

Cycles to failure: **5,248,880**

Dark etching area: **0.99 mm wide × 0.15 mm deep**

AISI 8620 vacuum carburized



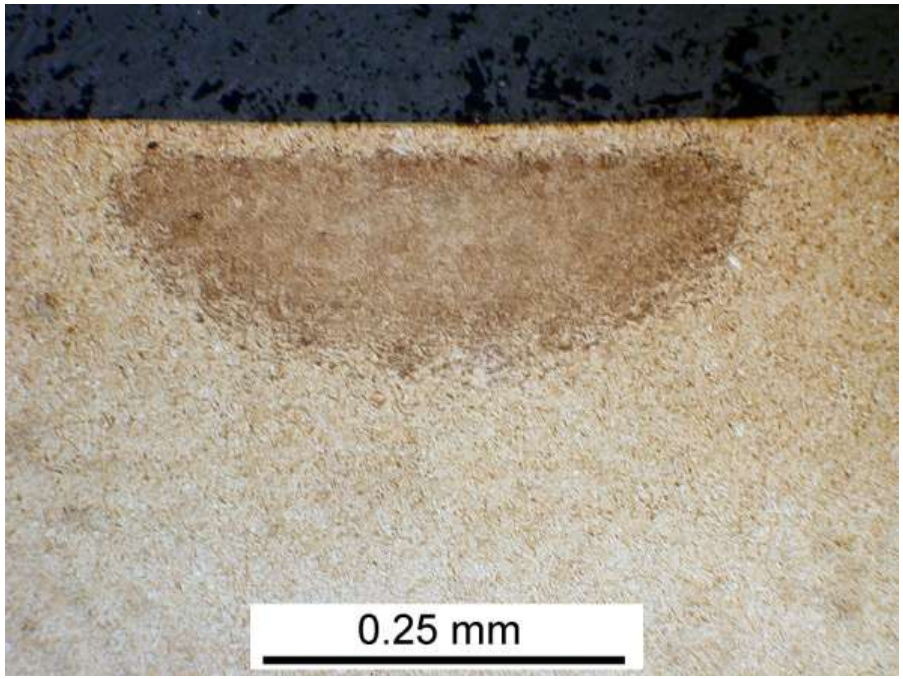


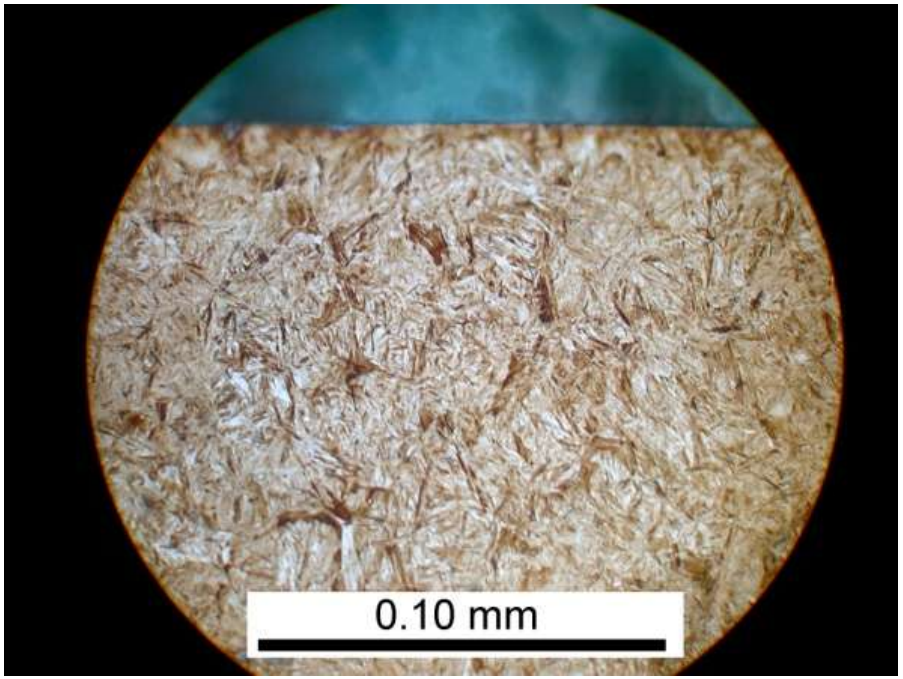
Case depth: **1.14 mm**

Cycles to failure: **29,872,800**

Dark etching area: **0.49 mm wide × 0.15 mm deep**

AISI 9310 vacuum carburized





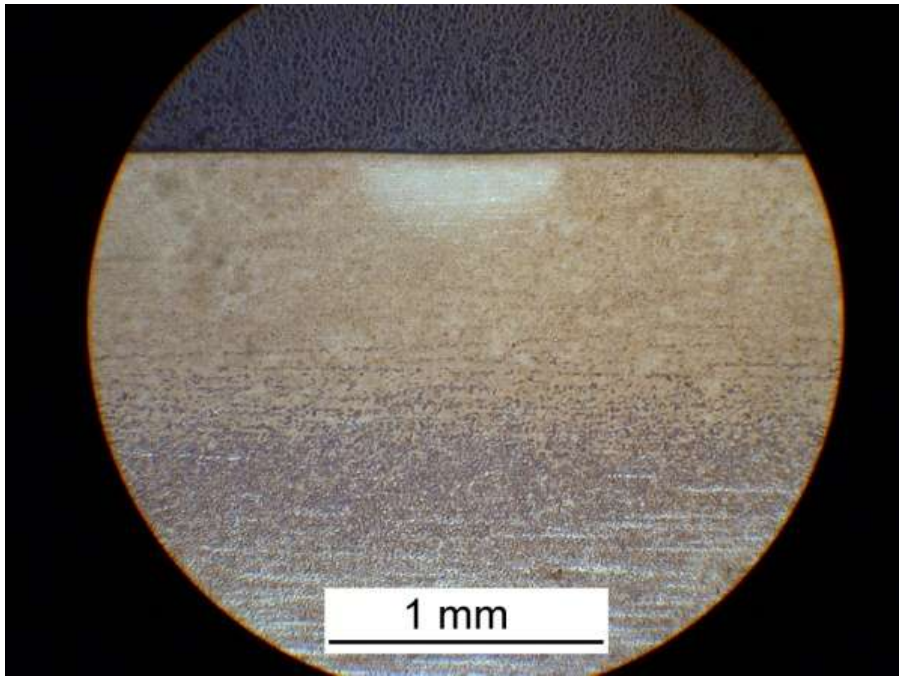
Case depth: **1.10 mm**

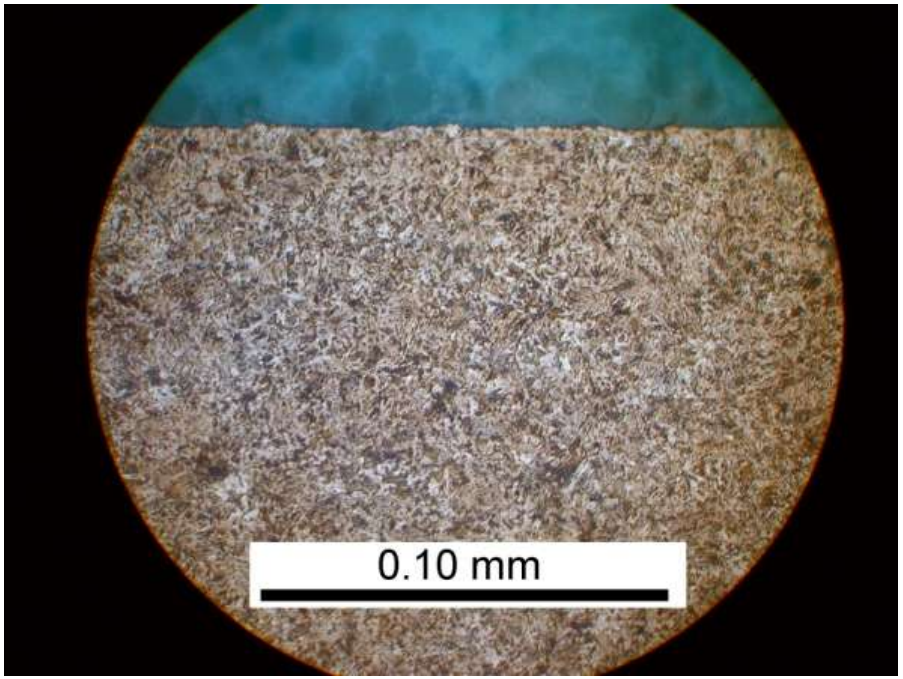
Cycles to failure: **51,256,800**

Dark etching area: **0.44 mm wide × 0.16 mm deep**

Metallography

AISI 4140 induction hardened



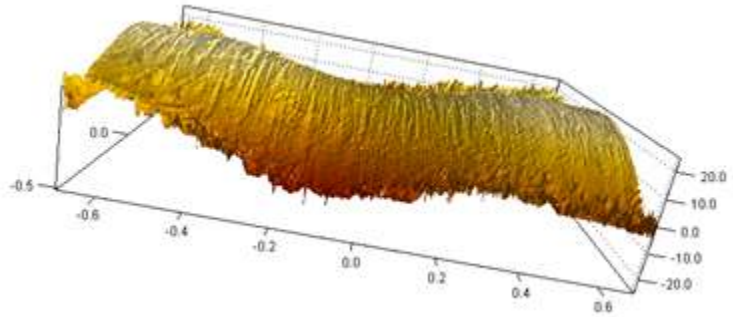


Case depth: **1.17 mm**

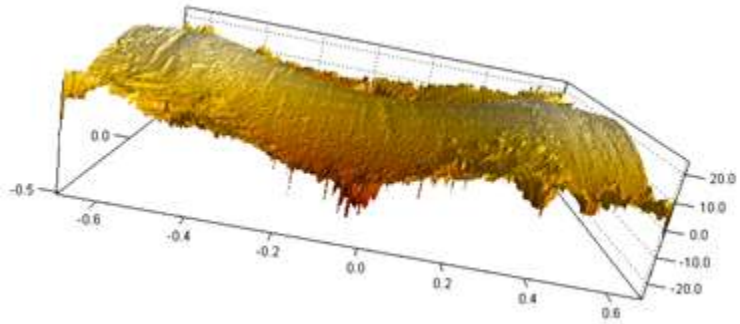
Cycles to failure: **874,800**

Dark etching area: **0.78 mm wide × 0.28 mm deep**

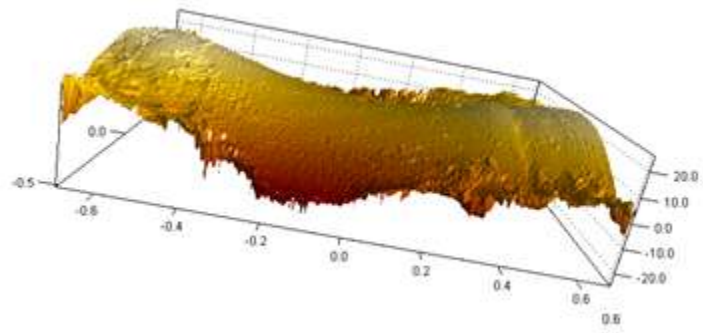
AISI 8620 atmosphere carburized



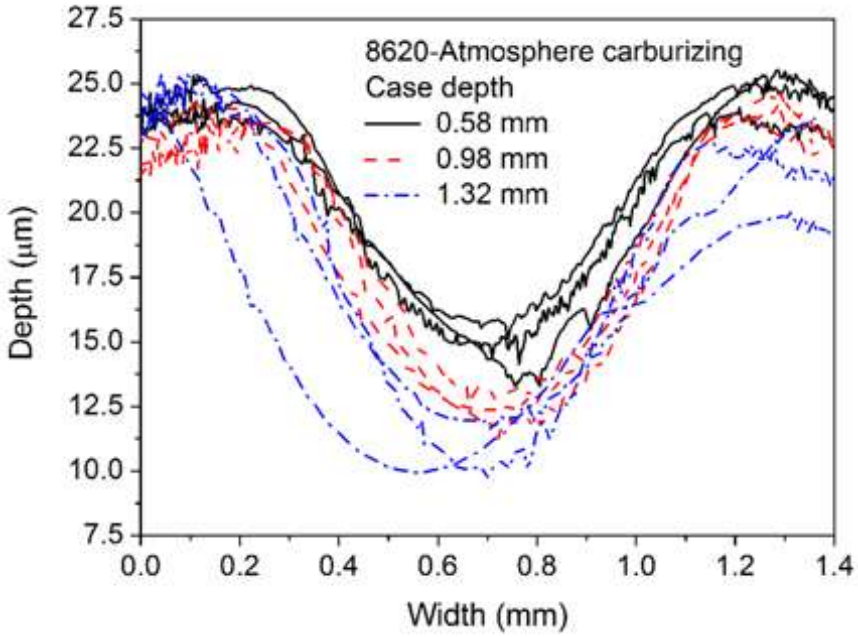
0.58 mm



0.98 mm

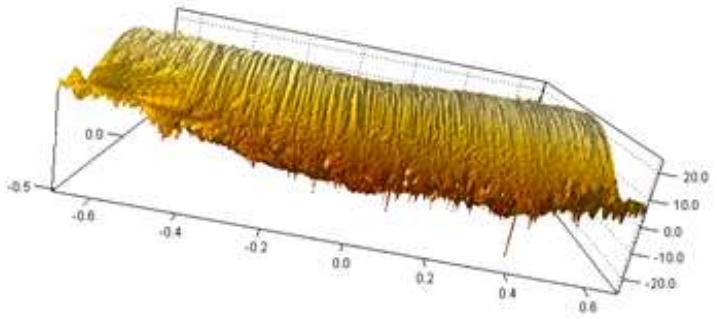


1.32 mm

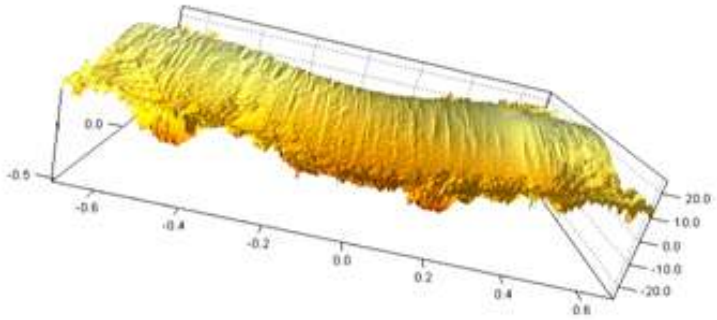


White-light interferometry

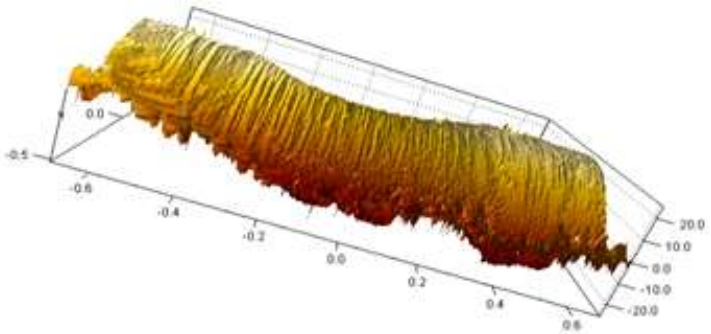
AISI 8620 vacuum carburized



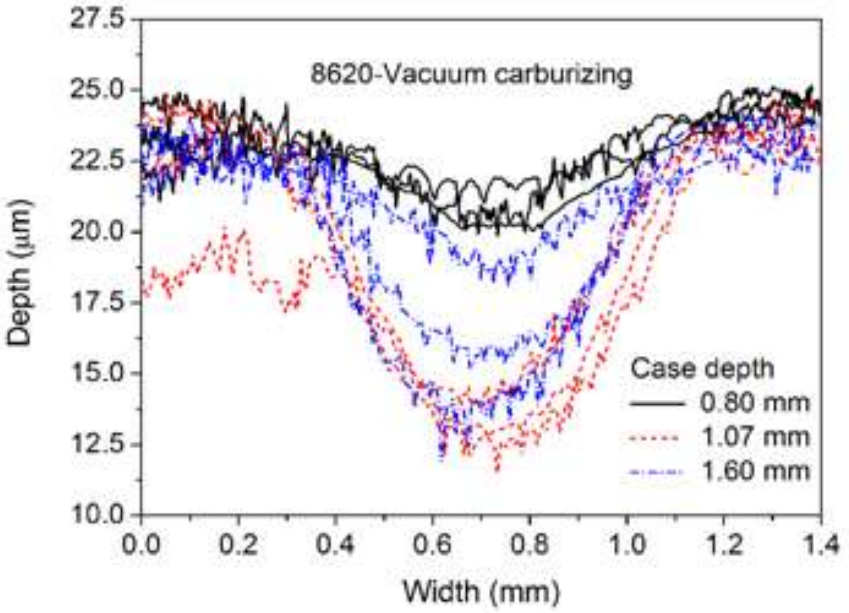
0.80 mm



1.07 mm

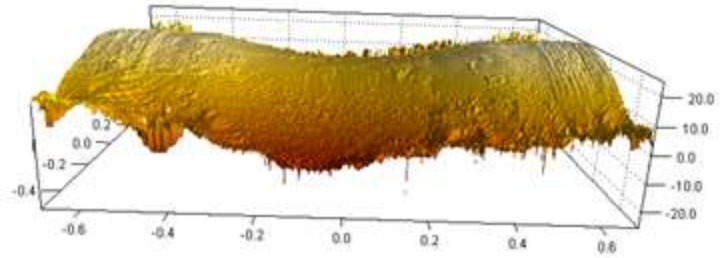


1.60 mm

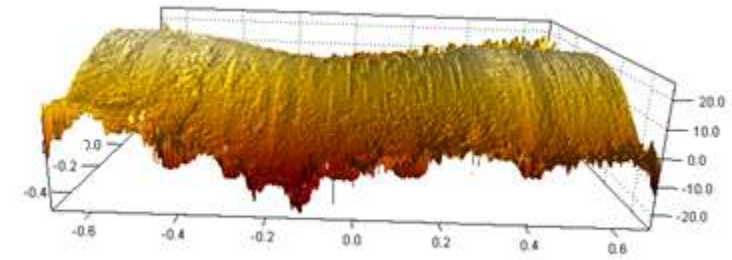


White-light interferometry

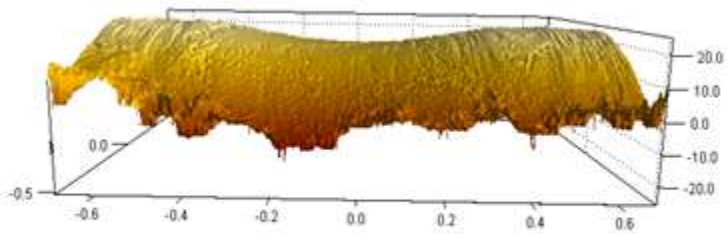
AISI 9310 vacuum carburized



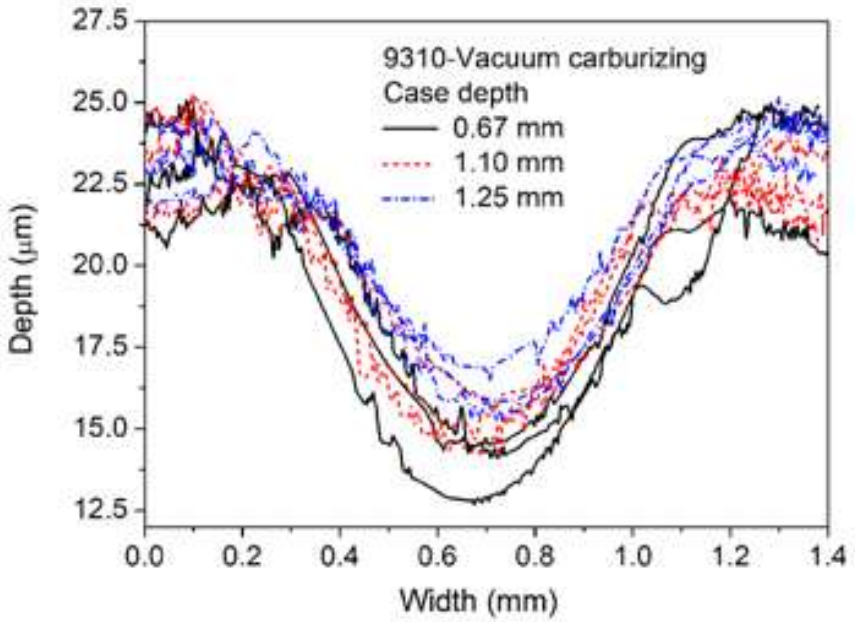
0.67 mm



1.10 mm

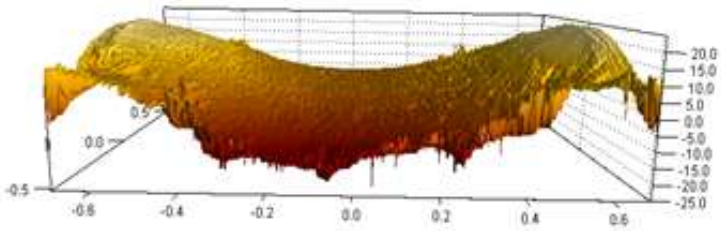


1.25 mm

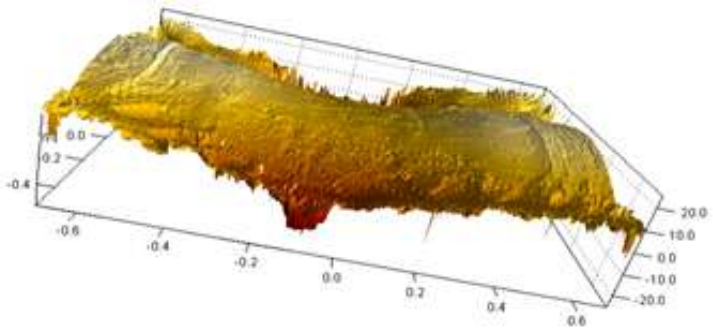


White-light interferometry

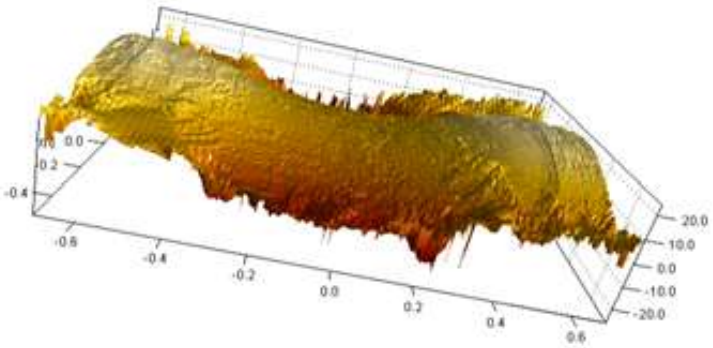
AISI 4140 induction hardened



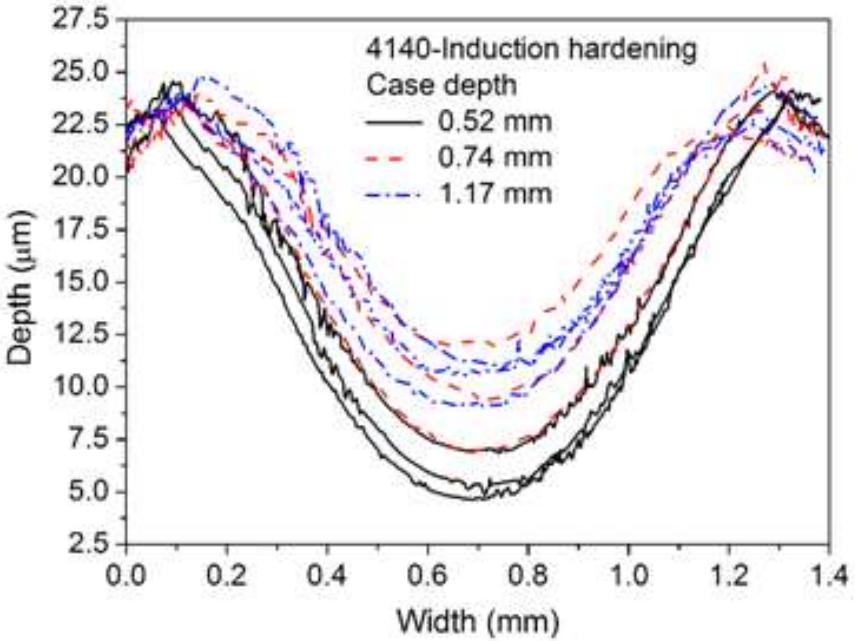
0.52 mm



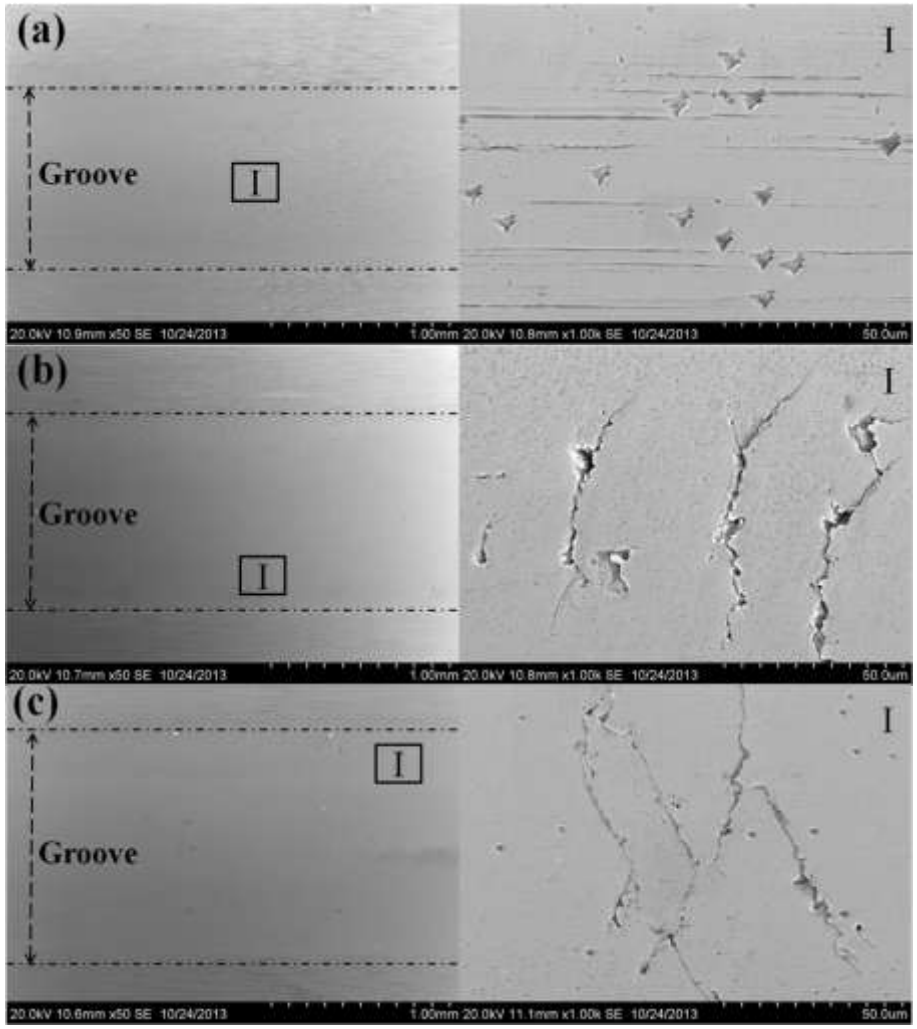
0.74 mm



1.17 mm



AISI 8620 atmosphere carburized

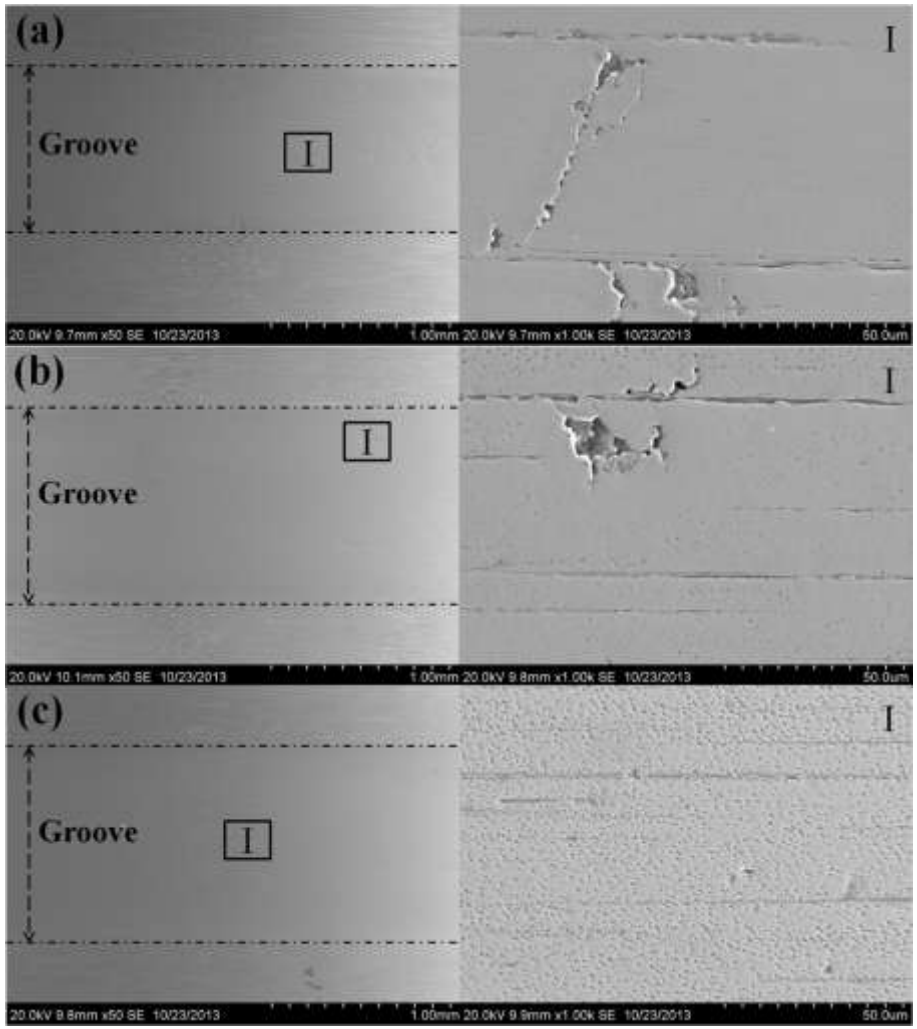


0.58 mm

0.98 mm

1.32 mm

AISI 8620 vacuum carburized



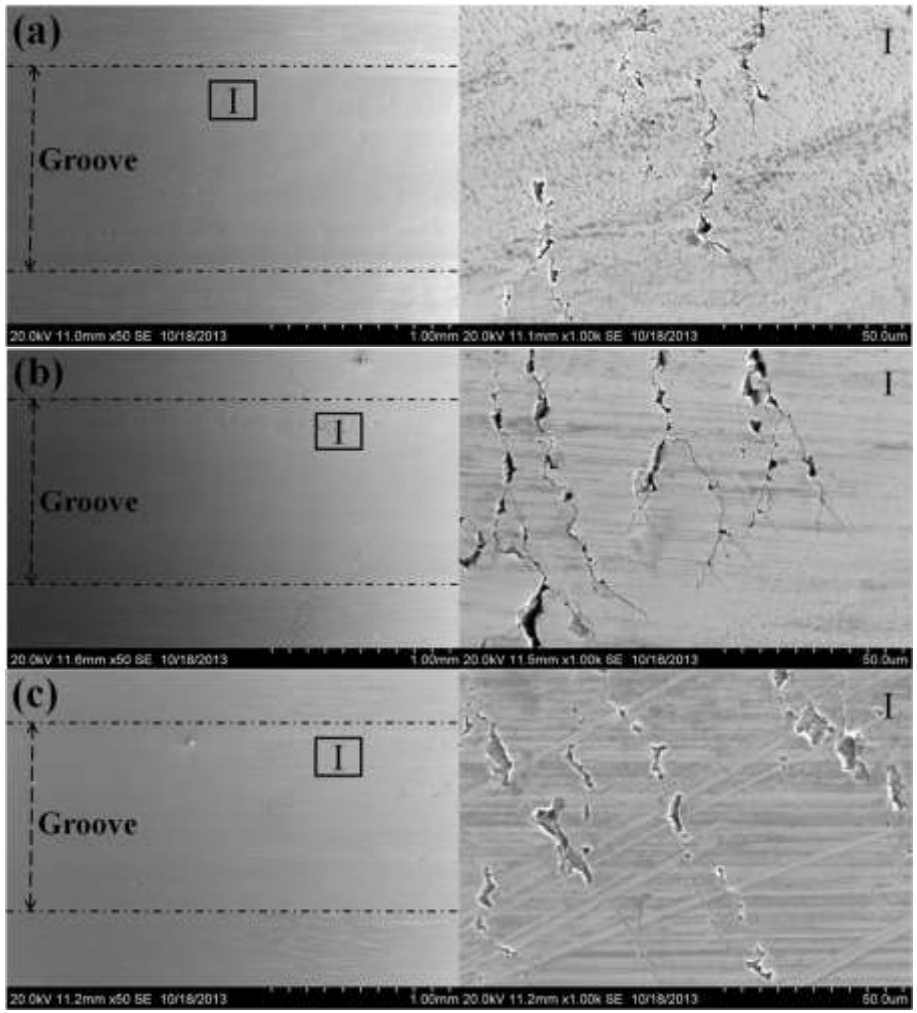
0.80 mm

1.07 mm

1.60 mm

Scanning electron microscopy

AISI 9310 vacuum carburized

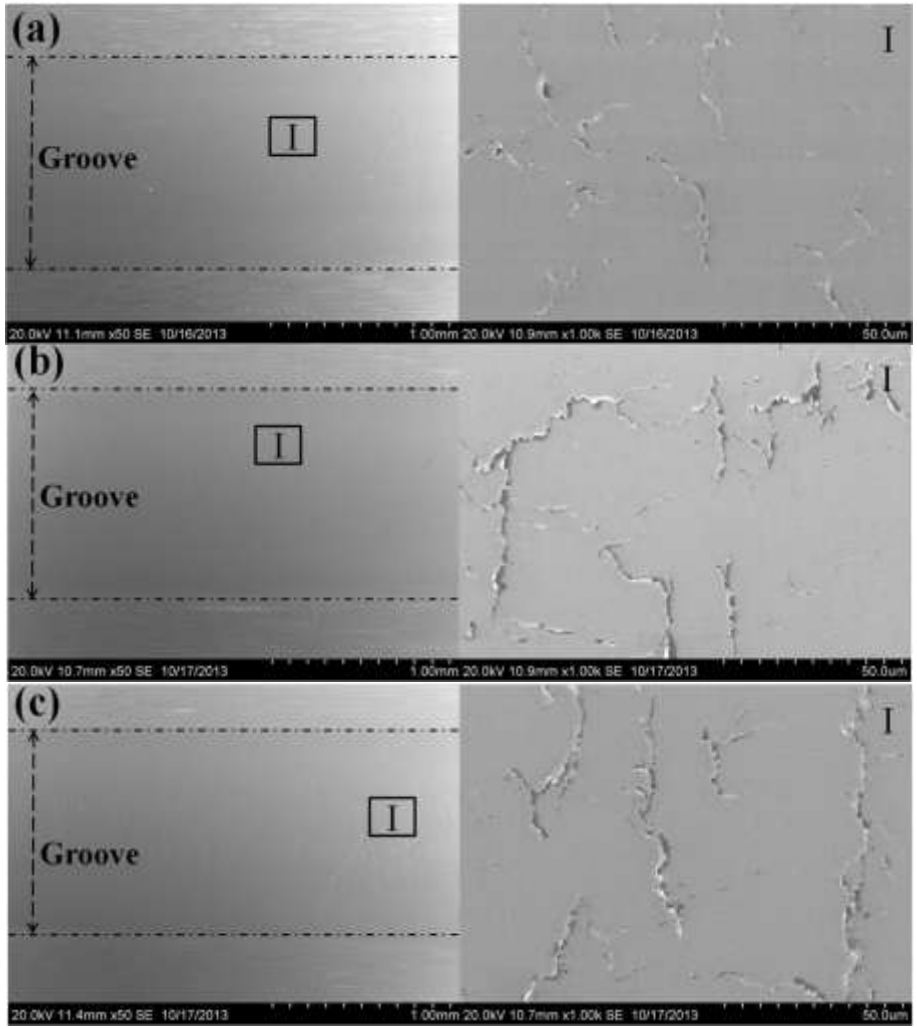


0.67 mm

1.10 mm

1.25 mm

AISI 4140 induction hardened



0.52 mm

0.74 mm

1.17 mm

Conclusions

Conclusions

- **Longest RCF lives:** vacuum carburized AISI 8620 and 9310
- **Shortest RCF lives:** induction hardened AISI 4140

- Vacuum carburizing provided the greatest **depth of high hardness (>613 HV)** at the same case depth.

- The **depth of high hardness** provided a better correlation to RCF life than the traditional definition of effective case depth.

Conclusions

- **Lowest case eccentricity:** vacuum carburized and gas quenched AISI 9310
- **Highest case eccentricity:** atmosphere carburized and oil quenched AISI 8620

- Eccentricity is a means of measuring uniformity of case depth, and an indirect measure of distortion.

- By minimizing distortion, the required grind stock can be reduced, potentially resulting in even greater improvements to RCF life.

Conclusions

- Based on SEM observation, with the exception of the vacuum carburized AISI 8620, **surface damage increased with increasing case depth.**

- For the vacuum carburized AISI 8620, **surface damage decreased with increasing case depth.**

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