SAE paper 2020-01-0179 Axle weight savings 40% Major discussion points

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- Chief researchers: **Michael Bujold, Ralph Larson, Edward Punch, and Magna ERT Team**
- Discussion: Methods used to produce 40% weight reduction in axle application
- Target major component weights (ring assembly, pinion assembly, differential, housing-aluminum & magnesium, bearings, stress analysis, deflection analysis, assembly-pinion cartridge…)
- Fracture mechanics based stress and life analysis has been used to further optimize size and life of primary gearing with steel cleanliness and processing (shot peening).
- Manufacture of primary gearing made from clean and standard steels to verify design and life predictions.
- This design has been implemented in various vehicles excellent performance, durability, and noise.
- Legacy axle weight: 20.55 kg.
  Ultralight axle weight: 12.326kg
- Although very important in life of gearing oil additives and surface treatments are not included in this paper.

Date

Footer

Axle weight savings

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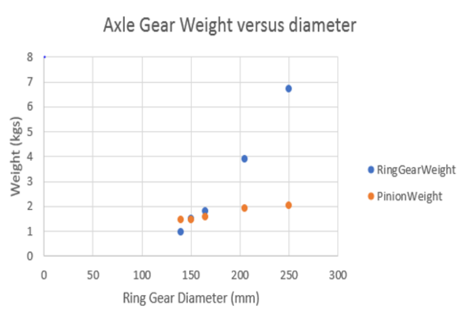
- This emphasizes the ring gear assembly as a primary area to target for weight reduction
- 250mm ring gear diameter 14.8lbs, pinion 4.5lbs, total19.3lbs
- 205mm ring gear diameter 8.6lbs, pinion 4.2lbs, total 12.8lbs
- 165mm ring gear 4.0lbs, pinion 3.5lbs, total 7.5lbs
- 150mm ring gear 3.3lbs, pinion 3.2lbs, total 6.5lbs
- 140mm ring gear 2.1lbs, pinion 4.2lbs, total 6.3lbs



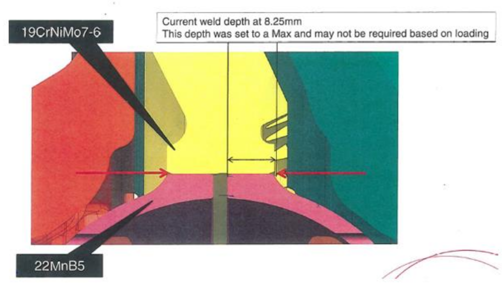
Axle weight reduction-components, pinion assembly

- Legacy pinion+bearings assembly weight: 2.2 kg.,Ultralight pinion+bearings assembly weight: 1.3 kg.

- Hollow pinion design
- Larger diameter bearing diameters for additional stiffness of pinion assemble, also angular contact bearings reduced friction for enhanced efficiency on high speed shaft
- Welded assembly allowed precise preload of bearings
- Cartridge design allows fine adjustment contact pattern for pinion to ring with threaded assembly

Axle weight reduction-components, ring and differential assembly

- Legacy ring assembly weight: 5.2 kg. Ultralight ring assembly weight: 3.42 kg.



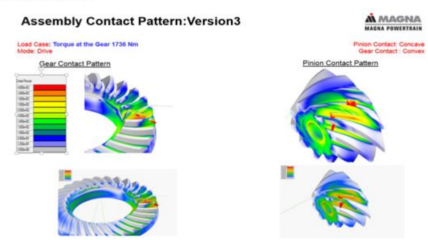
- Major areas targeted were ring size through stress analysis and fracture mechanics methods
- Reduce weight of differential housing used high strength light weight steel which replaced standard heavier cast iron, and weight reduction holes

Axle weight reduction-components, housing assembly

- Legacy housing weight: 7.3 kg. Ultralight housing Aluminum weight: 3.63kg
- Legacy housing Magnesium weight: No data kg. Ultralight housing Magnesium weight: 2.336kg
- Shrink wrap housing around ring pinion assemblies and add ribs for stiffening where required to minimum deflections (EPG&Alpha).

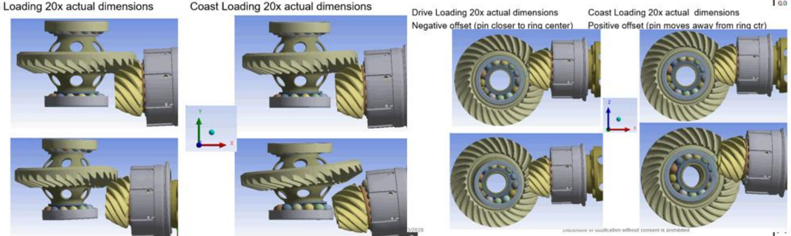
Ultralight axle development-software packages used to optimize stresses and deflections

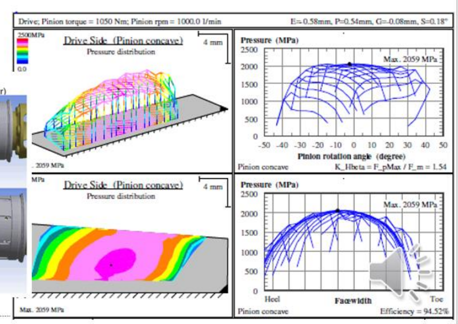
- Begin with Minors rule, cycles at load, and Stress vs Life predictions
- Determine system deflection through FEA: E,P,G, & Alpha
- Stress analysis: Gleason Cage, Klingelnburg, and Trans 3D
- Fine tune analysis with Crack Growth clean steel analysis



Drive Loading 20x actual dimensions Coast Loading 20x actual dimensions

Drive Loading 20x actual dimensions Negative offset (pin closer to ring center) Coast Loading 20x actual dimensions Positive offset (pin moves away from ring ctr)





Fracture Mechanics-life tests and clean steel modeling

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- A result of Thor's hammer, or a simple crack growth issue

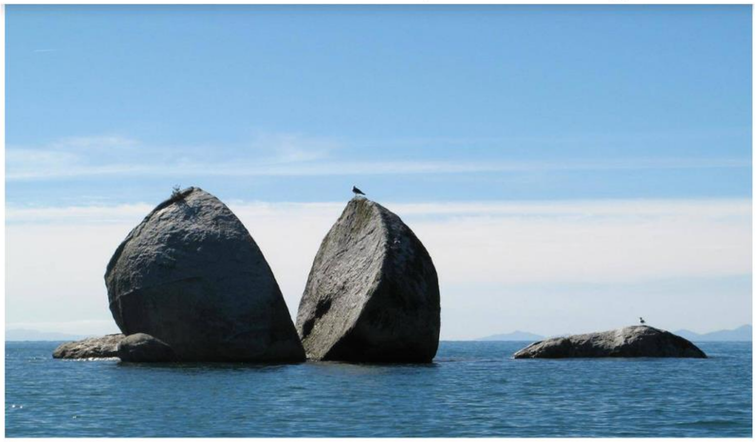

Photo credit: Imgur

The split is a result of a naturally occurring "joint" in the granite rock. The joints are weak spots in the granite that, over thousands of years, the waves and wind can erode.

Fracture Mechanics-life tests and clean steel modeling

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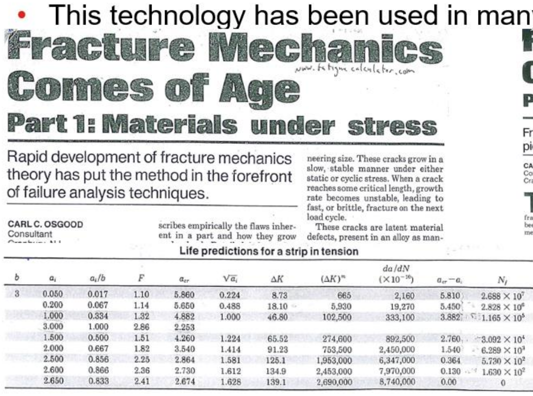
- Two sets of gears were manufactured: **The first set were made from a clean steel and all bending and contact fatigues were passed**. A second set of gears were made from standard steel and **failed initial bending and contact fatigue tests until additional processing was added in the form of shot peening and other processing**,
- The fracture mechanics approach takes an initial flaw size and a stress field and determines the amount of growth per cycle
- This technology has been used in many applications: Airline, ships, bridges,…



Fracture Mechanics Comes of Age

Part 1: Materials under stress

Rapid development of fracture mechanics theory has put the method in the forefront of failure analysis techniques.

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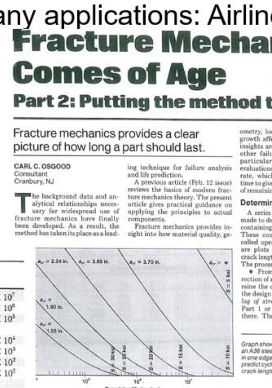
scribes empirically the flaws inherent in a part and how they grow

neering size. These cracks grow in a slow, stable manner under either static or cyclic stress. When a crack reaches some critical length, growth rate becomes unstable, leading to fast, or brittle, fracture on the next load cycle.

These cracks are latent material defects, present in an alloy as man-

Life predictions for a strip in tension

b	a_i	a_i/b	F	a_{cr}	$\sqrt{a_i}$	ΔK	$(\Delta K)^m$	da/dN $(\times 10^{-10})$	$a_{cr}-a_i$	N_f
3	0.050	0.017	1.10	5.860	0.224	8.73	665	2,160	5.810	2.688×10^7
	0.200	0.067	1.14	5.650	0.488	18.10	5,930	19,270	5.450	2.828×10^6
	1.000	0.334	1.32	4.882	1.000	46.80	102,500	333,100	3.882	1.165×10^5
	3.000	1.000	2.86	2.253						
	1.500	0.500	1.51	4.260	1.224	65.52	274,600	892,500	2.760	3.092×10^4
	2.000	0.667	1.82	3.540	1.414	91.23	753,500	2,450,000	1.540	6.289×10^3
	2.500	0.856	2.25	2.864	1.581	125.1	1,953,000	6,347,000	0.364	5.730×10^2
	2.600	0.866	2.36	2.730	1.612	134.9	2,453,000	7,970,000	0.130	1.630×10^2
	2.650	0.833	2.41	2.674	1.628	139.1	2,690,000	8,740,000	0.00	0



Fracture Mechanics Comes of Age

Part 2: Putting the method t

Fracture mechanics provides a clear picture of how long a part should last.

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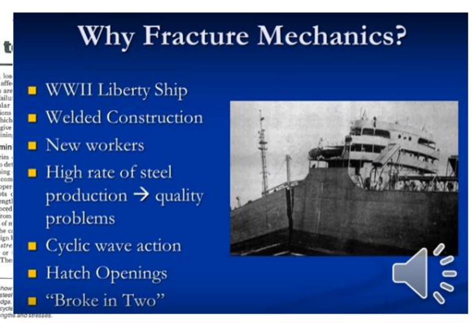
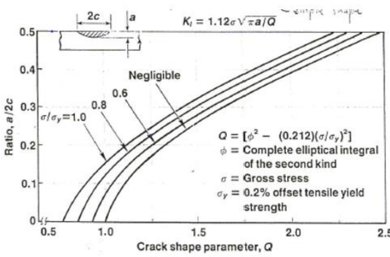
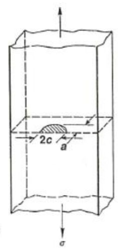


Fracture mechanics-Clean steel gear bending life predictions

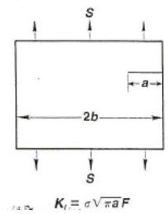
- Gear bending approach begins will half-penny shaped edge crack and then transfers to finite width edge crack at larger crack sizes. The associated form factors are determined for each case.
- Deeper flaw analysis uses a embedded crack solution and associated form factors.

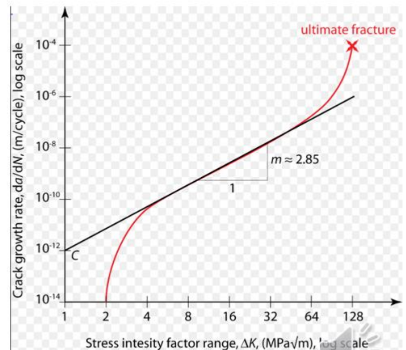




Case 3 — Finite-width plate with single-edge notch

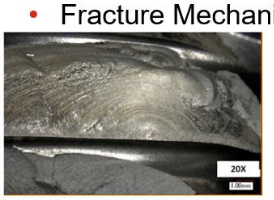
Ratio a/b	Form factor
0.10	1.15
0.20	1.20
0.30	1.29
0.40	1.37
0.50	1.51
0.60	1.68
0.70	1.89
0.80	2.14
0.90	2.46
1.00	2.86





Fracture Mechanics equations and modeling

- Fracture Mechanics stress and life prediction-Bending Stress and Life Analysis



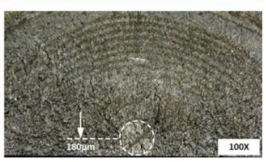


Fig 1: Material flaw measured in post test pinion.

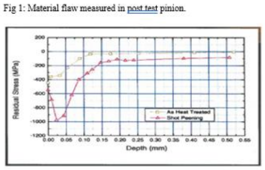
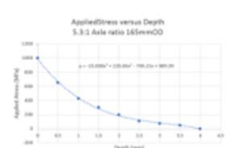


Fig 2: Residual stress for as heat treated and shot peened processes



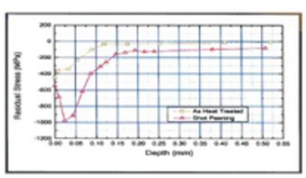


Fig 4: Applied Stress versus residual stress

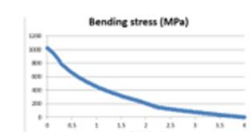


Fig. 3.4 Variation of root bending stress with depth into tooth

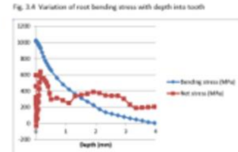


Fig. 3.5 Net stress (cyclic bending + shot peen), showing tension almost everywhere (i.e. crack growth is possible everywhere except at 0.01778 mm depth. Cracks are grown by the cyclic stress but only where the net stress is tensile.)

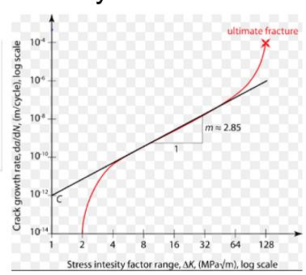


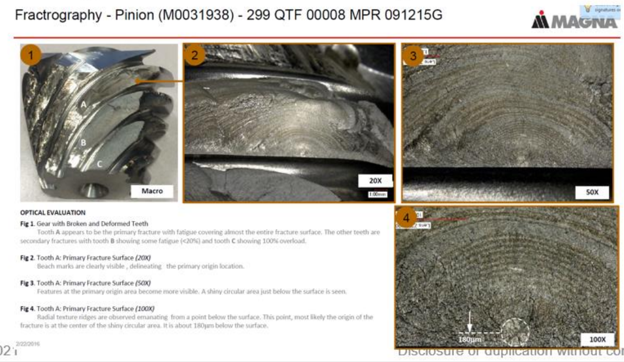
Fig 5: Material properties dA/dN versus delta K

Growth laws

Paris Law: dA/dN=c(ΔK)^m,

Fracture mechanics-Clean steel gear life predictions

- Material strengths and cleanliness factors play a large factor in gear strength. A clean steel could have an initial flaw size of 45um (.0017in) where a standard steel this would be 110um (.0043in) . The prototype gears in one application were made from clean steels and passed the qualification tests. The production gears were made from standard steels and initially failed qualification tests until further processing was added in the form of shot peening operations.
- In this gear the inclusion failure grew at a location where the residual stress was a minimum.



Clean vs Standard Steels, hypoid gears

- Evaluation of failed hypoid gears summarized the inclusion size and type for steel samples that passed (clean) and failed (Standard) the qualification tests.
- In this case the prototype gear sulfide level gave an inclusion size of 45um (.0017in) and passed the qualification tests
- The plant manufactured gears used a standard steel that had a 110um (.0043in) inclusion size and failed the qualification tests.

Table 6: Inclusion Content, ASTM E45, Procedure A

Inclusion Category		Clean	Standard
Sulfide (Type A)	Thin	0.5	1.0
	Heavy	0.0	0.0
Alumina (Type B)	Thin	0.5	0.5
	Heavy	0.0	0.0
Silicate (Type C)	Thin	0.0	0.0
	Heavy	0.0	0.0
Globular (Type D)	Thin	1.0	1.0
	Heavy	0.5	0.5

Fracture mechanics-Clean steel gear bending life predictions-as processed, no peening

- Bending life predictions versus initial flaw size, target life 500,000 bending cycles
- Vertical lines can in Fig7a define no growth at flaw size of .01mm and given loading conditions
- As initial flaw size is increased from .01, .01422 .0254, .1016, and .4826mm the final life values decrease to under 300,000 cycles
- If no growth is desired for this cycle with as processed steel an initial flaw size of .01mm (Fig7a) would be required of the steel cleanliness.
- If no growth is desired for the cycle with a shot peened processed, then an initial flaw size of .0154mm (Fig8a) would be required.
- As the initial flaw size is increased in from .01 to .4826mm (Fig7a -d) the resultant life decreases to less than the desired life of 500,000 cycles for as processed steel.

The bending stress values for each drive cycle conditions were calculated to determine applied stress intensity values of Mode 1 growth conditions. An initial calculation of stess intensity values of a semi-elliptical crack in a plate was used to determine the mode 1 stress intensity values (K1=1.12*(Sigma*(pi*crack size/Q)^.5) where Q is the crack shape factor. If the crack became large enough the equations for a finite width plate with a single edge notch K1=(Bending Stress*pi*crack length)^.5*F where F is the Form factor, were then used to to calculate the stress intensity values. The stress intensity values of the applied load were then summed with the stress intensity values generated by the residual stress to determine the resultant stress intensity values for the growth equation.

Application generated predictions for bending estimated lives

Numerous designs and test cycles were used to correlate the model. The data shown in Fig. 7 gives a design for an Asian market and shows cleanliness level versus life predictions. This target hypoid gear set exhibited bending failures on dynamometer life tests.

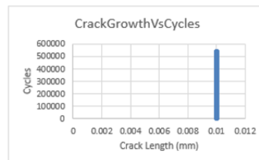


Fig7a, Initial flaw size=0.010mm, no growth, as heat treated

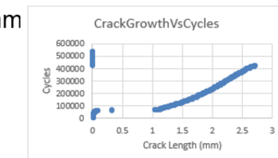


Fig7b, Initial flaw size= 0.01422mm, initial flaw size, as heat treated

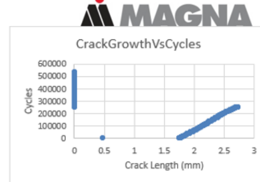


Fig 7c, Initial flaw size=0.0254mm, as heat treated

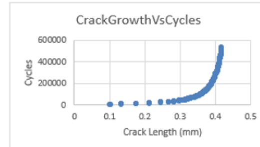


Fig 7d, Initial flaw size= 0.1016mm, as heat treated

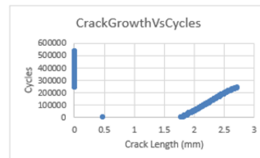


Fig 7e, Initial flaw size=0.4826mm, as heat treated

Fig. 7. As heat treated residual stress values versus initial flaw size

Fracture mechanics-Clean steel gear bending life predictions-shot peening added to process

- As the initial flaw size is increased in from .0154 to .1016mm with as processed steel and shot peening (Fig8 a -d) reflects the predicted lives.
- If no growth was desired for this duty cycle a cleanliness level of .0154mm would be required
- The addition of shot peening allowed the desired lives of 500,000 cycles to be attained with decreased cleanliness level of .1016mm

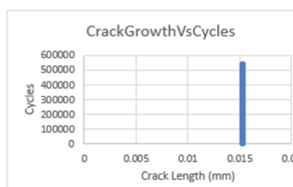


Fig 8a, Initial flaw size, 0.015424mm, no growth, shot peened

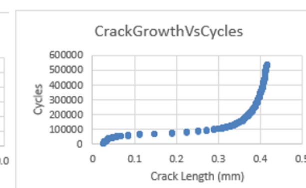


Fig 8c, 0.0254mm, initial flaw size, shot peened

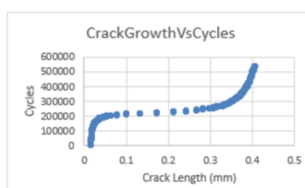


Fig 8b, 0.015494mm, initial flaw size, shot peened

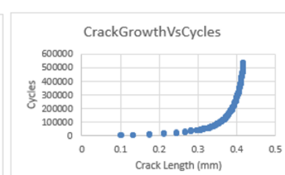


Fig 8d, 0.1016mm, initial flaw size, shot peened

Fig. 8. Shot peened residual stress life values versus initial flaw size

Fracture mechanics-Contact fatigue gear life predictions

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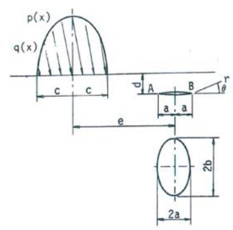
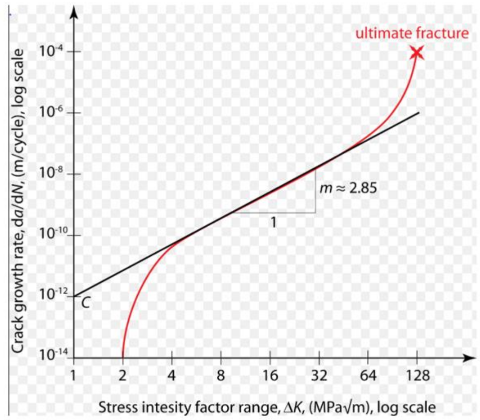
- Base Equations for Contact Fatigue
- A, B, and N were determined the value of delta K was then entered the growth equation.
- Delta K = (A*deltaK 1+B*deltaK 2)^N, where deltak 1 represents Mode 2 tensile stresses and deltaK 2 represents mode 2 shear stresses



[Reference] M. Kaneta, Y. Murakami and T. Okazaki [1]
[Method] Body Force Method
[Accuracy]

$p(x)=p_0\sqrt{(1-x^2/c^2)}$, $q(x)=fp(x)$

$K_I=F_I p_0\sqrt{\pi a}$, $K_{II}=F_{II} p_0\sqrt{\pi a}$



Fracture Mechanics Contact fatigue analysis

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- Fracture Mechanics stress and life prediction-Contact Fatigue Stress and Life Analysis- **as processed**, target life 12million cycles
- Contact fatigue life predictions versus initial flaw size
- The as processed steel could attain the target life with an initial flaw size of .0127mm.
- As the initial flaw size was increased from 0.0127mm to .0203mm the life decreased and the required life of 12E6 cycles could no longer be achieved.

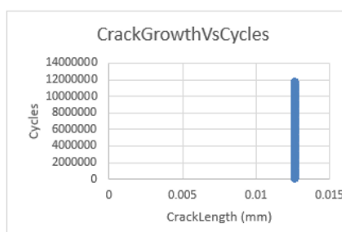


Fig10a, 0.0127mm, initial flaw size, as heat treated -no growth

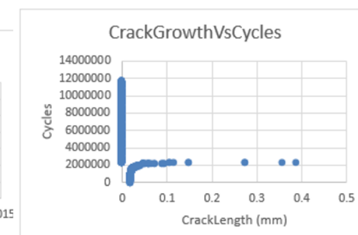


Fig 10c, 0.015494mm, initial flaw size, as heat treated

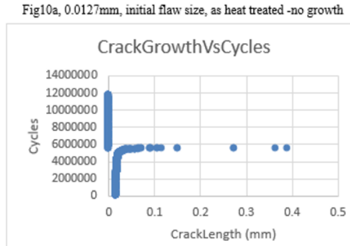


Fig 10b, 0.01778mm, initial flaw size, as heat treated

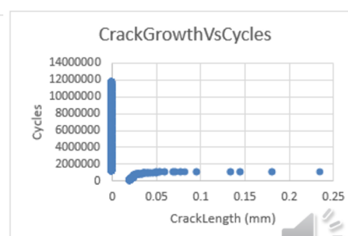


Fig 10d, 0.0203mm, initial flaw size, as heat treated

Fracture Mechanics Contact fatigue analysis

- Fracture Mechanics stress and life prediction-Contact Fatigue Stress and Life Analysis-**as processed + shot peen**, target life 12 million cycles
- The chart in Fig 11a-11d shows that the design with a higher level of residual stress could attain 12E6 cycles of life with an initial flaw size of .0254mm with no growth. This compares to the as processed steel with lower residual stress achieved no growth with a flaw size of .0127mm (Fig 10a).
- If the parts were processed with standard steel the initial flaw size could be increased to .0635mm with shot peening would allow the part to attain 12 million cycles of life (Fig 11b).

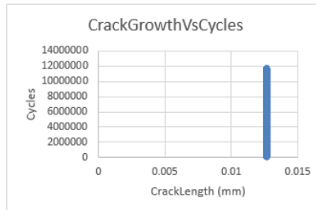


Fig 11a, 0.0254mm initial flaw size, no growth, shot peened

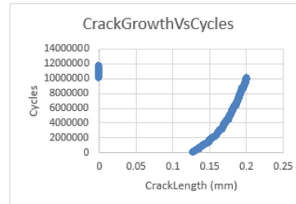


Fig 11c, 0.127mm initial flaw size, shot peened

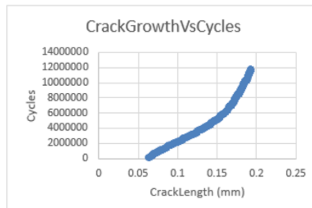


Fig11b, 0.0635mm initial flaw size, shot peened

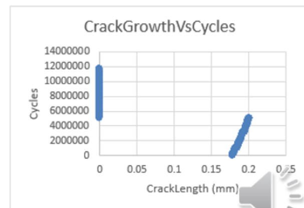


Fig 11d, 0.1778mm initial flaw size, shot peened

Ultralight Axle development -Conclusions

- Design methods for weight reductions have been presented for the Magna ultralight axle application
- Significant weight reduction can be seen through the use of novel manufacturing techniques and material processing
- Primary advantages to the Fracture Mechanics development use in the design of products:

-Another tool in our design box for light weighting of components- gears and other components

-Life prediction method determines component life based on material selection, residual stress, steel cleanliness, and drive cycle

-Development of component size based on process and material selection (standard versus premium material and residual stress levels based on standard peening techniques).

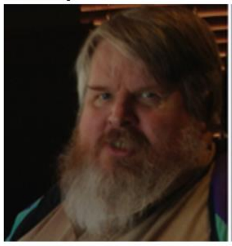
-Determine the remaining life of a component in high stressed areas.

-Accelerated test methods can use this technique to determine techniques to shorten test times with alteration of segmented drive cycle data.

-Determine cleanliness of steel required for specific design and drive cycle.

Ultralight Axle Development-Teamwork!

- Band of Brothers, Magna ERT Team
- Ralph Larson   Edward Punch



- Michael Bujold