Title	MXology® 250SX Design Verification & Validation of Materion High Performance Alloys
Report No & Issue	TR-0010-A
Object	Performance and durability improvements
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Summary

MXology designed and introduced several of Materion's high-performance alloys into its KX™250 race motocross/supercross engine. The engine was used by the REVO Seven Kawasaki® UK race team who competed in the West Coast Supercross SX250 Championship. Engines were also fitted to the UK MX2 motocross bikes with testing carried out in parallel on dyno and track.

Significant gains in performance and reliability over the standard race engine have been achieved which in part is due to the introduction of the new materials.

The piston, valve seats and guides have performed exceptionally well. Performance gains were also found with the connecting rod and valve spring retainer, albeit potential reliability issues were experienced and are in the process of being addressed.

The piston did not measurably degrade in performance over the testing period, which is an improvement over the 2618 alloy. Furthermore, it has demonstrated reliability at an increased level of performance exceeding that of the OEM piston whilst achieving its target life.

The gains found in performance using the connecting rod are attributed to the reduction in friction. The spring retainer with reduced mass allowed for an increase in rpm. Assuming the risks to reliability can be mitigated, both these components will be reintroduced to the programme.

Reliability during races was faultless and engine performance was very strong. The REVO Seven Kawasaki UK team and Dylan Walsh did exceptionally well, especially for a rookie season in Supercross. Dylan was made a Monster® athlete but couldn't compete in the last 2 races due to an injury and illness. Instead, the team stayed out to complete motocross testing in preparation for competing in several rounds of the 2022 USA Lucas Oil® Pro Motocross Championship.

This report was created by MXology for Materion in exchange for materials and support in design and testing. The project has been a great success and MXology would like to thank Materion for its support and the opportunity this has provided.

1. Introduction

This document reports the work carried out on the KX250 2022 race engine with respect to the introduction of Materion's high performance alloys. Reference proposal, *MXO-MB-SX-0001 Test & Validation of Materion's High Performance Alloys – Monster Energy AMA Supercross Championship: West Coast*

Materion's alloys were used for several key engine components to replace standard OEM or MXology parts. Components were designed to take full advantage of the new material properties.

Testing was carried out in the UK, Spain, and USA to verify performance and assess reliability.

The US West Coast Supercross 250cc championship was used as a competitive environment for validation. The team responsible for running the engines is MXology's development race partner, REVO Seven Kawasaki UK. The rider competing with the engine is British MX2 champion #101 Dylan Walsh.

2022 RACE SCHEDULE (West Coast) 250SX

ROUND 1	Sat, Jan 8	| Anaheim, CA **Angel Stadium**
ROUND 2	Sat, Jan 15	| Oakland, CA **RingCentral Coliseum**
ROUND 3	Sat, Jan 22	| San Diego, CA **Petco Park**
ROUND 4	Sat, Jan 29	| Anaheim, CA **Angel Stadium**
ROUND 5	Sat, Feb 5	| Glendale, AZ **State Farm Stadium**
ROUND 6	Sat, Feb 12	| Anaheim, CA **Angel Stadium**
ROUND 12	Sat, Mar 26	| Seattle, WA **Lumen Field**

In the UK the engine was fitted to the #40 test bike of Jamie Wainwright and used for his pre-season training and development work ahead of his British MX2 2022 championship.

The objective of the programme was to demonstrate a competitive edge, reliability, prove technology readiness, and promote awareness for MXology's performance engine hardware.

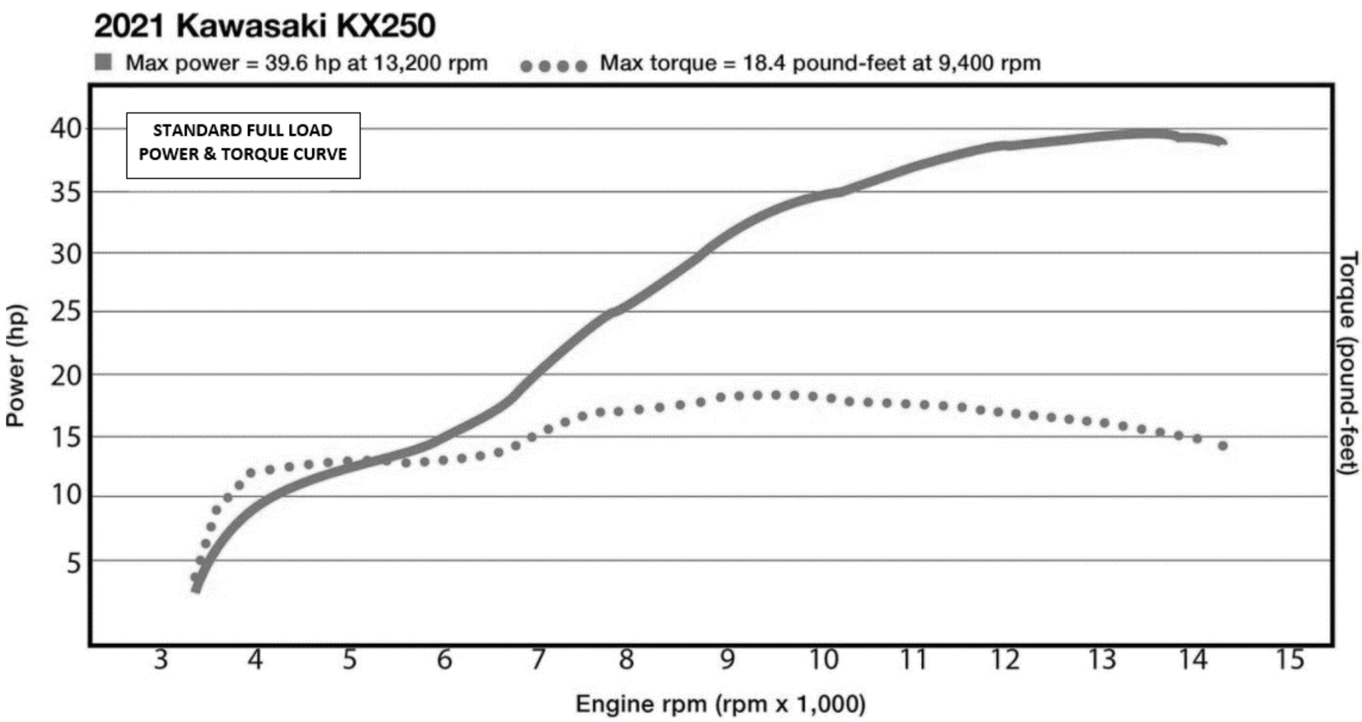
2. Engineering design and analysis

The following table lists the current or typical material used, and the replacement Materion alloy. The opportunity is also identified.

Component	Current/Typical Material	Replacement Alloy	Opportunity
Valve spring retainer	OEM: nitriding steel MXology: 100Cr6 After-Market (AM) typical: SAE 4140 or 4340 nitro-carburised	SupremEX® 225XF	Reciprocating mass reduction. Potential to increase RPM, reduce spring load (friction), or accept improved reliability (more spring coverage).
Valve guide	OEM: sintered steel matrix MXology: Colsibro®, CuBe AM typical: Hidurel®, Colsibro, CuBe	ToughMet® 3 AT110	Improved heat transfer (Ti valves) for higher thermal loading – less likelihood of knock/pre-ignition or damaged valves.
Valve seat	OEM: sintered steel matrix MXology: CuBe AM: Colsibro & Trojan Others: CuBe, MMV	PerforMet®	Improved heat transfer (Ti valves) for higher thermal loading – less likelihood of knock/pre-ignition or damaged valves. Improved valve dynamics/control (seat damping & stiffness).
Piston ring	OEM: typically steel CrN face coating, phosphate upper/lower faces	PerforMet – WS2 & DLC coatings to be tested	Reduction in peripheral piston temperature – fatigue life/piston mass – reduced crevice volume; reduced elastic modulus potentially reducing friction with gas energising.
Piston	OEM: cast hypereutectic Al alloy MXology: Al 2618 T651 AM: 4032 & 2618	AMC® 4632 T6	Reciprocating mass reduction and less wear due to improved fatigue strength and wear resistance (23% silicon). Target negligible performance deficit and extended life.
Connecting-rod	OEM: typically a forged steel 4340 or a carburising steel due to bearing ends	SupremEX 225CA	Reciprocating mass reduction for reduced friction.
Bush - connecting rod	OEM: bronze or parent steel MXology: tool steel or CuBe AM: Cube or bronze alloy	ToughMet 3 TS 160U	Less wear and friction – reliability.

Basic Engine Specification	Kawasaki® KX250	MXology® Final Specification
Bore, mm	78	-
Stroke, mm	52.3	-
Rod length, mm	85.5	-
# Cylinders	1	-
Capacity, cc	250	-
Rev limit, rpm	14,500	14,800 (15,200*)
Max. power, hp	39.6 @13,200 rpm	Not disclosed @13,600 rpm
Max. torque, Nm (lb-ft)	25 (18.4) @ 9,400 rpm	29 (21.6) @ 9,500 rpm
Max. BMEP, bar	12.6	14.7
Compression ratio	14:1	17.2:1
Combustion chamber / ports	-	Fully machined – de-shrouded
Valve size, inlet / exh, mm	32 / 26.5	33 / 27.2
Valve lift (0-lash), inlet / exh, mm	10.3 / 9.1	10.8 / 9.9

**15,200 was used with the SupremEX 225XF retainers, 14,800 with steel.*



i) Piston

Design objectives

- Design a replacement piston in AMC 4632 T6.
- Increase service life by 50%.
    - Kawasaki state piston replacement at 15 hours or 6 races. MXology's target is to increase this by 50% to achieve 22.5 hours or 9 races (pro-level duty cycle). Note, this is achieved at the increased performance level with higher cylinder pressure and engine speed.
    - During the interim, Kawasaki pistons are checked for wear on the skirts, pin bore, and ring grooves and replaced if outside of service limits.
- Improved performance.
    - A new MXology piston should match or exceed the performance of a standard piston.
    - The piston should not degrade in performance throughout its service life; degradation is due to skirt wear, ring groove wear/damage, and in some cases deformation, all of which can lead to increased blow-by and friction.
- The piston assembly mass should not be greater than the existing piston assembly.
- Increase compression ratio, equal to or greater than 17:1 (no head skim).

Materials

The table below compares the properties of the following piston alloys:

- A high-performance hypereutectic cast aluminium alloy as used by some OEM's.
- 2618 the mainstream used in motorsport and by some OEM's.
- AMC 4632 as used in this project.
- SupremEX 225CA metal matrix composite (MMC).

Property	Cast Alloy Hypereutectic	2618 T6	AMC 4632 T6	SupremEX 225CA T4
Rp 0.2% at 25°C (MPa)	230	370	380	440
Rm at 25°C (MPa)	270	448	430	610
Elastic Modulus (GPa)	80	72	94	115
Specific Modulus (GPa/g.cm^3)	28.6	26.2	34.8	39.9
Density (g/cm^3)	2.80	2.75	2.70	2.88
Heat Capacity (J/g/°C)	825	921	840	836
Coeff of Thermal Expansion (ppm/°C)	19	22.2	17.1	16.1
Thermal Conductivity (W/m.K)	120	138	127	150
Fatigue strength, (MPa) R=-1 N=10^7 300°C un-notched	50	60	90	109
Fatigue strength / density	17.86	21.82	33.33	37.85
Improvement in the above to OEM baseline (%)	0	22.18%	86.66%	111.94%
Wear rate performance	Good	Average	Very Good	Excellent

Fatigue temperature has been stated at 300°C which is typical of the maximum piston crown temperature experienced on a naturally aspirated race engine of this size: 290-310°C depending upon its level of performance.

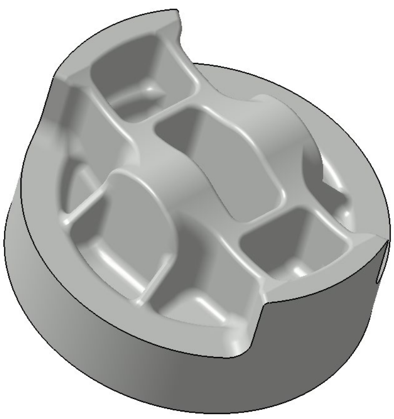
The geometry and mass of an optimised piston is largely influenced by the material's fatigue strength and density. The table above contains a metric for comparing these two factors, (fatigue strength/ density). This is indicative of the advantage AMC 4632 and SupremEX have compared with other piston alloys. Another important factor is the material's tribological performance, namely its behaviour with interacting surfaces: the cylinder bore, rings, pin, and connecting rod when applicable. This is with respect to wear and friction both of which are very good with AMC 4632 due to its high silicon content, and excellent with SupremEX due its 25% silicon carbide content.

SupremEX and AMC 4632 are extremely good piston alloys. In terms of this project the AMC 4632 offered less risk in terms of the commercial proposition, by mitigating higher tooling costs for polycrystalline diamond inserts needed for machining MMC. Furthermore, MXology's target life for a competitive piston is 22.5 hours or 9 races which is reasonable for a full race season, and this is considered achievable with AMC 4632 at a competitive price point.

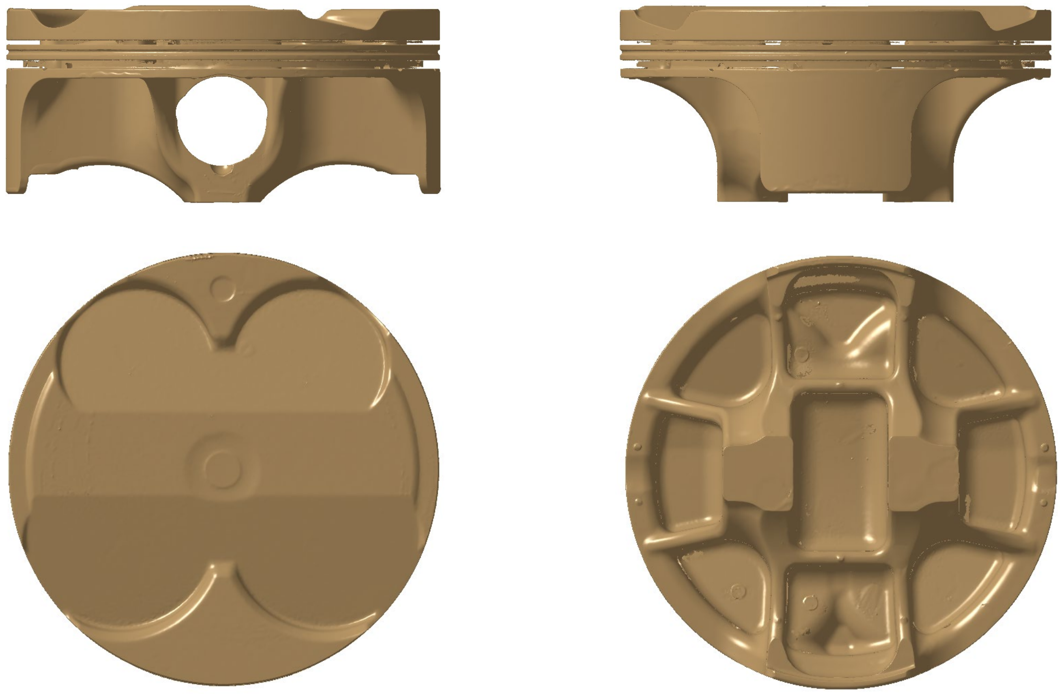
MXology intends to use AMC 4632 for its 4-stroke applications and SupremEX 225CA for 2-strokes: 2-stroke single ring race pistons have a particularly arduous time and are changed after 5 to 7 hours or 5 to 6 races at pro-level duty cycles. The intention is to double this figure with SupremEX whilst maintaining the same mass and no performance deficit – a step change in 2-stroke piston performance which is unlikely to be achieved with AMC 4632 due to the very high piston ring land temperatures and wear regime. 2-stroke pistons manufactured from a net shape forging is also predominantly turning – minimal machining.

Design constraints

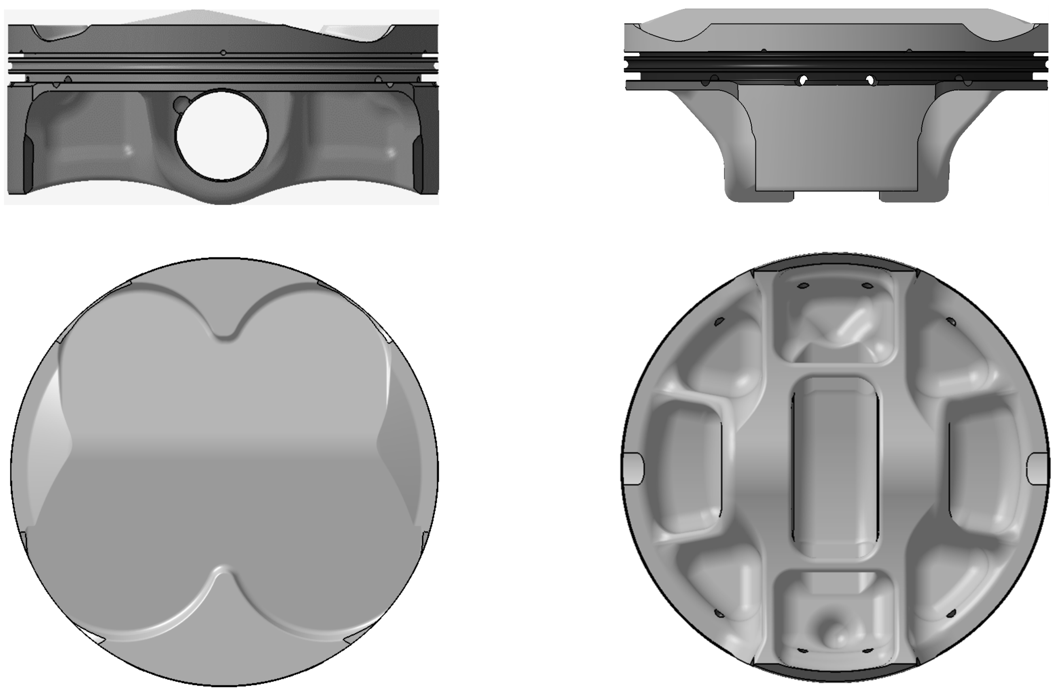
- Connecting rod length to remain unchanged. This is to allow the piston to be retrofit with standard hardware. It also mitigates the risk associated with introducing a SupremEX rod i.e. should an issue be encountered the standard steel rod can be the fallback solution crank guided. Note, gains in performance are likely to be achieved with a longer rod which may be considered at a later stage; the piston would also be lighter with the reduction in compression height.
- Carryover piston forging, 1000109. The standard forging tool will be used as the basis of the design. Material removal is required all over, it is not net shape forged.



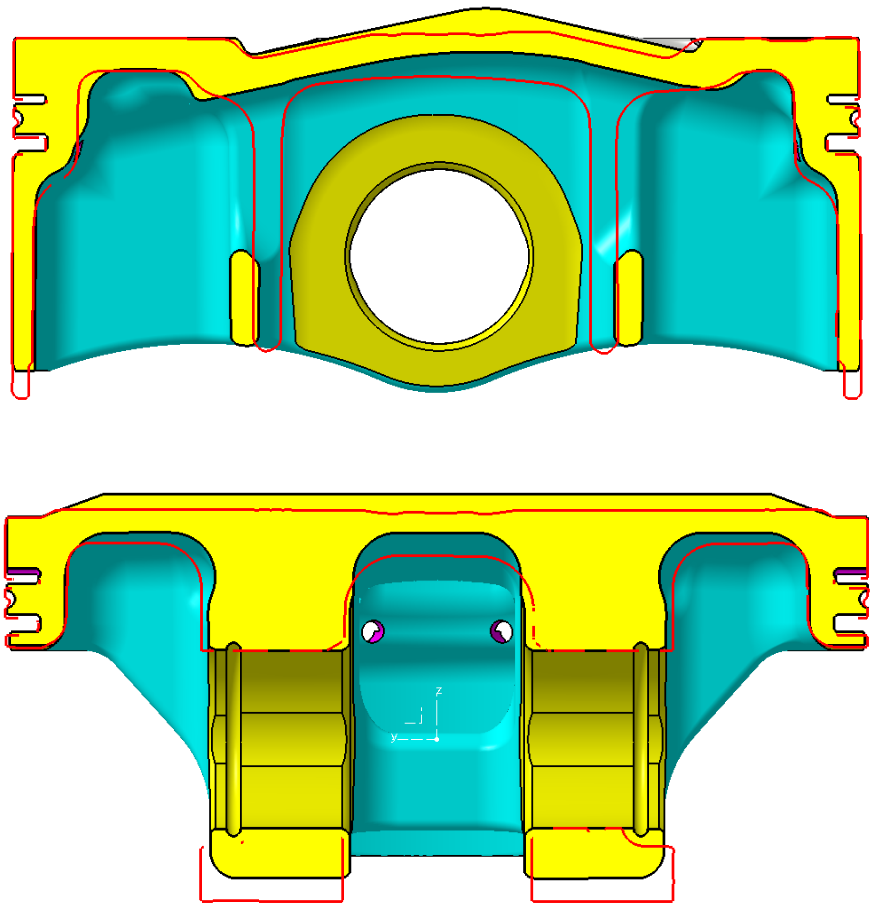
Piston design
Below is a scan of the standard OEM Kawasaki KX250 piston.



The MXology AMC 4632 KX250 piston CAD model is shown below.



Below is a section through both pistons, the scan is indicated by the red outline.



The OEM KX250 piston is very much a developed race piston from a premium series alloy which is evident in the design: crown and skirt thickness, skirt area, pin boss length, and ring heights. The safety factor of this piston is likely to be relatively low and well-understood by the OEM. Based on the number of cycles equivalent to the service life of 15 hours (~5 million 4-stroke cycles), I would expect it to be ~1.5 and ~1.2 at 10 million cycles (10^7). There are many reported piston failures in the field which are likely to be due to the service life not being respected or engine performance being increased beyond Kawasaki's design criteria. For example, it's not uncommon for teams to increase the compression ratio by skimming the head, using fuels with a higher-octane rating, and raising of the rpm limit.

The MXology piston has been designed with a safety factor of circa 1.5 at 10^7 cycles which equates to ~30 hours. The S-N curve for steel is asymptotic at 10^6 cycles but the endurance limit for aluminium is not definite but becomes nearly asymptotic at 10^8 (~300 hours). Setting 22.5 hours or 9 races as the replacement interval provides a sensible safety margin. Excursions beyond the rev limiter are inevitable due to the nature of the sport and these can significantly reduce piston life hence a reasonable margin is required.

Notable differences between the MXology and OEM piston is the raised crown to increase compression ratio from 14 to 17.2:1 (target achieved > 17:1). The pin has been shortened and the top ring moved up slightly to minimise crevice volume.

Piston Assembly Mass	OEM	MXology
Piston mass, g	142.0	138.2
Pin mass, g	37.5	33.0
Clips (x2), g	1.6	1.6
Ring pack	6.6	6.6
Total	187.7	179.4

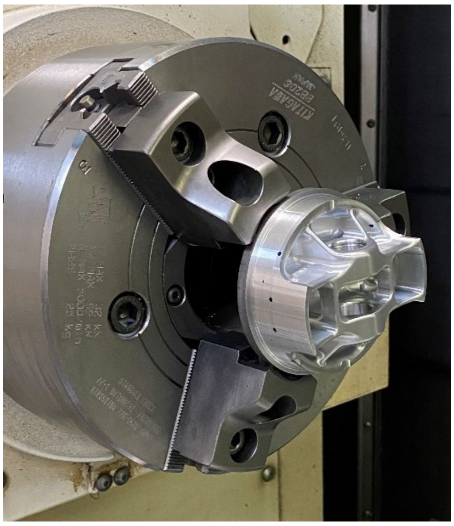
The reduction in mass equates to 4.5% (target achieved ≤ OEM).

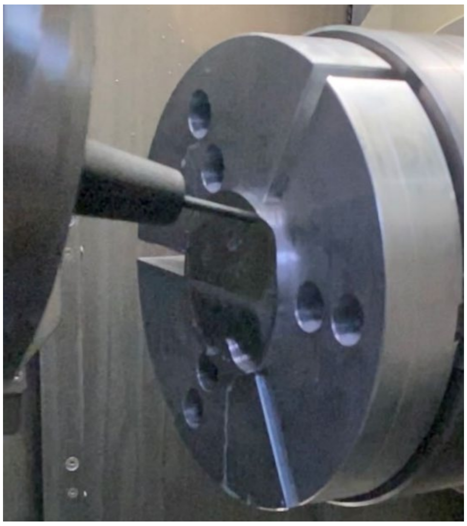
Piston Loads	OEM Estimated Baseline	MXology (AMC 4632 Piston)	% Change
Case 1, Combustion			
Peak pressure (estimated), bar	96	105	
Gas load, N	45,872	50,173	+14%
Case 2, Piston inertia load			
Max engine speed, rpm	14,500	15,300	+5.5%
TDC piston acceleration m/s^2	76,802	85,551	+11.3%
Inertia force (approx.), N	10,906	11,823	+8.4%

Piston loads have increased due to the improved performance level.

Piston manufacture

A quantity of 10 pistons were manufactured. A twin-chuck very high precision turn-mill is used to machine the piston forging complete. The image below left shows the forging being probed for datum alignment. The middle image is the first operation complete apart from ring grooves, and the right is the piston in the second chuck having the crown finish machined. The piston material was stable and cycle times were as per a conventional 2618 alloy.





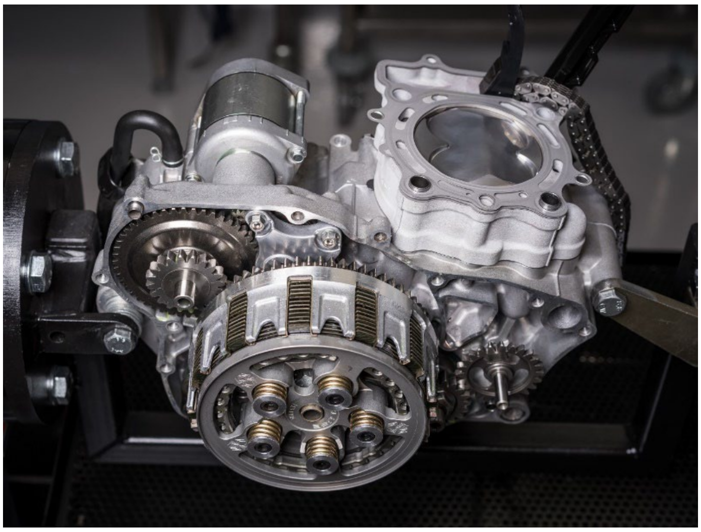
After machining, each piston is fully inspected to ensure it conforms to drawing.

The skirt is masked and sprayed with a Teflon™ coating, the crown is polished, and the piston is laser part marked with a unique serial number.

Finished piston and assembly images shown below.



Piston – engine assembly
The piston assembled into the engine with no issues. The SupremEX connecting rod covered in the next section is piston guided so runs a small clearance to the piston. The DLC pin is a conventional floating design. Clips retain the pin with minimal axial float. Assembly checks were carried out to ensure the squish height (piston to fire face distance) and valve drops (valve clearance to piston @ TDC) were as expected. The compression ratio was verified.



ii) Connecting Rod

Design objectives

- Design a replacement connecting rod in SupremEX 225CA.
- Introduce a ToughMet 3 TS160U small-end bush.
- Target a reduction in reciprocating mass respecting a minimum fatigue safety factor of 2 at 10^7 cycles.
- Change from a crankshaft guided connecting rod to piston guided.

Materials

The table below compares the properties of the following connecting rod alloys.

- Carburising steel as typically used when no small-end bushing is fitted.
- Through hardening steel.
- SupremEX 225CA.

Property	Carburising Steel + Shot Peening	Through Hardened Steel + Shot Peening	SupremEX **225CA T4
Rp 0.2% at 25°C (MPa)	830	925	440
Rm at 25°C (MPa)	1130	1230	610
Elastic Modulus (GPa)	210	200	115
Specific Modulus (GPa/g.cm^3)	26.8	25.4	39.9
Density (g/cm^3)	7.83	7.85	2.88
Hardness, HRc	Surface ~55 Core ~36	Core ~40	
Coeff of Thermal Expansion (ppm/°C)	12.3	12.3	16.1
Fatigue strength, (MPa) R=-1 N=10^7 150°C un-notched	650*	600*	279
Fatigue strength / density	83	76	97

* The endurance limit of the steel rod is indicative only based on prior knowledge; testing would be required to ascertain accurate numbers for comparison.

**225CA was used due to material availability and programme timing. However, 225XF at the lower operating temperature could offer an improvement compared to CA, for discussion.

Property	ToughMet 3 TS 160U
Rp 0.2% at 25°C (MPa)	1035
Rm at 25°C (MPa)	1140
Elastic Modulus (GPa)	144
Density (g/cm^3)	9.00
Hardness, HRc	34
Coeff of Thermal Expansion (ppm/°C)	16.4

MXology would be interested to understand if further improvements in fatigue strength can be achieved by shot peening SupremEX; improvements of 20% or more are commonly found in other Al alloys. Steel and titanium connecting rods are shot peened.

The specific modulus of the SupremEX is an improvement over the steel alloys, i.e., it is stiffer for a given mass. The ratio of its fatigue strength to density is also greater compared to the steel alloys.

To achieve adequate stiffness and fatigue life, the section has been increased and the rod optimised accordingly.

Design constraints

- Carryover pin sizes, and crankshaft unmodified if possible.
- Connecting rod length to remain unchanged.
- Connecting rod to be piston guided; current rod is crank guided.
- Connecting rod to carry over standard big end bearing shells (later changed).

Connecting rod design

The OEM connecting rod was measured for centre distance, bore sizing, and CoG. Images below.

SupremEX 225CA issue 01 connecting rod CAD images below.

Design constraints were respected except for the crankshaft which required a web clearance modification due to the thicker rod section. A 2 mm thick shell was also used as opposed to the 1.5 mm OEM part.

Stress distribution through the rod shank is evenly distributed with maximum stress and a minimum fatigue safety factor of ~2 at the small end strap, slightly higher at the big end strap on the shell split line. The big end bore was sized to suit the higher coefficient of thermal expansion of the SupremEX material. The small end bush is split due to it having integral thrust faces introduced to minimise the potential risk of scuffing that may exist between piston and rod. This was a precautionary measure, due to programme timing and a coating could be considered instead. ToughMet was deemed the best solution and one that potentially offers a further reduction in friction.

Issue 02 connecting rod
Prior to testing, assembly damage was encountered which lowered the rod safety factor to an unacceptable level. The rod design was revised accordingly, as is covered in the test section. The rod big end geometry was increased slightly in section and a single-piece big end bush replaced the two steel shells.

Issue 02 connecting rod CAD images below.

Connecting Rod Assembly Mass	OEM	MXology Iss01	MXology Iss02
Connecting rod, g	178	93.4	103.6
BE shells, g	24	29	24
SE bush, g	0	6.7	6.7
Total	202.0	129.1	134.3
Small end mass, g	57.42	37.62	37.89

A 34.5% reduction of the small end mass was achieved.

The big end rotating mass and inertia was less than standard hence a flywheel inertia ring was manufactured for test and evaluation on track. In terms of engine balance, the reduction in reciprocating mass and modification to the crank web resulted in only a small variation in the balance factor.

Connecting Rod Loads	OEM Baseline	MXology (AMC 4632 Piston SupremEX Rod Iss02)	% Change to Baseline
Case 1, Combustion			
Peak pressure (estimated), bar	96	105	
Gas load, N	45,872	50,173	+9.4%
Case 2, Inertia			
Con-rod assembly mass, g	202.0	134.3	-33.5%
Small-end mass, g	57.42	37.89	-35.1%
Big-end mass, g	144.58	96.41	-33.3%
Max engine speed, rpm	14,500	15,300	+5.5%
TDC piston acceleration m/s^2	76,802	85,511	+11.3%
Con-rod tensile load, N	23,908	22,837	-5.3%

Despite the increased engine speed, the tensile load in the rod has been reduced by ~5% due to the reduction in reciprocating mass (piston and rod). The gas load has increased due to the increased level of performance – increased volumetric efficiency and compression ratio.

Connecting rod manufacture

5 connecting rod assemblies were manufactured from SupremEX 225CA T4. Manufacture was carried out using PCD tooling and no issues were encountered. Rods were manufactured leaving a small amount of stock. A stress relief operation was carried out and the rods were finish machined to drawing.
The ToughMet bush was turned, assembled to the rod, and finish machined. The connecting rods are fully inspected and serial numbered.

As previously mentioned, it is recommended that a shot peening study be carried out. This will require fatigue testing and an evaluation of the shot coverage, size, and intensity. The two associated factors effecting fatigue strength being the residual compressive stress and surface roughness which are optimised to maximise any potential improvement.

Issue 01 connecting assembly shown below with conventional upper and lower big end bearing shells.

Small end ToughMet 3 TS 160U bushes prior to fitment

Issue 02 connecting rod and single piece bush below prior to assembly.

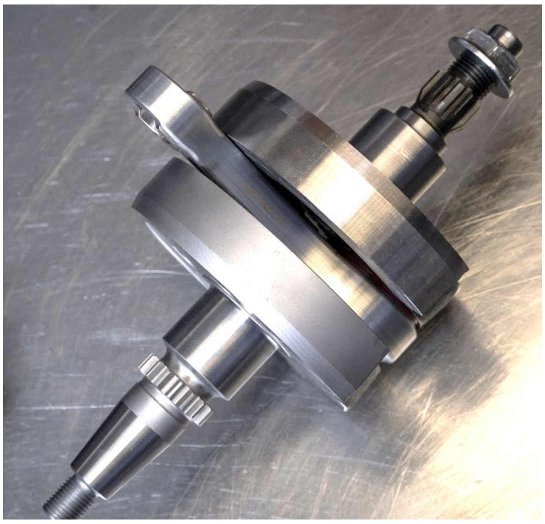
The single piece bush is a copper-based alloy with a coefficient of thermal expansion closely matching that of the rod, not dissimilar to the small end bush.

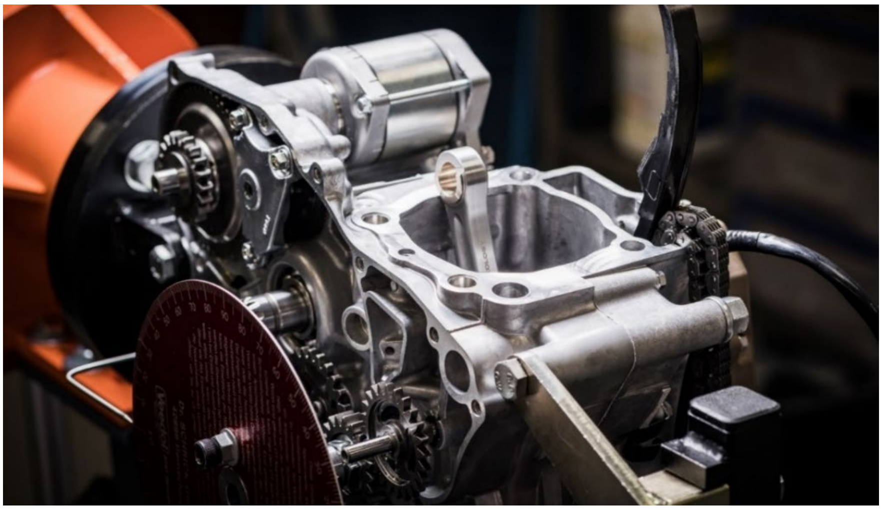
Connecting rod – engine assembly

The connecting rod assembled onto the press fit crankshaft and into the engine with no issues. The pistons control lateral movement with adequate clearance at the big end to crankshaft ‘thrust’ faces.

It’s worth noting the following feedback from engine build with respect to part handling:

The rod needs to be handled as you would a piston as they can be more easily damaged than a steel or Ti rod. For example, the rod must be rested alongside the barrel and not allowed to fall under its own weight. This is to avoid dings and scratches. Once fully assembled the risk no longer exists but care is required. A protective coating is an option under investigation.





iii) Spring retainer

Design objectives

- Design a replacement spring retainer in SupremEX 225XF to suit MXology’s standard valve spring.
- Target a reduction in mass over MXology’s tool steel retainer of 25%.
- Target a life of 10^7 cycles, circa 30 hours with an imposed limit of 22.5 hours or 9 races.

Materials
The table below compares the properties of the following retainer alloys.
- Through hardened steel nitrocarburized.
- Through hardened bearing steel.
- SupremEX 225XF.

Property	Steel Nitrocarburized	Bearing Steel Through Hardened	SupremEX 225XF T6
Rp 0.2% at 25°C (MPa)	665	1900	*623
Rm at 25°C (MPa)	850	2200	*772
Elastic Modulus (GPa)	200	200	115
Specific Modulus (GPa/g.cm^3)	25.5	25.6	39.9
Density (g/cm^3)	7.83	7.81	2.88
Hardness, HRc	Surface > 60 Core 28	56	18 (220 HV_{10})
Fatigue strength, (MPa) R=-1 N=10^6 150°C un-notched	Surface 550 Core 345	610	325
Fatigue strength / density	70	78	113

* Measured data from supplied bar; quoted minimum is 540 and 650 MPa.

The SupremEX 225XF retainer has a relative advantage in terms of its fatigue strength and stiffness compared to its mass.

Wear performance is not an attribute in the table, but it is well understood that SupremEX 225XF has outstanding wear performance due to its finely dispersed 25% silicon carbide. Its hardness is, however, relatively low in comparison to other conventional options. Steel retainers and titanium, not included above, rely upon a high surface hardness to prevent damage occurring from the hardened valve spring. Hence, they are heat treated. The valve, spring, and retainer rotate and move relative to each other. Under certain conditions such as an overrev, the contact between the two faces is no longer parallel and some angular ‘edge’ loading can occur with relative movement. Spring tang ends are fully dressed when requested, else they are deburred, but still a cause for concern with potentially sharp and non-uniform edges. The risk being surface damage, the introduction of a stress raiser, and subsequent reduction in fatigue strength.

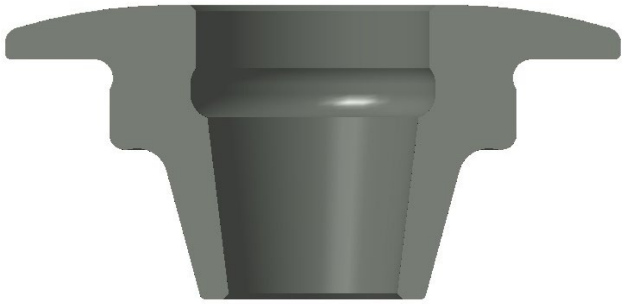
Design constraints
- Carryover valve spring, valve locks (cotters), and valves.

Spring retainer design
MXology has designed new camshafts, valves, and springs to target improved volumetric efficiency and higher engine speed. Beehive springs with a smaller inside diameter at the top were introduced to reduce reciprocating spring mass and raise its natural frequency. The existing springs and steel retainers were no longer suitable.

A bearing steel retainer was designed alongside the SupremEX retainer. Fatigue safety factors were greater than 2.5 for both retainers based on the spring force at seated and maximum lift.
The retainer outside diameter is just under 20 mm.

Below are images of the issue 01 SupremEX 225XF retainer design and the bearing steel retainer.

SupremEX 225XF



Bearing Steel

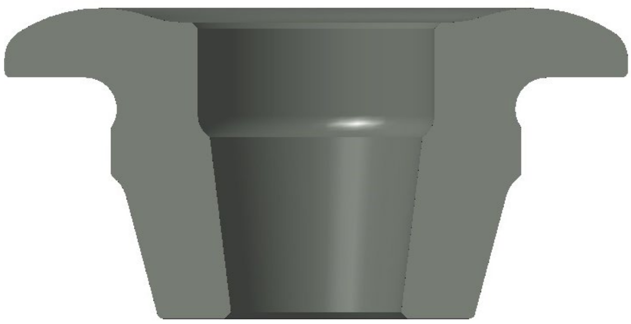
Issue 02 spring retainer

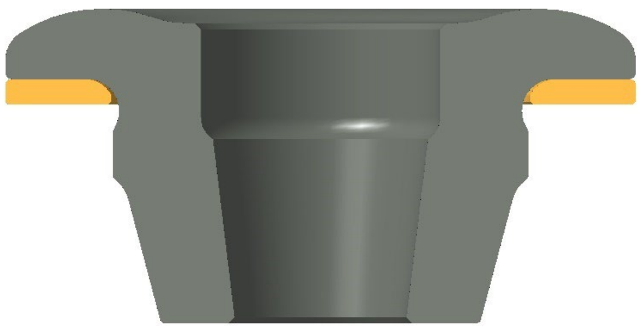
After initial testing, damage to the underside of the retainer was discovered and the retainer design was revised. The location and extent of the damage are covered in the test section. The damage was deemed to be a potential fatigue crack initiation site. The root cause of the damage cannot be categorically confirmed but is likely due to spring tang end contact, albeit the springs are high quality with dressed tang ends. The use of springs with fully rounded ends is also an option.

Some detail changes were carried out to the retainer and a ToughMet TS160U washer was introduced. Safety factors remain above 2.5 with the washer but it has increased the mass by 1.2g. Fitted length and spring loads remain the same.

In other race classes, SupremEX 225XF retainers have been and continue to be used reliably. It is not known which, if any, methods or designs they use to prevent or protect against damage on the retainer underside.

Below is an image of the issue 02 SupremEX 225XF retainer with and without the washer.





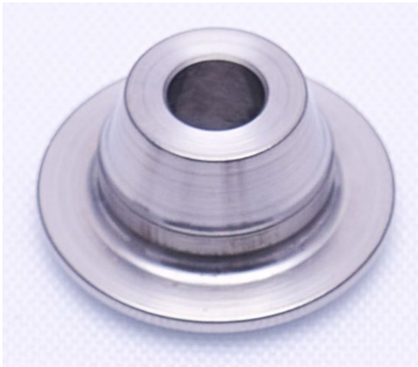
The washer introduced was 1.2 mm, but a 1 mm washer would likely be adequate.

Spring Retainer Mass	Kawasaki *Standard Inlet for Comparison	MXology Steel	MXology 225XF Iss01	MXology 225XF Iss02
Spring retainer (g)	9	6.136	3.110	3.195
Shim (g)	0	0	0	1.171
Total (g)	9	6.136	3.110	4.366
% Change to MXology steel	+47%	0	-49%	-29%

* The Kawasaki retainer has been designed for less spring load and no service life is stipulated.

The MXology retainers are designed with a considerable safety factor at 10^7 cycles.

Spring retainer manufacture
10 sets of retainers were manufactured from 1" bar stock using PCD tooling. The material was free cutting and the surface finish produced was as per the drawing requirements.



Spring retainer – engine assembly
No issues were encountered with the assembly. Fitment into the spring is a very light transition fit.

iv) Valve seats & guides

Design objectives

- Design PerforMet valve seats to replace the standard PM sintered steel parts.
- Design ToughMet 3 AT110 valve guides to replace the standard PM sintered steel parts.

Materials
The table below compares the properties of the seat and guide materials.

Property	PM Steel Seat	PerforMet Seat	PM Steel Guide	ToughMet 3 AT110 Guide
Rp 0.2% at 25°C (MPa)	1470	725	410	760
Elastic Modulus (GPa)	190	130	120	144
Hardness, (HV)	460	302	148	278
Coeff of Thermal Expansion (ppm/°C)	13	17.5	12	16.6
Thermal Conductivity (W/m.K)	30	160	34	38

Not listed in the table above is the material's damping coefficient which is an important factor along with its stiffness and effects the valve's dynamic behaviour during seating. It's MXology's belief that higher levels of damping exist in copper-based alloys and this more favourable in terms of the valve's response upon impact.

The standard valve material and MXology's valves are titanium which has a low coefficient of thermal conductivity (~7.2 W/m.K). The risk when operating at increased levels of performance is hotter valves, which can reduce volumetric efficiency and worst still lead to an exhaust valve failure.

OEM sintered seats and guides are very good from a wear point of view due to their hard matrix of materials, but their reduced thermal conductivity means compromises to the seat and valve design. Conversely, the concern switching to copper-based alloys is wear and distortion which can lead to poor sealing and regular seat and guide replacement on a race programme.

Seat & guide design
MXology's inlet and exhaust valves are larger in diameter, and the width of their seats and head thickness has been reduced slightly. This is to aid air flow and the reduced thickness helps with maximising compression ratio - a reduction in thickness of 0.3mm was achieved. Reliability at the reduced seat and valve thickness is reliant upon good heat transfer.

The seat and guide fitment tolerances have been chosen to ensure the correct interference fit is achieved based on the new material's coefficient of thermal expansion. This is also in terms of the guide bore and valve clearance.

Seat & guide manufacture
The material is free cutting, and no issues were experienced machining the parts. The seat and guide blanks are fitted to the heads and finish machined.

Cylinder head assembly – engine build
No issues were encountered assembling the valves and valvetrain components. Follower clearance was nominal, and valve drops were checked and verified for valve-to-piston clearance.

v) Piston Compression Ring

Design objectives

- Design a replacement PerforMet® ring for test and evaluation.
- Consider opportunities for improvement based on PerforMet's thermal conductivity.

Design constraints

- The ring must suit the standard ring groove geometry, a retrofit part.

Materials

The table below compares the properties of conventional ring materials and PerforMet.

Property	Chromium Steel	Spheroidal Graphite Cast Iron	PerforMet
Rm at 25°C (MPa)	1150	1300	860
Density (g/cm^3)	7.70	7.30	8.69
Elastic Modulus (GPa)	210	150	130
Hardness, (HV)	360	327	302
Coeff of Thermal Expansion (ppm/°C)	11	10	17.5
Thermal Conductivity (W/m.K)	50	36	160

Design considerations

Engine knock: The 250cc single cylinder engine due to its relatively small-bore size (Ø78mm), relatively ‘open style’ crown and chamber, and high-octane race fuel (102RON) does not suffer from knock. It may knock on standard 98 RON pump fuel.

Windage losses: Two piston oil squirt jets are used to cool the piston and limit its temperature.
At 14,000 rpm the peripheral speed of the crank web is circa 264 mph hence considerable air drag exists and more still when oil is present. The reciprocating rod and rotating big end also imparts energy into the fluid and the oil is heated in the process. Scavenge pumps can be used to reduce the losses, and running a partial vacuum is an advantage even considering the power required to drive the pump. Minimising the presence of oil and reducing blow-by at source provides an advantage.

Ring Friction: The compression ring and oil control ring is a major source of friction. If less oil exists in the crankcase there is less likelihood of oil carryover past the rings and hence there is the potential to reduce ring tension and lower friction.

Similarly, the compression ring is a source of friction, in particular during the intake, compression, and exhaust stroke.

Compression ring design

MXology has considered the above factors, and more, when contemplating what a PerforMet ring could offer. In terms of notable material properties, its thermal conductivity is significantly higher than the steel ring it replaces, and it has a lower elastic modulus.

The ring is 0.8 mm with positive twist and a barrel face so not dissimilar to the steel ring it replaces. The ring tangential force has been reduced to nominally 2.6 N which is half that of the steel ring. The piston has gas slots, so the ring is energised more effectively during the power stroke. The ring’s modulus is less so the ring’s free gap is similar to that of the steel ring, but half the force is required to install the ring.

The ring's higher thermal conductivity should conduct heat at a higher rate resulting in lower piston temperatures. The intention is to carry out baseline testing, and assuming the ring is performing satisfactorily with no performance deficit, development tests will be carried out to reduce oil cooling jet flow whilst maintaining a similar operating temperature. Hardness tests will be carried out using different pistons to establish before and after results at x hours.

Surface treatment
Steel and iron rings rely upon a surface treatment to protect their lower face, in particular against scuffing and micro welding in the ring groove. It's likely that a treatment will also be required on the PerforMet ring, but the mainstream solutions used for ferrous-based rings such as nitriding or phosphating cannot be used for PerforMet. An alternative is likely to be required.

The MXology piston relies upon its high silicon content to minimise ring groove wear and no other surface treatment is used such as anodising or electroless nickel plating. However, electroless nickel plating could well be a solution to a potential scuffing issue.

The external face of a conventional steel piston ring also requires surface treatment. Sometimes this is simply gas nitride but more common now is a PVD or CVD coating. Testing to date of the PerforMet ring suggests that the outer face against a hard plasma-sprayed or Nikasil®-coated cylinder bore does not require treatment and the tribology regime is good.

The concern that requires addressing is the risk associated with the upper and lower faces.

Manufacture
The preference for piston ring manufacture is by wire, but with few parts required and the lead time of wire rings (and minimum batch size) being considerable, MXology used its well-proven conventional piston ring manufacturing process. Rings produced this way are of the same physical quality conforming to drawing.

Below is an image of the finished batch of rings. Top and bottom faces are lapped, and the rings are all pre-gapped. Based on the higher thermal conductivity the ring gap is increased accordingly and, at temperature, should be that of the steel ring.

Coating
MXology considered a number of alternative coatings and settled on an all-over CVD carbon composite coating (2500-3000 Hv) for the first samples. This particular coating performed very well during a pin-on strip wear test compared to alternative coatings. A fixture was manufactured to hold the rings and the parts were coated.

Unfortunately, a problem occurred at the coating company whereby they coated the entire batch of rings, instead of a sample, and with the wrong coating. The rings were stripped but MXology had concerns about the stripping process. The rings were re-coated but there was visible inconsistency and texture to the coating. Unlike a PVD coating where the whole part is coated, CVD is targeted, and despite a number of attempts the parts were noticeably inconsistent. Engine testing was carried out, but friction was high and performance considerably down which was not an issue found previously when testing PerforMet rings uncoated. Hence the coating or process of stripping it was considered to be the root cause. During the limited testing carried out the coating was no longer present in places.

MXology plans to continue trials. First with no coating and then with alternative surface treatments such as DLC, WS2, and WPC. Unfortunately based on timing the ring development was put on hold.

Below is an image of the coated rings.

Engine Testing
The standard KX250 race engine was baseline tested on its standard OEM ECU.

The new Vortex race ECU had been previously populated with basic maps and sensor configuration. This was fitted to a standard engine and the map refined. This map would be used for the first fire-up of the MXology engine with Materion hardware.

The MXology KX250 engine was built and fired-up mid-October. The first race was taking place in California on January 8th, so the test and development program was very tight.

Standard protocols were followed to break the engine in, and the basic mapping was checked. Extended running was carried out on the dyno to ensure the map and engine were safe and ready for track test circa 2.5 hours on dyno, the majority at part load.

This engine was fitted to the US test bike and taken to a UK test circuit for first evaluation and feedback.

In parallel a further three engines had been prepared.

A full mapping exercise was carried out on the UK test bike engine starting at partial throttle and ending with wide open throttle runs and finally a full performance curve. The map was transferred to the US test bike and a further test was carried out on track in the UK before it was shipped to the USA.

Performance development work continued in the UK to optimise the engine's performance.

Once satisfied, the UK test bike took to the tracks to accumulate hours and some performance development work was carried out to refine its configuration.

A typical 1-day track test consists of 3 x 0.5-hour race sessions, plus starts.

The first race engine specification was finalised, and a second engine and hardware were hand-carried to California and updates carried out.

Testing in the UK, Spain, and US continued for the remainder of the year in preparation for the first race. There is a race each weekend, so time between races is precious and would involve parallel development activity on a dyno in the US and track testing at least twice a week. Reliability was paramount and hence the race engine hours were kept to a minimum and the test bikes accumulated the hours to potentially uncover any issues.

Racing commenced in January and the REVO Seven Kawasaki UK team competed in 5 of the 7 rounds. Unfortunately, due to injury and illness, Dylan Walsh could not start the last 2 events. Instead, he stayed on to carry out testing on a number of motocross circuits in preparation for Pro USA series.

Dylan's performance in the 250SX West class was outstanding for a rookie and overleaf are his placings. He ran in Group A, was made a Monster athlete and most importantly the engine was noticeably very competitive.

250SX West Results #101 Dylan Walsh.

- A minimum 40 riders compete in the qualifying group rounds with 40 making it through.
- The 40 riders compete in two heat races with 20 in each heat and the top 9 from each making it through to the main event race.
- Those not making it through compete in a Last Chance Qualifier (LCQ) race with the top 4 making it through to the main event of 22 riders.

2022 250SX West	Qualifying	Heat Race	LCQ Race	Main Event 1	Main Event 2	Main Event 3
Anaheim 1	25	12	1	17	-	-
Oakland	18	10	5	-	-	-
San Diego	19	8	-	11	-	-
Anaheim 2	19	13	2	11	-	-
Glendale Triple	17	-	-	13	11	11
Anaheim 2	-	-	-	-	-	-
Seattle	-	-	-	-	-	-

Dylan, due to injury and illness, missed the last 2 rounds and came 19th overall.

Test results and component assessment

The following is an assessment of each of the aforementioned components following the season's testing and racing.

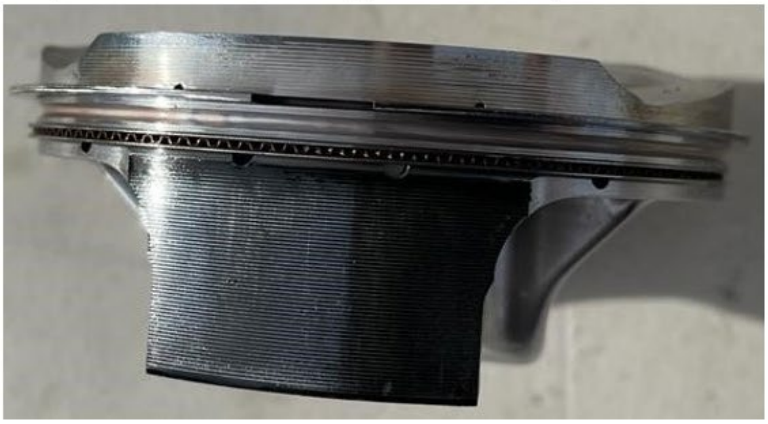
A) Piston

- The piston accounted for a good percentage of the engine performance gain. This can be attributed to the increase in compression ratio, reduced crevice volume, reduced skirt area, and reduction in mass.
- Two pistons exceeded the 22.5-hour service life with further pistons on test soon to achieve the target and beyond. 6 consecutive races were achieved with the piston, and it was switched to the UK test bike and a further 6.5 hours accumulated before an unrelated failure occurred.
- Following each test or race the engines were tested for performance and no loss was measured.

Summary of component hours (Nov'21 to end-Apr'22)

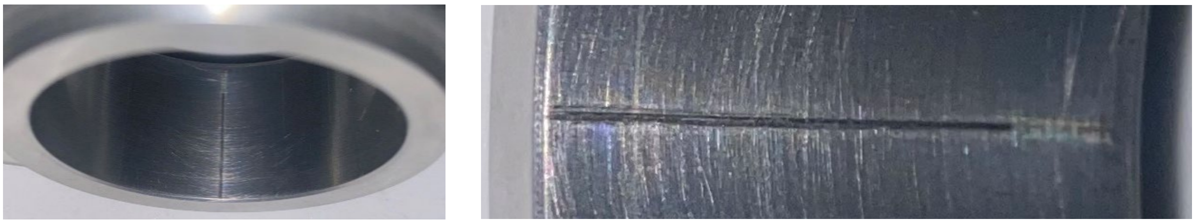
Piston No.	Chassis	Race Hours	Skirt Condition	Ring Groove Condition	Engine Performance	Notes
3	USA race SX	20	Very Good	No measurable wear	No deficit on dyno	Shipped to UK for inspection & further testing
6	USA race MX	0	-	-	-	
1	USA test	28	Very Good	No measurable wear	No deficit on dyno	Replaced with #7
7	USA test	0	-	-	-	
4	UK race	8			No deficit on dyno	Engine yet to be stripped
5	UK test	0				
2	UK test	3.25	-	-	-	Damage due to unrelated issue
3	UK test	26.75	-	-	No deficit on dyno	20h completed on USA race bike Damage due to unrelated issue

Piston #03 at 20 hours.
The piston skirt and ring lands look in very condition in terms of contact wear; they would benefit further from a very small change in ovality. There was no measurable groove wear, 2.5 microns being considered a potential measurement error.
The pin bore surfaces look very good in terms of pin contact and wear.



B) Connecting Rod

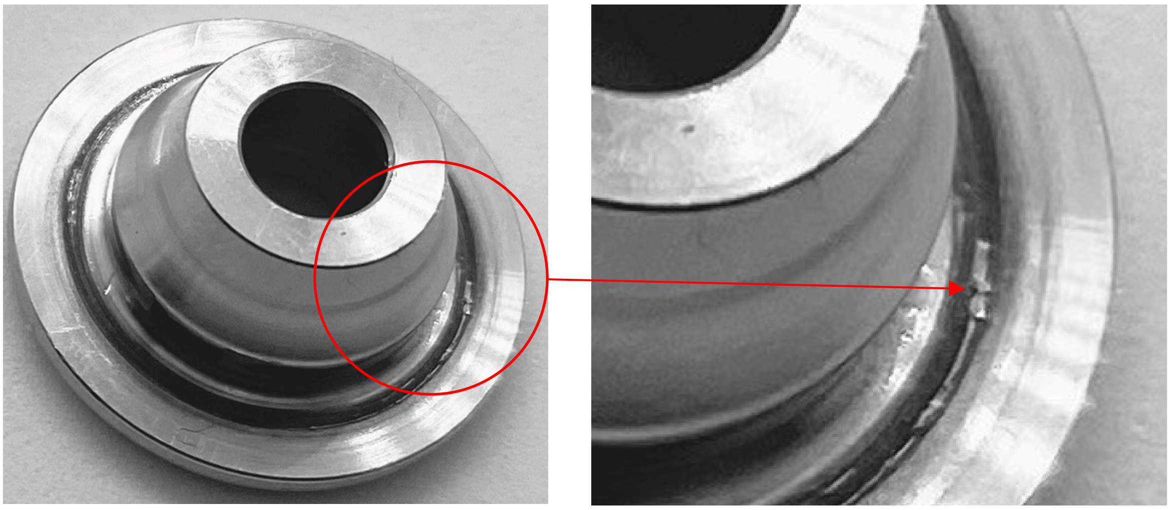
Prior to assembly of the rods into the engine, concerns were raised about the potential for scratching on insertion of the big-end bearings. Scratches or other damage to the big-end ID have been shown to form initiation sites for rod failure in both steel and titanium one-piece rods. Given the lower hardness of the base aluminium alloy in SupremEX, damage is more likely to occur to SupremEX than to steel or titanium during bearing insertion. Therefore, it was decided to remove the bearing shells from one of the rods and inspect for damage. The 2-piece conventional style bearing shells are fitted using an insertion tool. This was to minimise interference during insertion and avoid potential damage. However, despite best efforts damage occurred. Below is an image of the shell removed from one of the rods. The same damage is evident on both sides in all rods. The damage could occur during removal, however, rather than risk a rod failure, a redesign was implemented.



Initial engine testing demonstrated a performance gain with the new rod and hence the single piece bush solution was pursued and manufactured. The gain equates to 1-2% and is attributed to friction reduction. Testing will commence as soon as possible.

C) Spring retainer

- Spring retainers were fitted to all 4 engines. After less than 3 hours, one engine was stripped to check for damage on the retainer underside, per the concerns raised above. All retainers showed some damage which appears to be attributable to contact with the spring end. The decision was made to remove all SupremEX retainers and replace them with steel until a redesign could be completed.



Inlet side retainer contact damage.

The issue 02 design was implemented with a ToughMet washer to prevent the contact damage. This ran successfully for 6.75 hours over twice the hours as the previously damaged retainers had run. The redesigned parts look very good (as new) with no visible damage. The decision was taken to switch testing to a spin rig which would accumulate hours much quicker and with less risk. Below are images of the retainers and washers at 6.75 hours.

Spring side

Retainer side

D) Seats & Guides

The valve seats and valve guides have performed exceptionally well.

5 off cylinder heads were updated with PerforMet seats and ToughMet 3 AT110 guides.

As of the date of the report the heads have accumulated the following hours (they have since accumulated more):

- 28 hours USA race bike
- 20 hours USA test bike
- 10 hours UK test bike
- 3.25 hours UK test bike (damaged due to rod failure)
- 8 hours UK race bike

After each test a vacuum leak test is carried out to check valve sealing and guide wear.

All heads are within measurement error of being new heads which is remarkably good.

The seats visibly look good, and the guides are within tolerance.

On other motocross engines with very similar valvetrain geometry and rpm limits the guides would be replaced and seats re-cut or replaced at circa 12-15 hours based on leak test results or visible seat and guide wear/damage.

The image below is from the UK test bike at 10 hours. It's difficult to see in the image but seat contact is uniform and wear negligible. The RH image is a close-up of the exhaust seat contact.

Conclusion

Piston:
The AMC 4632 alloy provides a clear advantage over the conventional 2618 or cast hypereutectic material in terms of its high temperature fatigue strength and wear properties. It also has a lower density. The pistons have performed exceptionally with all targets being achieved. MXology will adopt this alloy across its range of pistons. Work will continue with Materion's SupremEX CA alloy with respect to manufacturability and tool life in particular. A SupremEX piston is currently in design for a 2-stroke motocross application.

Connecting rod:
The SupremEX 225CA MMC alloy has the potential for being a good connecting rod alloy due to its high specific fatigue strength. On Materion's previous engineering program the rod performed well in a 4-cylinder boosted engine test. The rods had conventional split caps, whilst the MXology rod is single piece and issues were experienced with the shell fitment. Failures initiating from big-end ID damage have been experienced on steel and titanium rods, so caution is necessary. The single piece bush will be tested and if the rod passes test, it will be introduced into the development program. It's fair to say that an MMC rod is a departure to the norm so further testing is required to gain sufficient confidence. Shot peening to further improve fatigue strength will also be considered.

Valve spring retainer:
The SupremEX 225XF MMC alloy has the potential for being a good retainer material. Contact damage with the potential for fatigue failure was observed. The shim was introduced, and the damage resolved. Further testing is required to validate the retainer. The retainer with shim still provided a 35% reduction in mass compared to the bearing steel retainer and this can likely be improved further. The production process is simple compared to a retainer that requires nitriding and shot peening. However, shot peening should also be considered to achieve a uniform surface finish and compressive residual stress benefit. Furthermore, the gain in engine rpm provided an advantage on track hence testing of the SupremEX retainer is continuing.

Valve seats and guides:
The PerforMet seats have performed very well as have the AT110 guides. This combination will be introduced to all MXology cylinder heads. The increased thermal conductivity of the seat allowed for its geometry to be optimised and also that of the valve head where improvements have been made.

Compression ring:
Further testing is required to appraise the PerforMet material as a piston ring alloy. Unfortunately, issues were introduced during coating and a valid test could not be carried out. Alternative coatings are in the process of being applied and will be tested as soon as possible. In the 250cc motocross application combustion knock is not an issue, so the potential advantages of the alloy's high thermal conductivity are limited to piston cooling and potentially reducing piston oil let flow to reduce windage losses. There may also be a gain to be found in ring friction at the very low tangential forces which can be achieved with the material's lower spring rate whilst maintaining a margin of safety for relaxation and ring control.