

Evolution of Residual Stress Through The Processing Stages in Manufacturing of Bore-Chilled Sand-Cast Aluminum Engine Blocks With Pressed-In Iron Liners

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Abstract

The cumulative global emissions produced by the automotive industry over the last decade has put a tremendous strain on the environment. Consequently, automotive engineers and manufacturers have been forced to improve the efficiencies of their automobiles which is frequently accomplished by increasing the operating pressure, and therefore temperature, of the combustion engine. Unfortunately, in addition to the rise in operational pressures and temperatures, large tensile residual stresses often accumulate in the cylinder bridges during the casting process of aluminum engine blocks due to the use of cast-in iron cylinder liners, leading to combined stress magnitudes above the strength of the currently used aluminum alloys. Thus, the present study aims to characterize the evolution of residual stress, with application of neutron diffraction, at several critical stages of the manufacturing process of sand-cast aluminum engine blocks that have eliminated the iron cylinder liners from the casting process and replaced them with cylinder bore chills that are pressed-out after the thermal sand reclamation process. The replacement of the iron liners shifted the stress mode from purely tension to purely compression until the bore chills were removed. Following removal of the bore chills, the maximum tensile stress at the top of the cylinder bridge was $\sim 70\%$ lower than the engine's predecessor which was produced with iron liners. Moreover, in the production-ready state (i.e., T7 heat treated, machined and press-fit liners inserted), the stress mode maintains the partially compressive nature with low magnitudes of tension, thereby lowering the material's susceptibility to crack growth and propagation.

Introduction

In early developments of combustion engines, cast iron alloys were the most frequently used material due to its high-temperature strength, good castability and heat treatability. However, the relatively high density of iron (Fe, density: 7.87 g/cm^3) resulted in excessively heavy engines that could not allow manufacturers to meet strict governmentally mandated efficiency regulations. Thus, it was necessary for manufacturers to start developing and utilizing lighter materials such as aluminum (Al, density: 2.70 g/cm^3) or magnesium (Mg, density: 1.74 g/cm^3) alloys. During the early implementation of lightweight materials, both Mg and Al alloys have been used for engine block production. However, Suman (1991) [1] indicates that Mg alloys have a high tendency to creep during elevated temperature loading (i.e., at $\sim 125 \text{ }^\circ\text{C}$), resulting in the quick outperformance and replacement by their stronger and more modifiable Al-based competitor alloys.

Although Al alloys have sufficient castability to produce high quality powertrain components, design engineers and manufacturers are still facing several issues related to the premature failure of their components. These failures are frequently caused by the presence of residual stress. Barson and Rolfe [2] indicate that the development of residual stress is most commonly attributed to gradient loading (thermal and/or mechanical), leading to non-uniform deformation in a constrained material. In cast components, this unequal loading is typically caused by thermal gradients within the casting that are produced by non-homogenous cooling and/or by a coefficient of thermal expansion (CTE) mismatch between varying material compositions. An example of the latter occurs in conventional Al engine blocks which require

protective Fe cylinder liners to resist the wear caused by the reciprocating piston during operation [3]. These Fe liners are typically cast-in, and due to the CTE mismatch between the gray Fe liners and the Al engine block, high tensile residual stresses accumulate along the cylinder bores during casting and post-heat treatment cooling. For example, Lombardi et al. [4], [5] observed that approximately 170-200 MPa of tensile residual stress accumulated in the Al cylinder bridges during the casting and heat treatment process of an as-cast V6 Al engine block with cast-in Fe liners. This magnitude of residual stress accounts for more than 80% of the alloy's available strength and once subjected to in-service operating conditions, the engine block may endure permanent dimensional distortion or cracking. This deformation or cracking can result in increased carbon emission, reduced engine efficiency, and/or complete engine break down.

Fortunately, this unwanted residual stress can be reduced by post processing techniques such as solution heat treatment (SHT) and artificial ageing. For example, solution heat treatment of A319 (AlSiCuMg alloy) Al engine blocks with cast-in gray iron liners has been carried out by Lombardi et al. [5] to analyze the relief in the residual axial strain via *in-situ* neutron diffraction (ND). It was observed that soaking the engine block at 470-500 °C for 8 hrs led to a ~50% reduction of the tensile residual stress present in the cylinder bridges. The study, like many, focused on the cylinder bridge of the engine block since this area experiences the greatest magnitude of thermomechanical loading and is therefore the most prone to cracking [6], [7]. After applying a commercial T4 heat treatment (SHT + quench), the stress in certain locations and orientations (i.e., most pronounced in the radial direction), of the cylinder bridge were observed to be in compression rather than in tension. This transition from tension to compression is particularly beneficial; though it may still contribute to possible engine block distortion, it should not cause cracking [8].

In another study, Lombardi et al. [9] also observed that the magnitude of residual stress in the cylinder bridges of a sand cast V6 Al (A319 alloy) engine block with cast-in gray iron liners was reduced considerably at the top of the cylinder bridge after a T7 heat treatment. However, the middle and bottom portion of the cylinder bridge experience only partial relief. The dissimilar stress relief from top to bottom of the cylinder bridge was presumed to be attributed to non-uniform cooling throughout the cylinder bore following solution treatment. It was also found that the over-aging portion of the T7 treatment caused a redistribution of the tensile residual stress from the top of the cylinder to the bottom. As a result, upon completion of the full T7 treatment, the residual stress was reduced by ~90 % and 10 % at the top and bottom of the cylinder, respectively, as compared to pre-heat treated state (i.e., after thermal sand reclamation (TSR) process).

Although the two latter described engine blocks were successfully introduced to the automotive market and contributed towards improving the efficiency of automobiles, the demand for greater efficiencies and consequently higher cylinder pressures in next generation engines leads to combined stress magnitudes above the relatively low strength of the cylinder bridge material (i.e., $YS = \sim 195$ MPa and $UTS = \sim 205$ MPa in TSR condition, Lombardi et al. [9]). The strength of the cylinder bridge material is limited due to coarse microstructure caused by insufficient cooling rates below the deck surface (i.e., top) of the engine

block. Specifically, the cooling rate decreased by 88% from the top to the bottom of the cylinder bridge (i.e., 12.5 °C/s at the top and 1.5 °C/s at the bottom). The large difference in cooling rates from top to bottom not only results in inconsistent mechanical properties but also in the development of residual stress, in addition to the residual stress already caused by the presence of the cast-in Fe liners. Thus, to develop the next generation of closed-deck or semi closed-deck Al engines, it is necessary to modify the currently used manufacturing methods and focus on improving the material's strength while reducing the accumulation of residual stress.

To combat the issues related to residual stress and insufficient/inconsistent mechanical properties, automotive manufacturers, such as Nemak, have begun introducing new methods for increasing the solidification cooling rates, minimizing gas entrapment during casting, and refining the microstructure of their alloys. For example, in a previous study conducted by the authors, Stroh et al. [10] investigated the effects that two process modifications (i.e., eliminating the cast-in liners from the casting process and integrating cylinder bore chills) has on the solidification cooling rates and tensile properties of the cylinder bridge material in an as-cast inline, six-cylinder Al engine block. The study found that the use of bore chills during the production of the I6 engine block led to a more refined microstructure and homogenized the mechanical properties along the entire depth of the cylinder bridge, as compared to the cylinder bridge of the V6 engine block described by Lombardi [11]. Specifically, the study revealed that the yield strength and ultimate tensile strength at four depths along the cylinder bridge (i.e., Top, Middle, Lower Middle, and Bottom) deviated less than 5% from each other. The high degree of homogeneity was attributed to the lower variance in cooling rates from top to bottom (i.e., variation between maximum and minimum cooling rate was 20% lower in the I6 engine block) as compared to the V6 engine block. Moreover, the average YS and UTS also increased by ~5 and 35%, respectively.

Although the bore chills led to a notable homogenization of the microstructure and improvement of the mechanical properties of the cylinder bridge material, the effects that the bore chills have on the evolution of residual stress is unknown. Therefore, the current study aims to characterize, for the first time, the effects that integrating steel bore chills during the casting process has on the evolution of residual stress in the cylinder bridge of sand-cast Al engine blocks. At the same time, the current study will characterize the impacts that removing the protective Fe cylinder liners from the casting process and pressing them in a later date have on the residual stress profiles of the I6 engine block.

Materials And Methods

The engine blocks examined in the present research were produced at the Nemak Windsor Aluminum Plant in Windsor, Canada. The engine blocks were cast using a precision sand casting technique that is based on the Cosworth process. The modified casting process ensures quiescent mould metal filling, thereby improving component structural integrity by reducing the entrained oxide biofilms as well as oxide induced shrinkage porosity in the castings. A schematic of the Nemak-Cosworth core package, with an illustration of the "rollover" process, is shown in Fig. 1.

The modified Nemak-Cosworth casting process, which is detailed by Byczynski and Mackay [12], utilizes a mechanical pump to enable complete upward filling, as this eliminates the need for a pouring basin and downsprue, and precise control of the mould filling profile to mitigate the formation of casting defects. Upon complete filling of the sand mould, the package is rotated 180° (“rollover”) while remaining pressurized by the pump to ensure effective feeding of shrinkage from the risers (which acted as the in-gates prior to the rollover) to reduce the volume fraction of porosity in the casting. In addition, the most recent Nemak-Cosworth process utilizes steel chills that are inserted into the cylinder bores and the crankcase (bulkhead) to accelerate the cooling rates in regions adjacent to these chills. The increasing solidification cooling rate improves the local strength in these critical locations and reduces shrinkage porosity defects in the thick casting sections. The increased strength, as a result of chills placed in the cylinder bores of the I6 block, was evidenced by a yield strength of approximately 271 MPa in the head bolt columns adjacent to the cylinder bridge of this block in the T7 heat treated state as compared to approximately 183 MPa for the T7 treated V6 Al engine block that was cast using the same 319 type alloy, but without the bore chills.

The composition of the modified 319 Al alloy used for the production of the I6 engine blocks described in the present study is listed in Table 1. Following the Nemak-Cosworth casting process described above, the engine blocks were subjected to a TSR treatment at 485°C for approximately 5 hrs (although the castings are only at this temperature for ~1.5 hrs during TSR) to ensure that all of the sand was effectively removed from the castings. The castings were then de-gated, followed by the removal of the bore and crankcase chills. Then, the engine blocks underwent a solution heat treatment at 485°C for 6 hrs followed by a forced air quench (T4 condition).

During operation, this high-performance engine can experience peak temperatures in the range of ~180-190°C. As a result, in the TSR and T4 condition, this temperature would artificially age the 319 Al alloy and while the property changes are not necessarily problematic, the dimensional growth is an issue for bearing clearances and bore distortion. Consequently, the T4 engine blocks were then artificial aged at 210°C for 5.5 hrs (T7 condition). Following the T7 treatment, select blocks were machined and then the cylinder bore regions were heated to approximately 150°C and the gray iron liners were press-fit into the cylinder bores.

Table 1
Composition of aluminum 319 alloy used for production of the cast engine blocks

Alloy	Si	Cu	Fe	Zn	Mn	Mg	Sn	Ti	Ni	Cr	Sr	Al
319	8.50	2.76	0.59 max	0.50	0.44	0.33	0.08	0.13	0.07	0.04	0.01	Bal.

To determine the evolution of residual stress throughout each step of Nemak’s manufacturing process, residual stress mapping using ND was performed on the cylinder bridges of five sand cast, inline 6-cylinder Al engine blocks. The engine blocks were in the following conditions: i) as-cast with steel bore chills remaining in place (TSR + Chills), ii) as-cast with the steel bore chills removed (TSR), iii) T4 heat

treated (T4), iv) T7 heat treated (T7), and v) production ready T7 engine block with pressed-in Fe liners and final machining (T7LM) (see Fig. 2).

Since the upper part of the cylinder bridge is exposed to the greatest level of thermomechanical loading during in-service operation [6], [7], Nemak has incorporated a ~ 10 mm tall, 3 mm wide cooling channel (see Fig. 3) in each of the cylinder bridges. Byczynski and Mackay [12] conducted a preliminary finite element thermal simulation of a cylinder bridge without a cooling channel, with conventional drilled cooling channels, and with the cast cooling channel. The qualitative results clearly show that the cast inter-bridge cooling channel reduces the thermal load experienced by the cylinder bridge during engine operation, leading to lower temperature-related failures. Moreover, the increased cooling capacity and may allow Nemak to increase the operating pressure and therefore efficiency of their engines. However, the effect that the cooling channel has on the residual stress has not been studied or reported in open literature.

The first experiment (i.e., TSR) was performed on the NRSF2 beamline at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, USA and the second (i.e., TSR + Chills and T7) and third (i.e., T4 and T7LM) were performed on the Kowari beamline at the Australia Nuclear Science and Technology Organization (ANSTO) in Lucas Heights, Australia. The instrument setup for ORNL and ANSTO are described in detail in [13], [14]. The analysis was performed from the top ($z = 6$ mm) to bottom ($z = 146$ mm) of the center of the middle and edge cylinder bridges of non-sectioned engine blocks (see Fig. 3). A detailed description of the ND theory is explained in [3], [15], [16], and the experimental setup and data processing is described in [11], [17].

Due to the high attenuation of the neutron beam with the thick-walled, steel bore chills in the TSR + Chills engine block, the radial orientation of strain could not be measured. Consequently, it was necessary to remove some of the steel along the neutron beam path (see Fig. 4). To ensure the residual stress in the Al cylinder bridge was not significantly affected after removing material from the chill, the outer and inner wall of the bore chill remained fully intact. It should be noted that even after removing some of the iron from the chill, the high attenuation of neutrons in Fe prevented accurate measurement of the radial strain below the 42 mm position of the middle bridge of the TSR + Chills engine block.

Results

3.1 Residual Strain

3.1.1 Residual Strain in the TSR + Chills Engine Block

The residual strain profiles for each of the engine blocks are shown below in Fig. 5 to Fig. 10. Similar to Fig. 2, the strain charts are presented in order of the manufacturing process. The high solidification cooling rate of the cylinder bridge material (~5-14°C/s), as reported by Stroh et al. [10] and caused by the integration of the thermally-massive bore chills, led to the evolution of compressive strains (i.e., negative

strain) for all three orientations of strain (i.e., axial, radial, and hoop) along the entire depth of the cylinder bridge of the TSR + Chills block. C. Dong et al. [18] found that increasing the cooling rate from 0.5°C/s to 40°C/s led to an increase of the compressive stress in their alloy from approximately -200 MPa to -400 MPa.

In addition to the compressive stress caused by the relatively fast cooling rates, the smooth surface of the Fe bore chills, as opposed to the ribbed surface of conventional cast-in liners, allows for a less restricted contraction of the solidifying Al relative to the steel chill. The ribbed surface of conventional cast-in Fe liners is present to promote mechanical interlocking at the interface between the Al cylinder wall and the Fe liner. This is one of the primary factors, in addition to the increased cooling rate, for the observed compression in the TSR + Chills block, as compared to the engine block with cast-in Fe liners [5], [11], [19].

In more detail, qualitatively, this phenomenon can be explained as followed. In the sand-casting process described in these earlier studies, once the molten Al alloy was poured around the pre-heated Fe liners, the liner could quickly reach the solidification temperatures of Al. Following this, the temperature differences between different parts of the casting system (Fe liner, Al engine block, and interior surfaces of the sand mould/cores) were relatively small, leading to mostly volumetric shrinkage of Al around the cast-in Fe liner. During further cooling, the accelerated rate of contraction of Al (relative to the chills), which was constrained by the ribbed liner, led to formation of tensile forces in the Al cylinder bridge.

In the modified Nemak-Cosworth process presented here, Al solidification initiates around the thermally massive steel chills, rapidly forming a cylindrical solid shell around the chill. The smooth surface of the tapered chill prevents interlocking and, as already mentioned, allows for relative sliding motion at the chill-shell interface. As a result, no tensile stress is formed in the Al shell. As the process evolves, the large amount of material surrounding the cylinder bridge contracts towards the center of the cylinder bridge, bringing the hoop orientation into compression. It is exactly this contraction in the hoop direction that is causing the observed compression in the radial orientation. As both sides of the engine block are contracting inwards in the hoop direction (i.e., towards the center of the bridge), the contracting material, and compressive forces, have no other option but to redistribute outwards in the radial direction. However, since the material near the center of the bridge has solidified and is now fixed rigidly in place by the iron chills, the outward motion in the radial direction is restricted, leading to the observed compression in the radial orientation.

Comparing the strain profiles for the edge and middle bridge of the TSR + Chills engine block, reveals that in addition to improving the mechanical properties of the cylinder bridge material, the homogenous cooling applied by the steel chills has also resulted in similar strain profiles through each of the engine's cylinder bridges. Specifically, at the top of the bridge, the hoop and axial orientations of both bridges experience approximately -400 to -500 $\mu\epsilon$ and -2300 to -2400 $\mu\epsilon$, respectively. Progressing down the cylinder bridge, the hoop and axial strains merge towards approximately -1200 $\mu\epsilon$ from the 50 mm to the 110 mm depth, where further down the bridge, the strains begin to diverge in opposing directions. These

magnitudes of strain in the axial and hoop orientation are comparable to previous ND stress experiments, although in compression rather than in tension. Although the hoop and axial orientation are similar in magnitude to previous studies, the radial residual strain at the top of the cylinder bridge is much greater than typically observed, reaching approximately $-3400 \mu\epsilon$. Fortunately, the radial strain decreases nearly linearly in magnitude with increasing depth along the cylinder bridge. One of the main reasons for the gradual decrease in the magnitude of radial strain from the 6 to 42 mm position is the tapered wall thickness of cylinder bridge (i.e., ~ 10 mm and 19 mm at the top and bottom, respectively) which is incorporated to facilitate the extraction of the steel chill after the casting process [10]. The larger wall thickness at the bottom of the cylinder bridge permits a greater distribution of the forces at this location, as compared to the top, and therefore results in the observed decrease in strain. This claim is supported by the results presented by Carrera et al. [20] who characterized the residual strain/stress in V8 engine blocks using strain gauges. They found that an increase in wall thickness from 3.4 mm to 4.8 mm led to a 40 MPa reduction of stress in their cast V8 Al engine block.

3.1.2 Residual Strain in the TSR Engine Block with Chills Removed

Prior to heat treatment, the steel bore chills are mechanically removed from the engine blocks. The effect that this operation has on the magnitude of strain is shown in Fig. 6. The removal of the bore chills released a significant portion of the axial strain at the top of the cylinder bridge, reducing its magnitude from ~ -2400 to $\sim -600 \mu\epsilon$. As the chills are mechanically pressed out of the engine block, the material around the cylinder bores is partially pulled along the axial direction. However, the further away from the free surface (i.e., away from the top deck of the engine block), the harder it is for the strain to be released. Thus, the axial strain from the 30 mm to the 146 mm, remains relatively unchanged. In general, the hoop orientation of strain has been reduced for the majority of locations along the cylinder bridge with the exception of the top location (i.e., 6 mm). The lack of strain release at the top of the cylinder bridge is due to the initially low magnitude of strain present at this location prior to removing the Fe chills. Conversely, the removal of the steel chill led to a large shift in the nature of the radial strain from highly compressive to moderately tensile, particularly at the top of the bridge. This suggests that the mechanical interaction between the steel bore chills and the Al bridge is elastically locking the radial stress in place and it is not until the chills are removed that the stress can be released. Unlike the axial and hoop orientations, which can glide more readily against the smooth bore chills, the flow and contraction of the material during solidification and subsequent cooling in radial direction oppose one another and are bound between two adjacent Fe chills.

Similar to the strain in the TSR + Chills block, the strain in both the middle and edge bridge of the TSR block is nearly identical, owing to Nematik's unique manufacturing process which results in homogenous cooling throughout the each of the cylinder bridges.

3.2.3 Residual Strain in T4 and T7 Treated Engine Blocks

The effect of the T4 heat treatment on the residual strain is shown below in Fig. 7. In general, the strain at nearly all locations shifted from compression to tension and the magnitude of strain in all three orientations was also reduced. For instance, the maximum magnitude of strain is now less than 1000 $\mu\epsilon$, which is considerably lower than in the TSR + Chills ($\sim 3400 \mu\epsilon$) and the TSR ($\sim 1700 \mu\epsilon$) blocks. The cause for this strain reduction is driven by the solutionizing step of the T4 process, in that during the elevated temperature holding (485°C for 6 hrs), the yield strength of the alloy is greatly reduced, and thus plastic flow occurs more readily and results in the relaxation of the material. One of the main reasons for the shift towards tensile strain is caused by the forced air quenching process that occurred immediately after solution heat treatment. To explain the results, the hoop orientation is considered. Since the cylinder bridge is the thinnest section in the engine block, the quenching process forces the cylinder bridge to contract more quickly than the surrounding thicker material. Towards the end of the quenching process, the thicker sections of the engine block contract more rapidly than the cylinder bridge, due to the equilibration of temperature gradients in adjacent sections of the block, causing tensile stresses to be exerted on the cylinder bridge and resulting in an overall tensile residual stress profile in this region. The bridge is less constrained in the axial orientation, but it can be implied that the overall reorientation of the contraction forces brings the bridge to some added axial tension, at the same time somewhat reducing the radial tension.

It is important to note that unlike the V6 Al block with cast-in gray iron liners presented in [5], the residual strain profiles of the I6 blocks, discussed in the present study, were relatively uniform and of significantly lower magnitude. The primary cause for the lower magnitudes of strain in the I6 block is the absence of the ribbed iron liners, which minimizes the stress-generating thermo-mechanical mismatch experienced by the cylinder bridge during and after quenching.

Figure 8 shows the strain profiles for the cylinder bridges of the T7 engine block. Similar to the TSR and T4 bridges, a large resemblance between the two T7 bridges, particularly for the axial and hoop orientations, was observed. The high temperature aging (210°C) portion of the T7 heat treatment has redistributed the strain along most of the cylinder, as compared to the T4 heat treated block. For example, it was observed that the upper middle section ($\sim 30-75$ mm) of the cylinder bridge transitioned from tension to compression for the axial and hoop orientations. An explanation behind this observation is offered later in this paper, in the discussion of the stress profiles calculated from the strain measurements.

3.2.4 Residual Strain in the T7 Treated Engine Block with Pressed-in Liners

It has been well documented by Lombardi et al. [9], [11] that the CTE mismatch between the Al block and the cast-in liners, introduces a considerable amount of residual strain during solidification and subsequent cooling. Fig. 6 to Fig. 8 clearly show that this issue has been resolved by removing the liners from the casting process. However, without an additional protective layer inside the cylinder, the Al alloy walls would quickly wear during in-service operation. For this reason, the cylinder bores are first machined

and then heated to insert a thin (~2 mm thick) press-fit Fe liner. The increase in temperature temporarily enlarges the bores and consequently allows for facilitated insertion of the liners. Once the engine block returns to ambient temperature, the aluminum contracts around the Fe liners and results in a retaining force between the Fe liners Al cylinder block. This is exactly what is shown in Fig. 9. The two adjacent Fe liners resist the contraction of the Al bridge (contraction of a hole during cooling results in a smaller internal diameter) during cooling and both liners apply an opposing radial force onto the bridge, resulting in the observed increase in compressive strain in the radial orientation. The strain in the axial and hoop directions are much less affected by the insertion of the liners and thus are very similar in magnitude as compared to the linerless T7 block (see Fig. 8). The minor differences in the axial and hoop strain are attributed to the removal of material during the machining process.

Although the strain profiles shown in Fig. 5 to Fig. 9 provide a great indication of the how the strain evolves during each of Nematik's manufacturing process, it is difficult to directly compare them to the alloy's strength. For this reason, the residual stress was calculated using the generalized Hooke's law and the results are presented in the following section.

3.3 Residual Stress

Figure 10 shows the stress profiles in the TSR + Chills engine block. The high attenuation of neutrons in Fe restricted the measurement of radial strain to below the 42 mm position. For this reason, the stress could only be calculated within the 6 to 42 mm position. It was observed that very high magnitudes of compressive stress were present in all three orientations, reaching maximums of about -350 to -500 MPa. Although the magnitude of strain in the axial and hoop orientations for this engine block were comparable to literature, and likely tolerable, the effect of Poisson's ratio can clearly be observed (i.e., high magnitude of compressive strain in radial orientation leads to larger compression in axial and hoop directions). It was also observed that the tapered wall causes a near linear decrease of the magnitude of compressive stress, reaching just over -300 MPa by the 42 mm position.

The residual stress profiles for the TSR block are shown below in Fig. 11. As expected, the stress profiles of the edge bridge follow a similar trend as compared to the strain profiles shown in Fig. 6. The radial orientation of stress is tensile above the cooling channel (maximum of ~100 MPa) and below the lower half of the cylinder bridge (maximum ~ 75 MPa). Moreover, although the cooling channel provides additional cooling to the cylinder bridge during operation, it seems to be acting as a stress concentrator, as evidenced by the consistent shift in strain/stress above and below the cooling channel.

The exact stress produced during engine operation is difficult to quantify but Satyanarayana et al. [21] suggests that up to approximately 60 MPa of stress may be introduced during normal operation of typical unmodified diesel engines. Garat [22] suggest a slightly lower stress of about 20-30 MPa. Regardless of the exact value, even with the combined contribution of operational and residual stress, the magnitude of tensile stress in the cylinder bridge is still well below the materials as-cast yield strength of ~ 205 MPa [10].

The combined contribution of the tensile strain that has evolved during the quenching portion of the T4 heat treatment led to an increase in tensile stress at all locations of the cylinder bridge, with the exception of section above the cooling channel (see Fig. 12). The maximum magnitude of residual stress in the T4 engine block reached approximately 150 MPa, which is approximately 30% lower than reported by Lombardi et al. [5] for a solution heat treated engine block that was produced with cast-in gray iron liners.

The high strength and low residual stress present in the TSR and the T4 engine blocks would likely perform sufficiently in-service. However, the automotive industry is continuously driving towards improved performance and efficiencies which are both largely related to the internal combustion pressure and temperature. For this reason, Nemak has chosen to further improve their engine blocks by applying a T7 heat treatment for the 319 Al alloy, which results in a dimensionally stable casting during service, reducing cylinder bore distortion and associated negative side effects (i.e., blow by and oil consumption). The ageing process has shifted the stress from tension to compression at the 30 to 70 mm position (compare Fig. 12 and Fig. 13), whereas the tensile stress in the bottom half of the cylinder bridge has relaxed and reduced in magnitude. The relatively long elevated-temperature ageing process led not only to stabilization of the microstructure, but also to a new redistribution of the residual forces locked in the component. Fig. 14 indicates that following artificial ageing, the resulting stress profiles somewhat resemble again the profiles observed in the after-TSR engine block, with the upper middle part of the cylinder bridge (i.e., below the cooling channel) being in compression. Seemingly, the fast-cooling rates associated with the quenching process resulted in a quasi-stable stress distribution throughout the component, which was reduced in magnitude during ageing and re-modified in the slow cooling to room temperature. The tensile stress at the top of the cylinder bridge remains mostly unchanged and reached a maximum magnitude of 61 MPa which is slightly improved as compared to the T4 block (~69 MPa).

Finally, Fig. 14 shows the residual stress in the production-ready, sand-cast Al engine block which has been machined and Fe liners have been mechanically inserted into the cylinder bores. Comparing Fig. 13 and Fig. 14 reveals that no significant change has occurred in the axial and hoop stress profiles. However, the insertion process, including pre-heating of the engine block, has shifted the radial stress at the upper middle to middle section towards a higher magnitude of compression. As mentioned in the section on strain, this shift is attributed to the temporary radial enlargement of the Al cylinder bore during heating which causes a subsequent compressive radial force to be applied by the liner onto the Al cylinder bridge after returning to room temperature. The magnitude of stress at the top of the cylinder bridge was observed to vary between -10 and +50 MPa, suggesting, that in addition to the ~ 60 MPa operational stress for diesel engines, more than half of the alloy's strength remains useable at this critical location of the cylinder bridge.

Discussion

Neutron diffraction was used to study, for the first time, the effects that integrated bore chills and the use of pressed-in iron liners, as opposed to cast-in iron liner, have on the evolution of residual stress in the cylinder bridge of sand-cast I6 aluminum engine blocks. The maximum magnitudes of stress at four

depths along the cylinder bridge (i.e., top, upper middle, lower middle and bottom) of this I6 block is compared to a V6 Al block with cast-in gray iron liners (see Table 2).

In the present study it was observed that the steel bore chills led to a considerable amount of compressive stress in the cylinder bridges, reaching over -300 MPa in compression. Fortunately, by mechanically removing the chills, a considerable portion of this compressive stress is released, particularly at the top of the cylinder bridge: the location most prone to cracking. Once subjected to the T4 heat treatment (i.e., solutionizing and quenching, the stress profiles in all three orientations (i.e., radial, axial, and hoop) shift nearly entirely to tension. This shift is primarily caused by the quenching portion of the T4 treatment due to the variation in material thickness between the thin cylinder bridge (i.e., fast cooling) and the thicker surrounding material (i.e., slower cooler). In both the as-cast (TSR) and T4 treated state, it is likely that the combined magnitude of operational and residual stresses would not exceed the yield strength of the alloy (~205-210 MPa). However, the elevated operating temperature of the high-performance engine (i.e., 180-190°C) would result in artificial ageing and could lead to dimensional instability. Thus, an elevated temperature (i.e., 210°C) T7 temper was applied. In addition to improving the geometric stability of the engine block, the T7 treatment reduced the residual stress at the top, lower middle and bottom section of the cylinder bridge, as compared to the T4 I6 block.

Table 2
Residual stress evolution in sand cast engine blocks (units in MPa)

Engine Type		Bore Chills and Pressed-in Fe Liners (Current study)					Cast-in Fe Liners Lombardi et al. ([5], [9])		
		TSR + Chills	TSR	T4	T7	T7LM	TSR*	T4	T7
Top	Radial	-505	93	69	44	0	-65	25	17
	Axial	-447	-4	48	61	23	63	55	9
	Hoop	-351	6	60	-15	51	158	120	21
Upper middle	Radial	-300	-75	31	-44	-84	38	-75	55
	Axial	-303	-168	38	-128	-126	160	45	101
	Hoop	-330	-167	43	-90	-99	225	100	103
Lower middle	Radial	-	59	66	35	-71	55	-80	41
	Axial	-	-41	72	15	-31	160	35	102
	Hoop	-	-26	72	27	-20	208	-10	149
Bottom	Radial	-	36	55	-11	41	-95	-125	49
	Axial	-	-58	68	31	60	15	5	106
	Hoop	-	2	73	24	65	88	-30	157

*** Average between TSR A and TSR B**

Comparing the residual stress profiles presented in this work to Lombardi et al. [5] who utilized neutron diffraction to determine the stress in a sand-cast engine block with cast-in iron liners, clearly shows the effectiveness of the recently developed Nemak-Cosworth process. The magnitude of residual stress in almost all sections of the I6 engine block with pressed-in liners is lower in magnitude, as compared to its predecessor which was produced with cast-in liners. For example, in the TSR condition, the use of pressed-in liners results in a maximum tensile stress at the top of the cylinder bridge of only 93 MPa, whereas the stress produced with cast-in liners reaches 158 MPa. Combined with operating loads of up to ~ 60 MPa and stress concentrators like porosity and cracks [23]–[25], it is possible that the high tensile stress in the cast-in Fe lined engine block would surpass the material's yield strength, particularly at elevated temperatures.

Although the T4 I6 engine block shifted from compression to tensile, the magnitude of stress was consistently lower than the engine block produced with cast-in liners. Further, once subjected to the T7 heat treatment, machined and the thin Fe liners were inserted, the residual stress remained lower at almost all locations in the I6 block as compared the engine block produced with cast-in liners. Thus, with

the refined microstructure, improved tensile strength, and generally lower residual stress, the I6 engine block can withstand greater operating pressures, and could lead to an overall efficiency increase.

Conclusions

This study characterized the evolution of residual strain and stress in Nemak's newly developed inline 6-cylinder sand-cast Al engine blocks. The latest generation Nemak-Cosworth casting process utilizes integrated steel bore chills to refine the microstructure in the cylinder bores and adjacent head bolt columns of the cast engine blocks. This study evaluated the evolution of residual strain/stress through five individual steps along the manufacturing process, including i) post TSR with chills remaining in place (TSR + Chills), ii) after the chills have been removed (TSR), iii) solutionized and quenched (T4), iv) aged (T7), and finally v) production ready (T7 with bore machining and insertion of Fe liners). The following conclusions can be drawn from the study:

1. The use of steel bore chills during the casting process led to a significant accumulation of compressive stress (i.e., greater than -300 MPa) in the radial, axial and hoop orientations in the cylinder bridge. However, the removal of the bore chill allowed the cylinder bridge to relax elastically and reduced the magnitude of stress at the top of the bridge in the radial, axial, and hoop directions to ~100, -4, and 6 MPa, respectively. This magnitude of stress is considerably lower than the alloy's as-cast yield strength of ~205-210 MPa.
2. The T4 heat treatment reduced the magnitude of radial stress at the top of the cylinder bridge but has shifted the nature of the stress below the cooling channel to tension. The shift towards tensile stress is primarily caused by the quenching portion of the T4 heat treatment, in that the thicker material adjacent to the cylinder bridge contracts more slowly than the thin cylinder walls and pulls the center of the bridge into tension towards the end of cooling.
3. To further improve the dimensional stability, thermal stability, and elevated temperature properties of the I6 engine block, a T7 temper was applied. Compared to the stress in the T4 engine block, the T7 temper lowered the magnitude of stress at the top, lower middle, and bottom of the bridge and shifted the upper middle section to compression.
4. The combined effects of pre-heating and mechanical insertion of the liners in the T7LM block did not considerably affect the axial and hoop stress; however, the radial stress in the upper half of the cylinder bridge shifted slightly towards more compression. Since the top of the cylinder bridge is typically the area exposed to the greatest level of thermo-mechanical loading and is most prone to cracking, it is one of the locations most concerning for engine manufacturers. The results from this study indicate that the combined contribution of the in-service operational stress (~ 20-60 MPa for diesel engines) and the maximum residual stress at the top of the cylinder bridge that has developed during the manufacturing process (~ 51 MPa) will account for less than ~ 50% of the material's yield strength.
5. The contribution of the integrated bore chills and replacement of cast-in Fe liners with mechanically inserted Fe liners has reduced the magnitude of tensile stress present throughout the majority of the cylinder bridge. Moreover, the nature of the stress shifted from purely tensile to partially in

compression, thereby lowering the material's susceptibility to crack growth and propagation. Combined with the improved mechanical properties of the 319 Al alloy, the T7LM engine block will help the automotive industry meet their strict, governmentally enforced efficiency targets. Moreover, the results presented in this study provide manufacturers with key information regarding the effects that each step of the manufacturing process has on the evolution of residual stress, allowing for process optimization focused on obtaining optimum residual stress to strength ratios.

Declarations

Acknowledgments

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Statements and Declarations

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b. Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

c. Availability of data and material

The raw and processed data required to reproduce these findings are available to download from Mendeley Data ["Data for Residual Stress in I6 Engine Blocks, <http://dx.doi.org/10.17632/vz6krysd36.1>"].

d. Code of availability

Not applicable.

e. Ethics approval

Not applicable.

f. Consent to participate

All authors give consent to participate in the study and its subsequent publication.

g. Consent for publication

All authors consent to publication.

h. Authors contributions

All authors contributed to the study conception and design. Material preparation was performed by Joshua Stroh, Dimitry Sediako, Anthony Lombardi, and Glenn Byczyński. Data collection and analysis were performed by Joshua Stroh, Dimitry Sediako, Mark Reid, and Anna Paradowska. The first draft of the manuscript was written by Joshua Stroh and all authors commented on all versions of the manuscript. All authors read and approved the final manuscript

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Figures

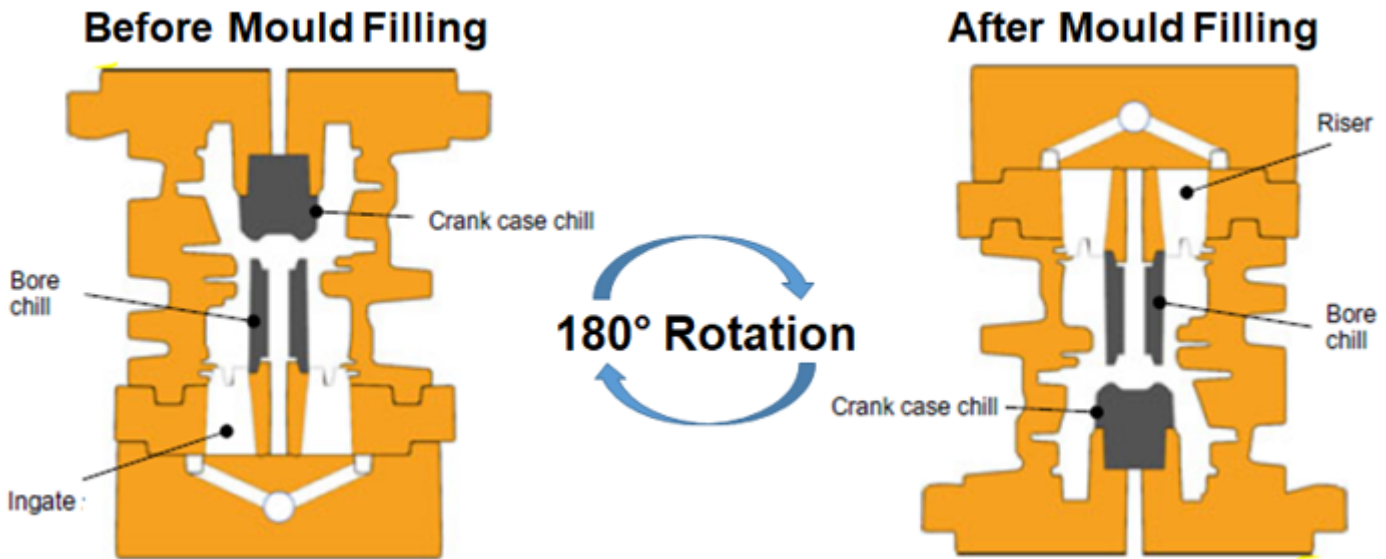


Figure 1

Schematic of Nemak-Cosworth mould design used to cast the engine blocks (Adapted from Byczynski and Mackay [12])

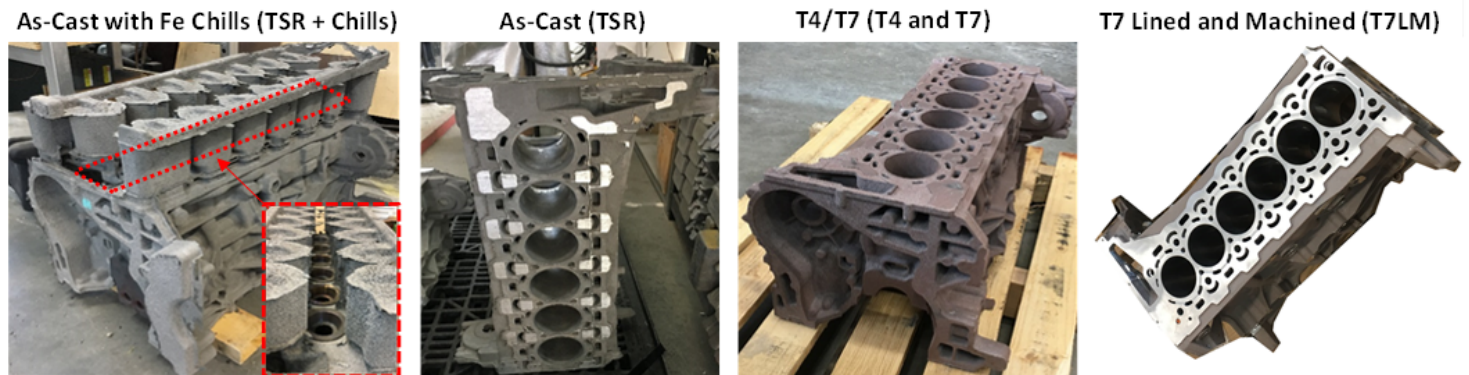


Figure 2

Engine block samples used for the completion of this study

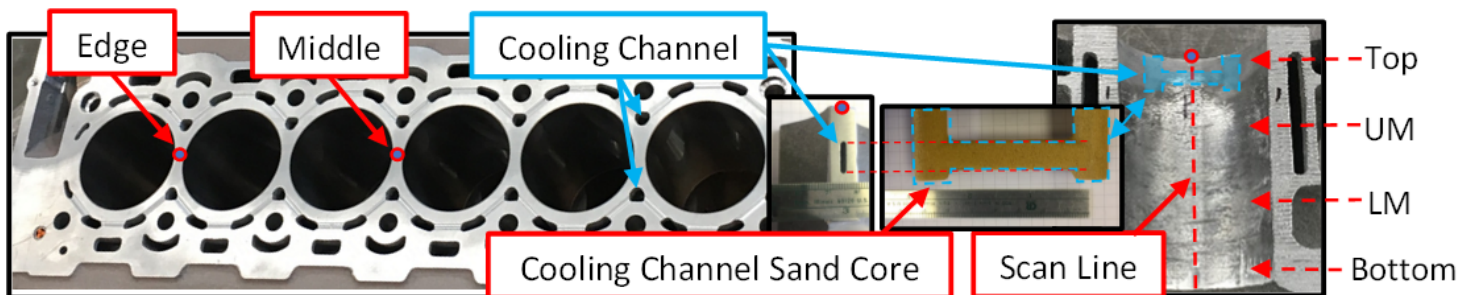


Figure 3

Location of scan lines and cooling channel

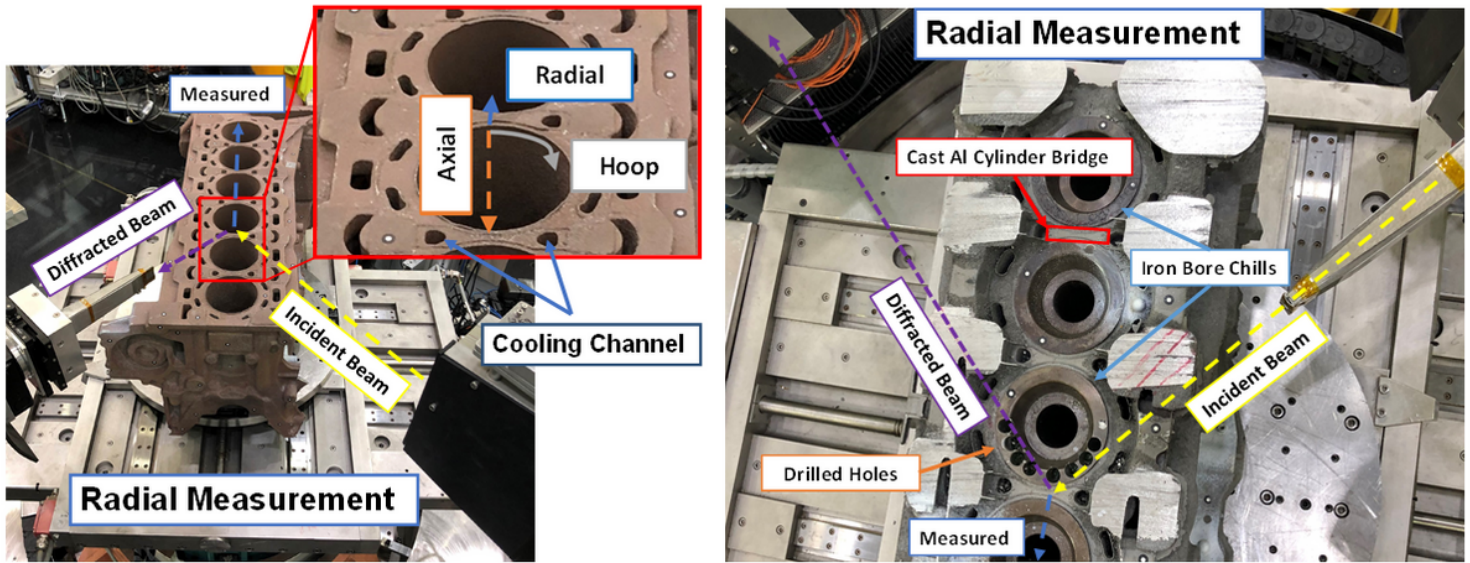


Figure 4

Neutron diffraction and sample setup on the Kowari instrument for radial strain components, left) orientation of measurements, right) removal of iron from neutron beam path for the TSR + Chills engine block

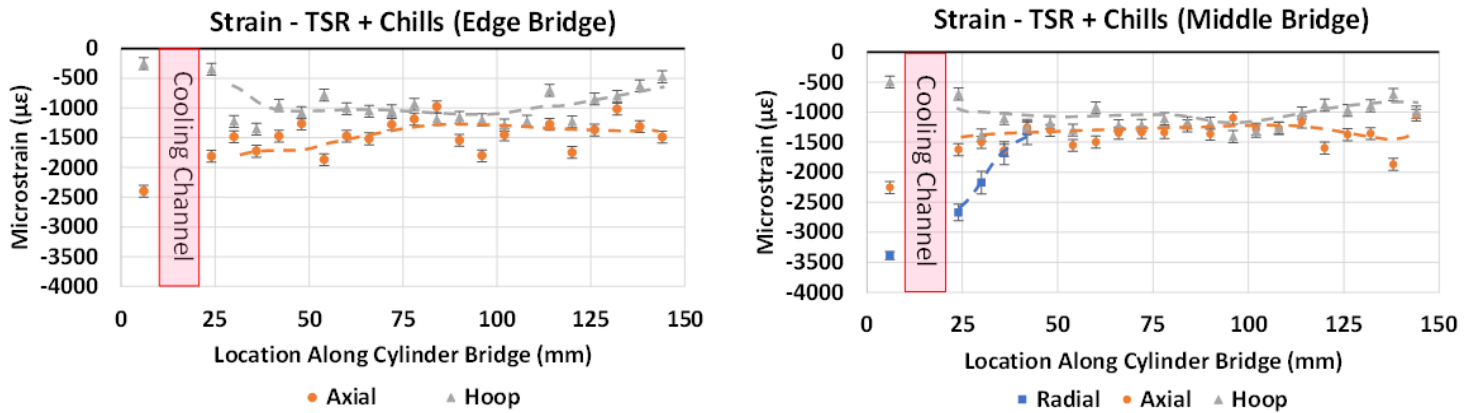


Figure 5

Residual strain profiles for TSR + Chills engine block

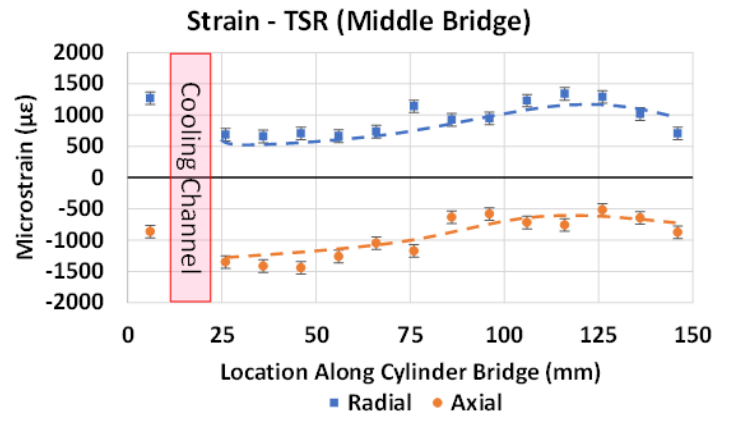
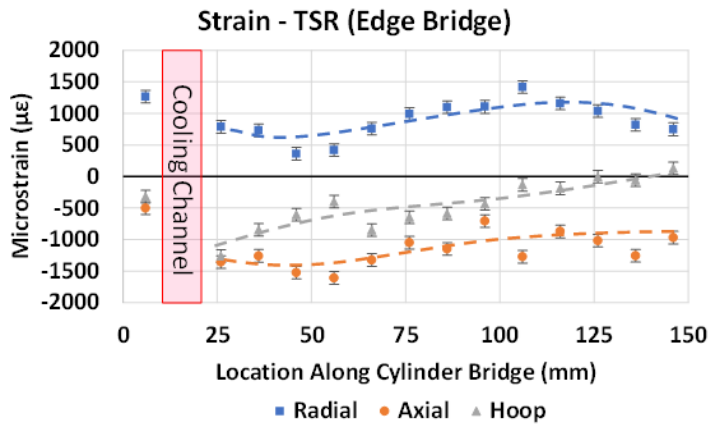


Figure 6

Residual strain profiles for TSR engine block

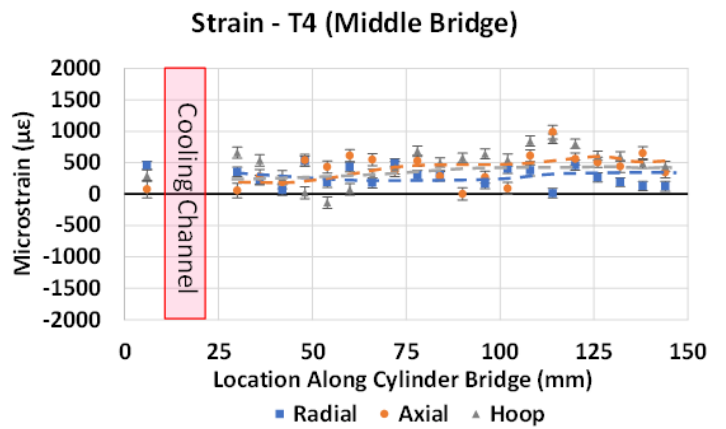
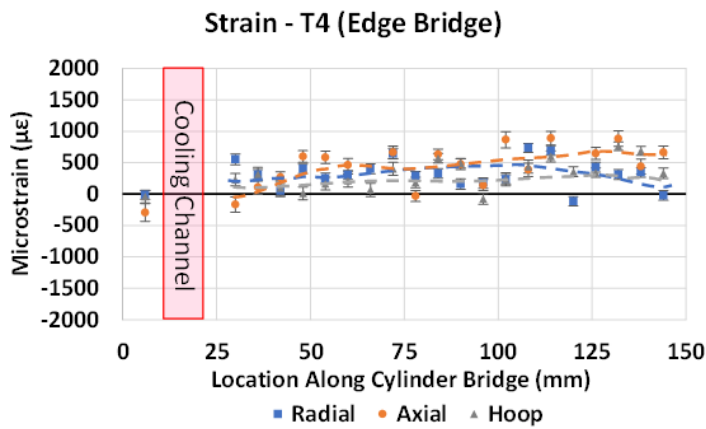


Figure 7

Residual strain profiles for T4 engine block

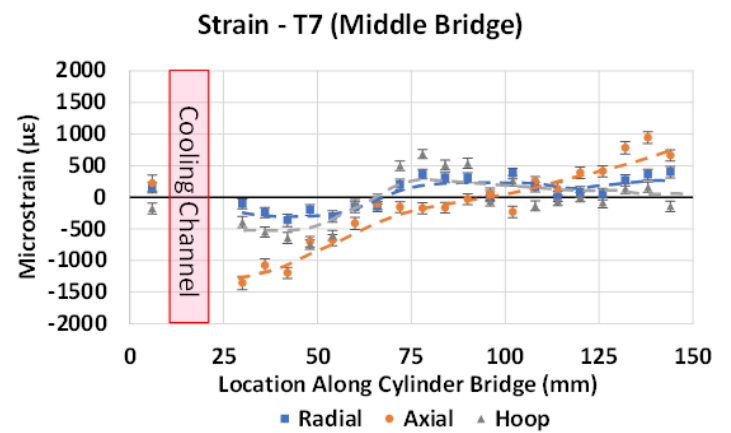
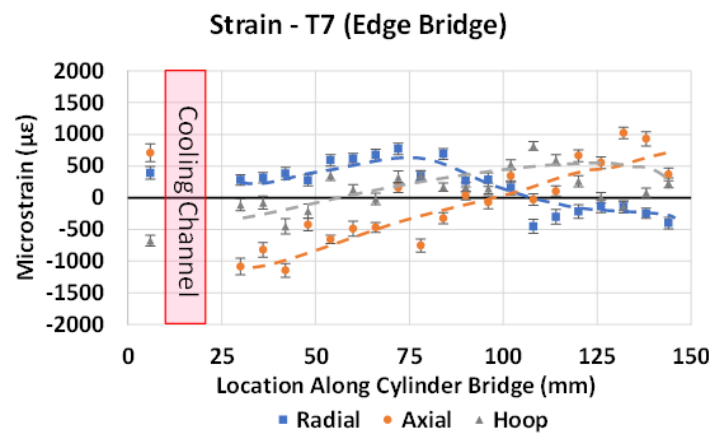


Figure 8

Residual strain profiles for T7 engine block

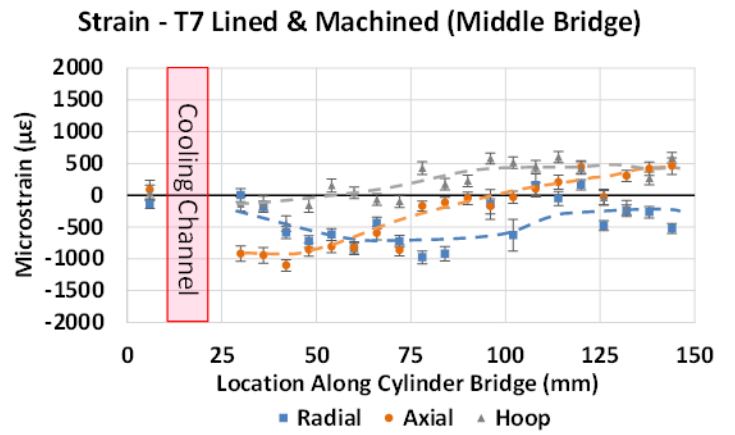
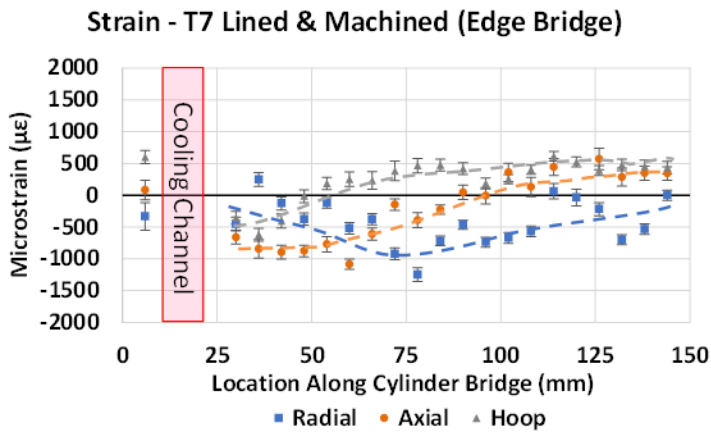


Figure 9

Residual strain profiles for T7LM engine block

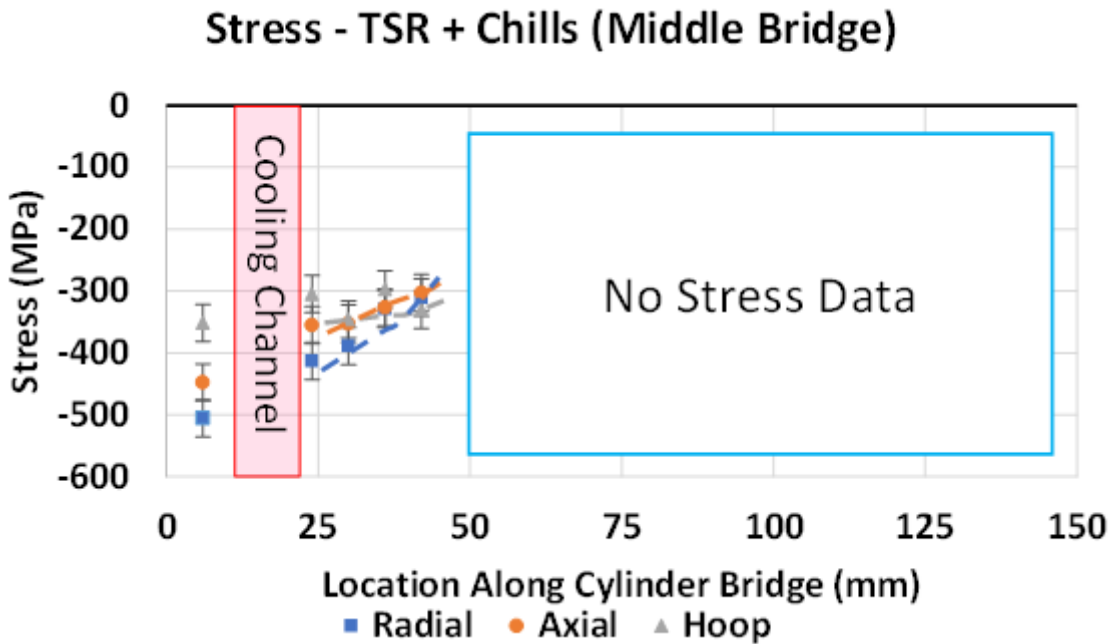


Figure 10

Residual stress profiles for TSR + Chills engine block

Stress - TSR (Edge Bridge)

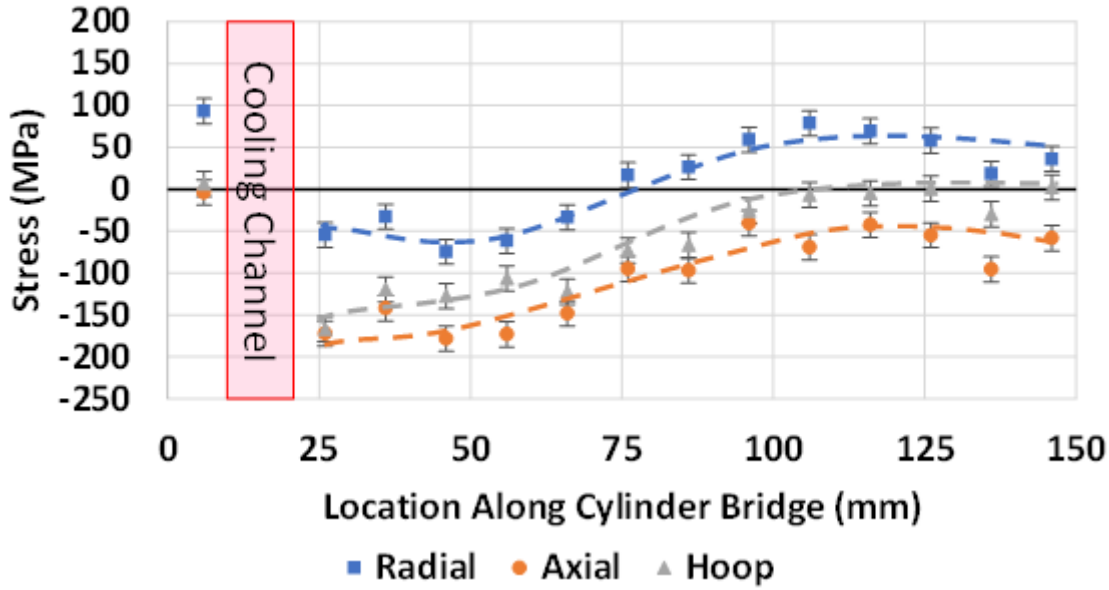


Figure 11

Residual stress profiles for TSR engine block

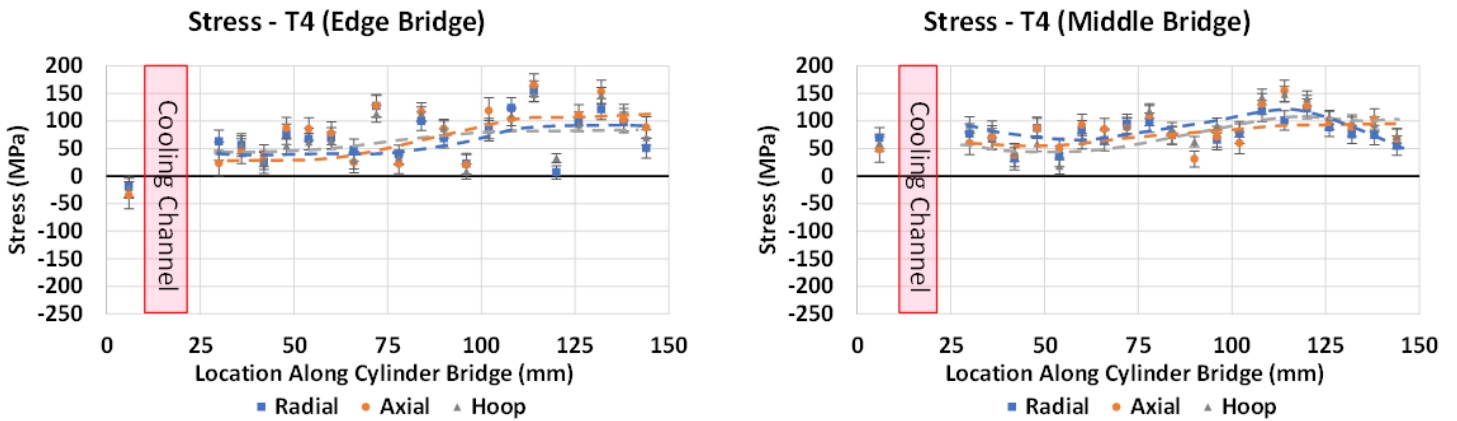


Figure 12

Residual stress profiles for T4 engine block

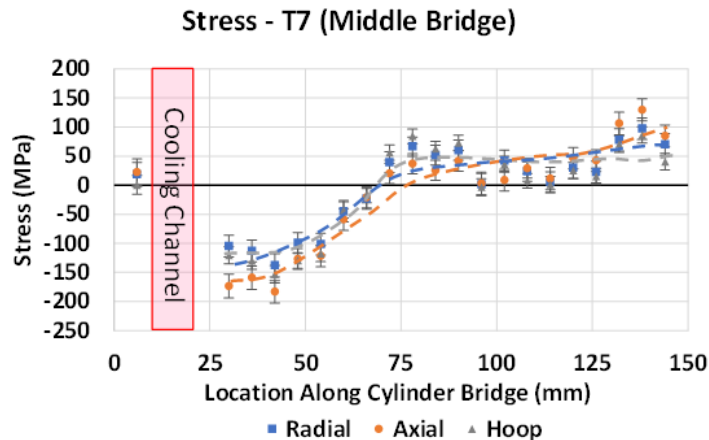
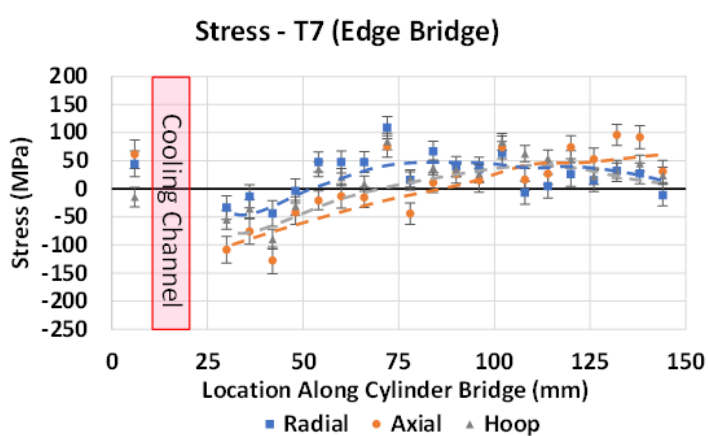


Figure 13

Residual stress profiles for T7 engine block

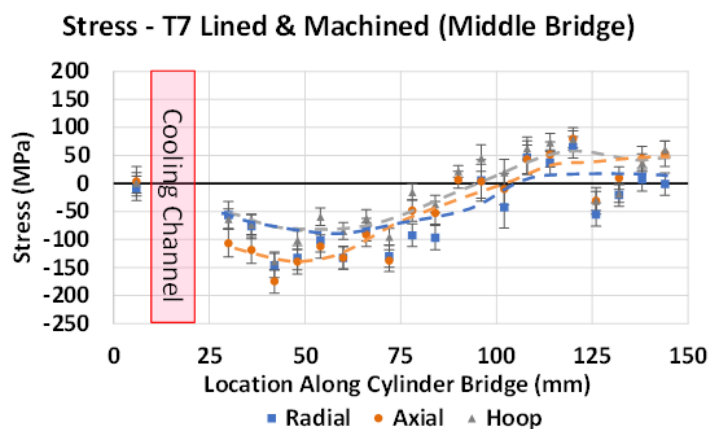
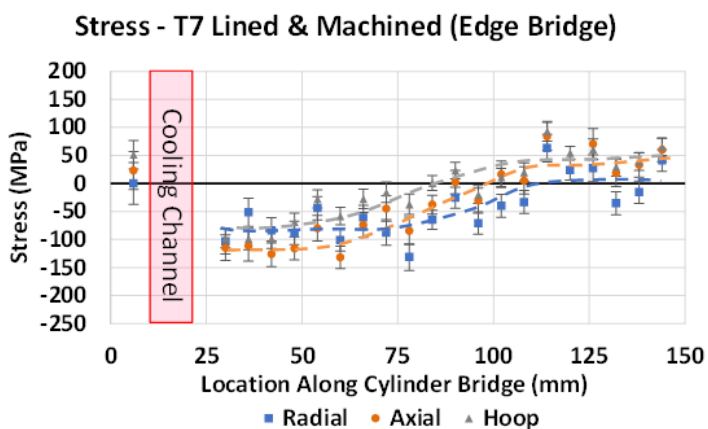


Figure 14

Residual stress profiles for production ready T7LM engine block

Supplementary Files

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