Innovated Friction Coating Process

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Abstract

This development has been conducted by Japan Science and Technology Agency for solving global warming problem.
A novel surfacing process is proposed for the inner bores of aluminum engines, which is the heaviest parts of automobile. This process is characterized by a plasticized coating with the use of frictional heat. Coating material is heated by frictional heat and plasticized by a rotating rod. The coating material is metallurgically bonded to the aluminum cylinder by plastic metal flow. Process advantages include no fusion of the substrate, minimized influence of heat, and sound coatings without any porosity and crack. Another advantage is the fine-grained structure of the coated material that results from the process.
As conclusions, a novel process was developed to coat the inner surface of aluminum cylinders with fine-grained material with modified hardness. In the case of Al-Cu35% eutectic alloy coating, the maximum temperature reached 700K. Higher rotational speed of core rod gave harder coating layers. This is attributed to the development of fine-grain structure on increasing the rotational speed. No defect was observed inside the coating layer as well as at the interface between substrate and coating.
An actual engine cylinder was coated by this friction surfacing process. In the result, sound interface was obtained and the thickness of coating layer was uniform and thin.

1. Introduction

Recently aluminum alloys are being used as a material for engine blocks to reduce car weight. This helps to solve the global warming problem, which has been the most important industrial development since Kyoto Protocol. Aluminum engine blocks – particularly their inner surfaces – suffer from wear and heat. Here, a novel hard surfacing process is proposed decreasing those problems and preliminary experimental work is reported.
One of the conventional remedies is to use cast iron inner cylinder as a cast-in insertion to give a hardened and self-lubricated layer. However, this process has the limitation of process-complexity and also there is recycling problem with cast iron and aluminum. To solve these problems, it is suggested to harden the inner surface by using an aluminum-base alloys using a novel hard surfacing process.

2. Principle of coating process

Figure 1 shows a schematic illustration of this friction coating process. Coating material between a rotational rod and a cylinder is plasticized by the generation of frictional heat. During this process, there is severe plastic flow of the coating material, which is pressure-welded to an inner surface of the aluminum cylinder.

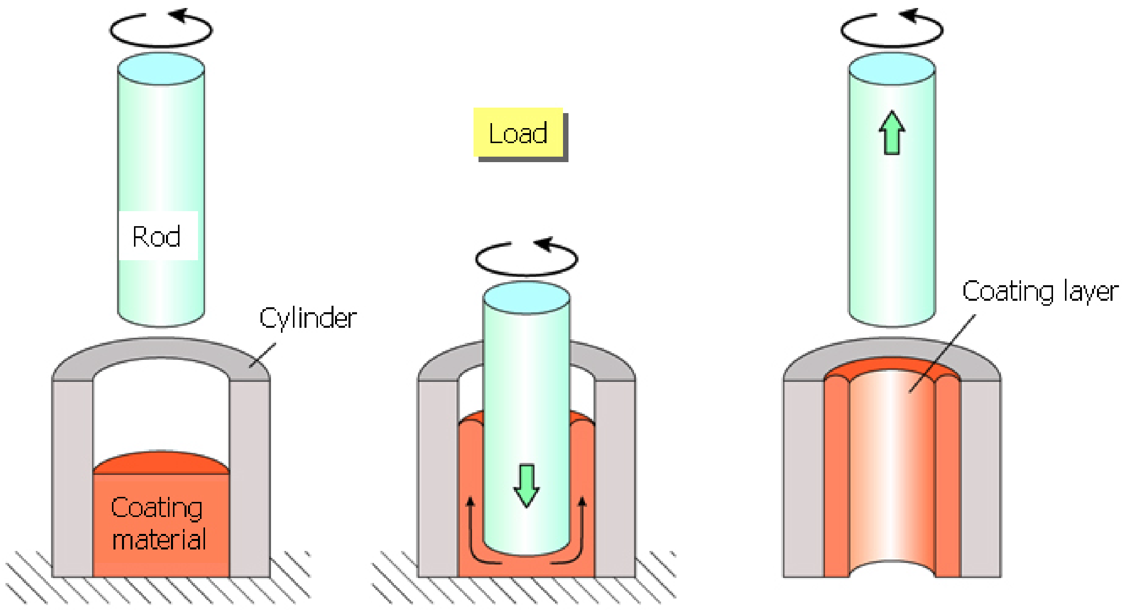

Fig.1 Schematic illustrations of friction coating process

3. Experimental procedure

This governmental project has been carried out for two step procedures, which are coating for small scale bores simulated engine, and second coating for practical scale bores. The former dimension is ranging from 20 – 45mm in diameter and the later is 80mm diameter with 110mm length as practical cylinder size.

A5056 extruded aluminum alloy was selected as the substrate material for a small scale cylinder. The dimensions of cylinder were 60mm height, 60mm outer diameter with an inner diameter of 23mm or 25mm. Two compositions of aluminum alloys were selected as coating materials namely - Al-Si13% eutectic cast alloy and Al-Cu35% eutectic cast alloy. The core rod material to generate frictional heat in the coating material was high-speed steel with 20mm diameter. The rotational speeds of the core rod were 1500, 2000 and 2500 rpm. Friction time was varied between 31 and 421 seconds, which were depending on frictional pressure. In case of large scale cylinder, Al-25% sintered alloy was selected as coating material, which is recently developed for motorcycle engine. Al-Cu alloy and metal matrix composite (MMC) was also coated to A5056 aluminum cylinder.

Quality evaluations were carried out by conventional metallurgical procedures and shear strength test of coating layer.

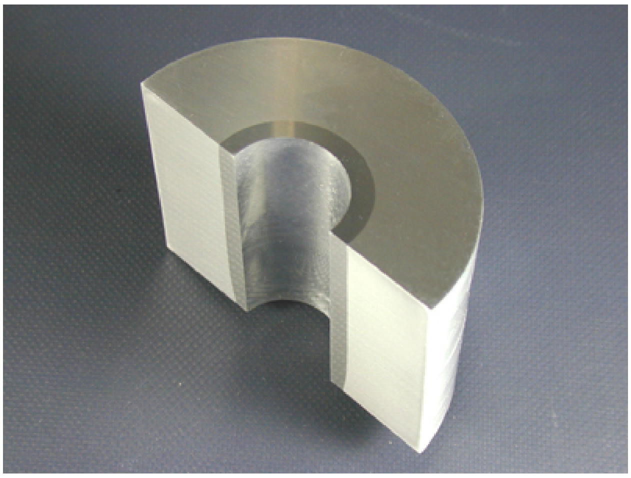

Fig. 2 Result of small scale bore coating

4. Experimental results and discussions

4.1 Small scale bore coating

4.1.1 Coatings with Al-Si13% eutectic alloy

Figure 2 shows a photograph of cross section of a typical surface coated cylinder. Figure 3 shows the microstructures of cast alloy and coating layers produced at different rotation speeds. There is a marked grain refinement in the coated layer with uniform dispersion of proeutectic Si. The size of acicular eutectic Si in the as cast structure is reduced by about a factor of four after the coating process is performed. The high rotational speed results in finer eutectic Si, but there is no clear influence of friction time on the eutectic Si size.

Figure 4 shows the microstructures after every 20 seconds of processing. After the initial 20 seconds, the coating near the surface shows grain refinement but towards the substrate side, primary Si particles are still seen. A defect can be seen at the interface between substrate and coating. After 40 seconds, few primary Si particles are seen in the coating layer and the interface is moved towards the substrate. After 60 seconds, no defect is seen at the interface, which is further penetrated into substrate interface

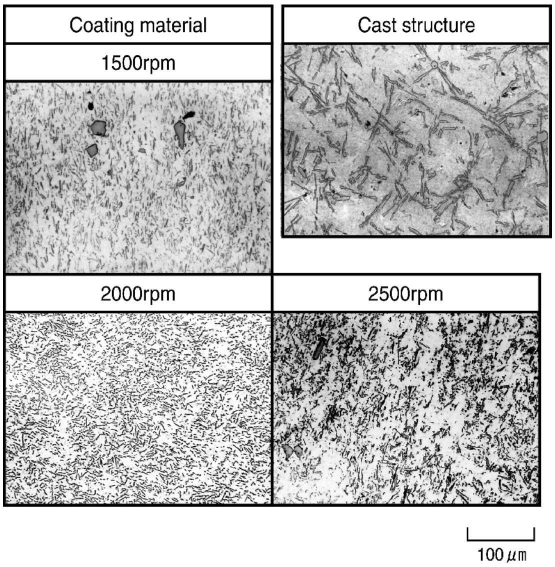

Fig.3 Microstructures of cast alloy and surface coated layers by Al-Si13% coating material

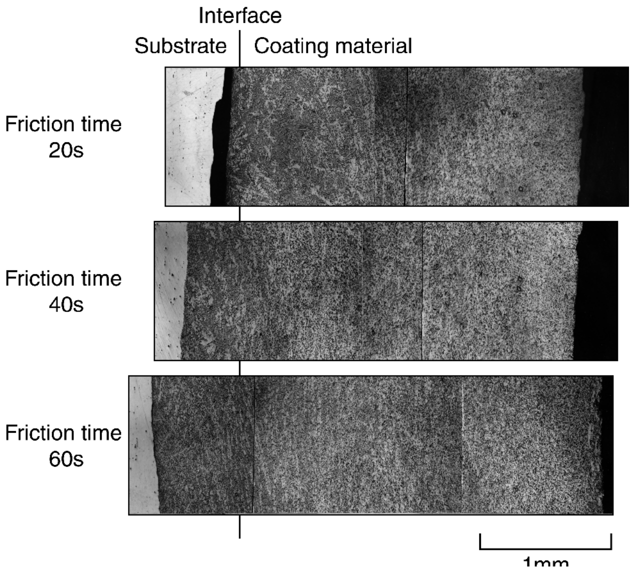

Fig.4 Development of coating with respect to friction time

reached 0.5mm after 60sec processing.
The surfacing rate is defined as the ratio of initial weight of the coating material to processing time. The shorter the processing time, the higher is the surfacing rate and lower is the frictional heat input and vice versa. Figure 5 shows the microstructures of the interface at a constant speed of 2000 rpm with different surfacing rates. Higher surfacing rates lead to imperfect interfaces between the substrate and coating layer due to low heat input and insufficient metal flow. This situation is similar to the lack of fusion observed during arc welding when heat input is low. Sound

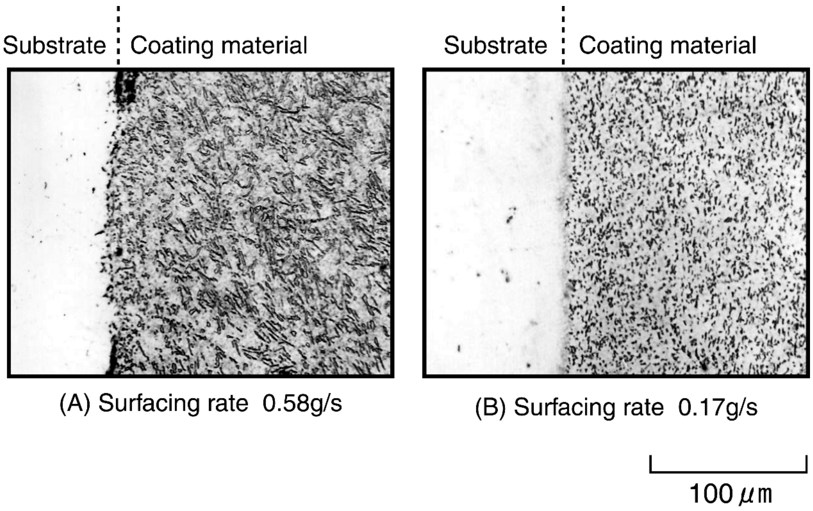

Fig.5 Effect of surfacing rate on coating microstructure for Al-Si alloy

interfaces are achieved when surfacing rates are low, indicating enough frictional heat generation and sufficient metal flow. It appears that there is a critical surfacing rate of about 0.3g/s to avoid the defects at interface.
Hardness tests were performed across the coating interface. The hardness of the coating material ranges between 50 to 70 Hv, which is only slightly modified as compared with A5056, the substrate material of the cylinder for the Al-13%Si eutectic alloy.

4.1.2 Coatings with Al-Cu35% eutectic alloy

Same experimental procedures were performed using Al-Cu13% alloy of coated material as previously mentioned.
Figure 6 shows the microstructure of interface of surface coated layer with Al-Cu35% alloy for 25mm diameter bore. Careful observation indicates perfect-defect free interfaces and modified coating layers. The surface of the coated layer was quite smooth in appearance under all operating conditions. The microstructures observed optically and by using SEM indicate that the original eutectic cast structure has transformed into a uniformly distributed and refined form. Figure 7 shows SEM microstructures of the as cast and as processed coating material.

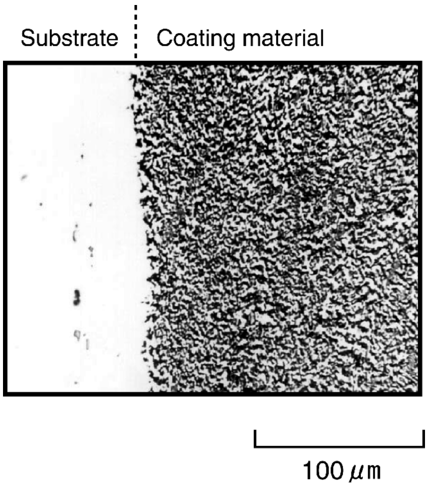

Fig.6 Microstructure of coating with Al-Cu35%

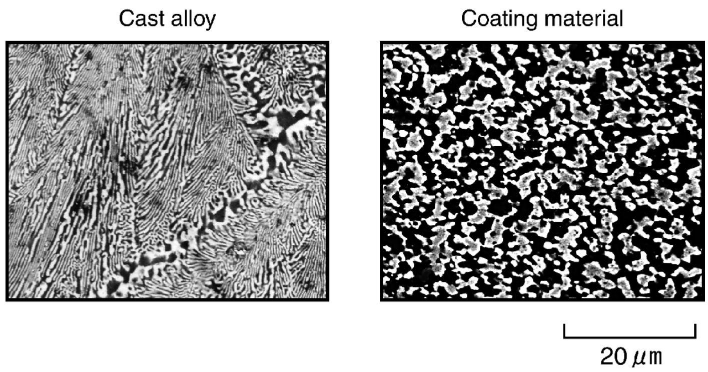

Fig.7 SEM microstructures of as cast and surface coated layer of Al-Cu alloy

The average hardness of the Al-Cu35% coated layer reaches about 170Hv. High hardness of the coating layer is achieved when high rotational speeds of the core rod are employed. This increase in hardness can be attributed to the development of a fine-grain structure on increasing the rotational speed. When an internal diameter of 23mm and 2500rpm were used, the hardness reached a maximum of 195 Hv after 106 seconds of process time. The coating thickness under these conditions was 5mm.

4.2 Thermal cycle measurement

Thermal cycles were recorded at the interface to 20-25mm coating. The results show that the maximum temperature ranges achieved were between 673 and 758K for coating of Al-Cu35% alloy; a range of 547 and 648K was observed for coating with Al-Si13% alloy. It should be stressed that the respective maximum temperatures do not reach the melting points of these alloys, i.e. the process is solid-state surfacing.
Figure 8 shows thermal cycles achieved during coating of Al-Cu35% alloy. It clearly shows the effect of the inner diameter of the substrate cylinder on the maximum temperature when the core rod diameter is the same. In the case of a smaller inner diameter cylinder, a higher maximum temperature is reached as compared to that for the larger inner diameter cylinder. The heating rate seems to be higher in the initial period. The rotational speed of the core rod has no significant influence on thermal

cycle when inner diameter of cylinder is 23 mm. In case of 25 mm inner diameter cylinder, there is a slight deviation in heating rate with respect to rotational speed, but the maximum temperature does not change.

Figure 9 shows the difference in thermal cycles for coating of Al-Cu35% and Al-Si13% alloys. The heating rate for the Al-Si13% alloy is faster than that of the Al-Cu35% alloy. Al-Si13% undergoes plastic deformation quickly and hence frictional heat input rate is faster leading to an increased heating rate. Due to its high hardness, Al-Cu35% alloy needs the longer time for plastic deformation, thereby leading to slower heating rate. An increased time for plastic deformation also causes more frictional heat input, which leads to higher maximum temperature as compared to those achieved during coating of Al-Si13% alloy. The respective maximum temperatures reached during coating of Al-Cu35% and Al-Si13% alloys are 735K and 648K respectively.

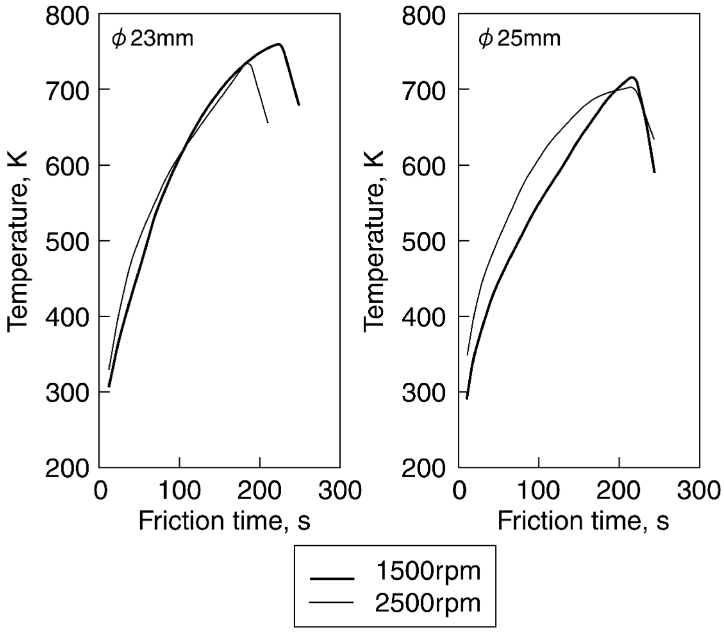

Fig.8 Thermal cycles for coating with Al-Cu35% alloy

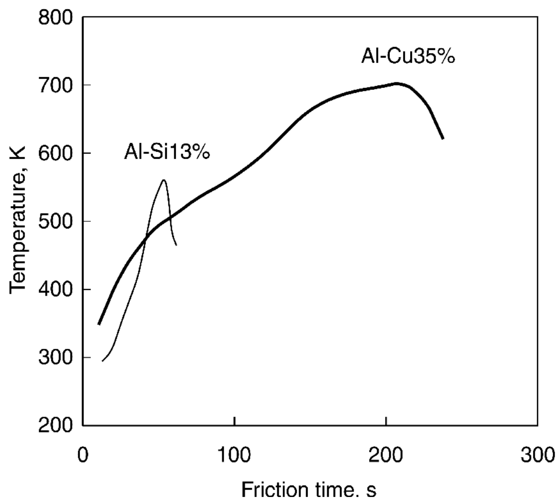

Fig.9 Effect of coating composition on thermal

4.3 Increase the diameter of cylinder

Considering an application of this novel surfacing process to an actual aluminum engine cylinder, it is necessary to confirm the process can coat large diameter cylinder. So the diameter of cylinder was enlarged from 25mm to 80mm. Moreover, the formation of uniform and thin coating layer was considered because thickness of coating layer was important in products.

Enlargement of diameter caused a difficulty of deciding coating conditions. When large diameter cylinder was coated, the coating results may be different to coating small diameter cylinder due to difference of friction heating and deformation resistance. This suggests that coating conditions should be optimized for each diameter of cylinder. However, as the results of coating experiment, it was revealed that coating parameters were principally based on the results of preliminary experiments that were carried out with small diameter, when the diameter of cylinder became large. In large diameter process, this coating process is also solid-state process because the maximum temperature during coating was in the range of 620-750K.

Figure 10 shows the cross section of coated cylinder with 80mm diameter. The material of cylinder was A5056, and coating layer was Al-25%Si. The thickness of coating layer was uniform and thin.

The novel surfacing process can applied to large diameter cylinder without serious problem, and obtained the suitable coated layer.

4.4 Evaluation of coating layer

In this section, results of coated layer evaluation were shown. Soundness of coated layer was primarily evaluated because the inner coating process is one of the surface treatment processes. Evaluations were carried out to coated large diameter cylinder, which is close to the actual product.

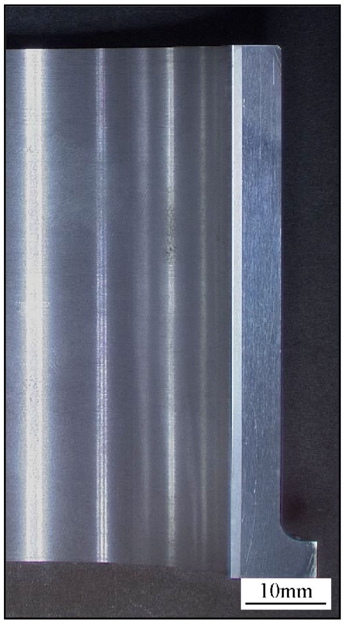

Fig.10 Cross section of coated cylinder with 80mm diameter

4.4.1 Observation of cross-section of coating layer

No defects were observed in sound interface between coating layer and substrate by visual observation. Therefore, detail observation of interface was carried out by microscope.
Figure 11 shows the microstructures of layer that was coated by various materials. All coating materials were able to obtain the sound layer without defect, and grain size became refined than that of base metal as the results of plasticized deformation during the duration of coating process.

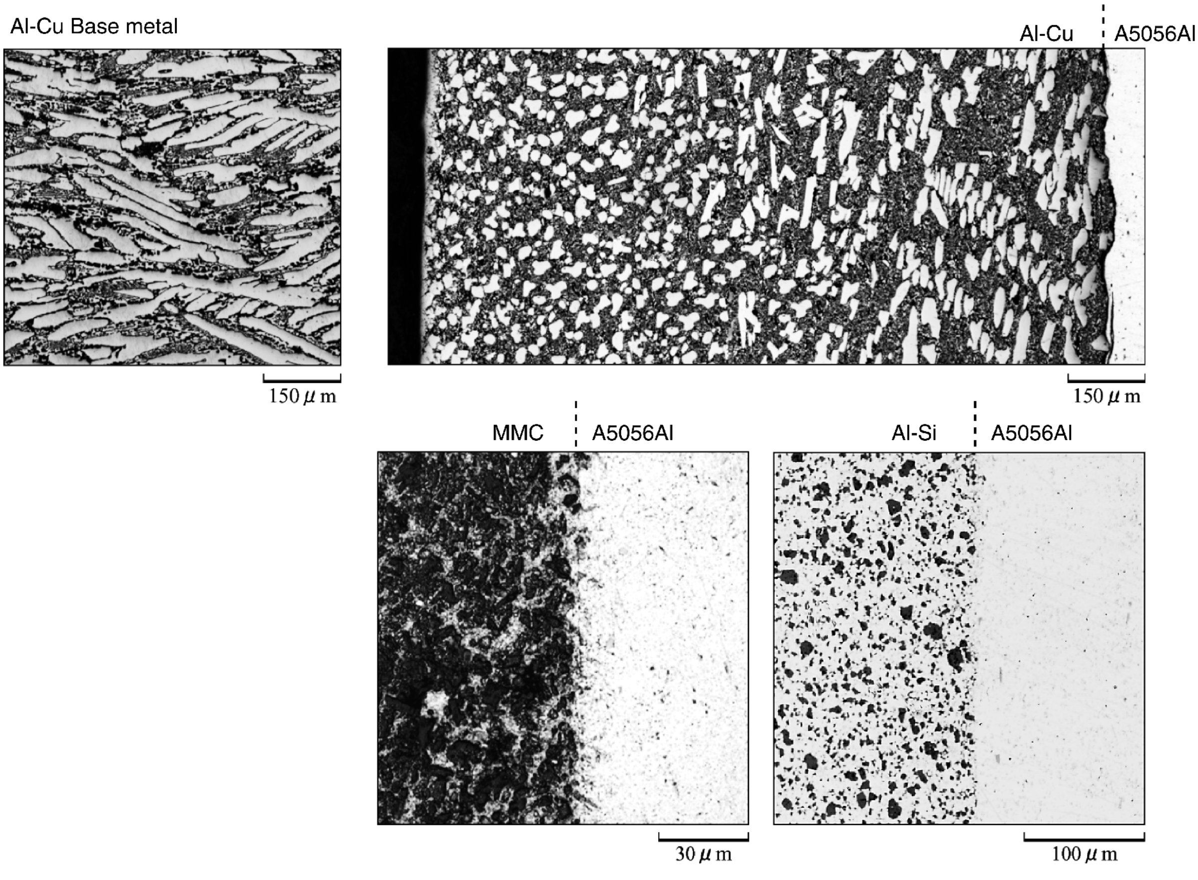

Fig.11 Microstructures of coated layer

Figure 12 shows the hardness distribution across the coating layer. Uniform hardness level of about 250Hv is found throughout the coating layer. A 0.5mm hardness transition layer is also observed at the interface. Because the level of frictional heat at the interface is relatively small, there is no annealing effect observed in the substrate material. This fact can be explained by the uniform hardness in the substrate. The thickness of coating layer is about 4mm in this case.

4.4.2 Evaluation of soundness at coated interface

Two tests, dye penetrant testing and ultrasonic testing, were carried out to evaluate the soundness at coated interface. Tests were carried out to the coating layer without defect by visual test.

Figure 13 shows the results of dye penetrant test. There is minute defect in part of interface, which was considered to be sound by visual test. Thus it was revealed that the evaluation test should be carried out to defect inspection.

Although dye penetrant test was carried out to sliced cylinder, it was difficult to evaluate the entire coating layer. In visual or penetrant test, it takes a long time to evaluate the interface and only limited number of samples are examined, because these tests require preparing a test piece by sawing. Nondestructive and rapid inspection is required to secure the reliability of inner coating process.

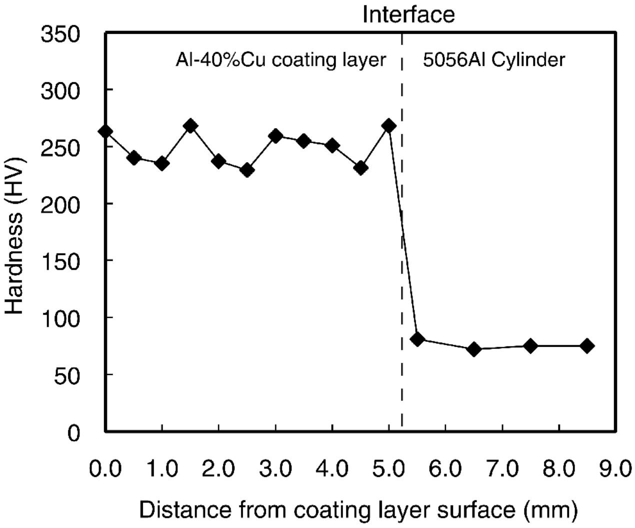

Fig.12 Hardness distribution of coating layer and substrate

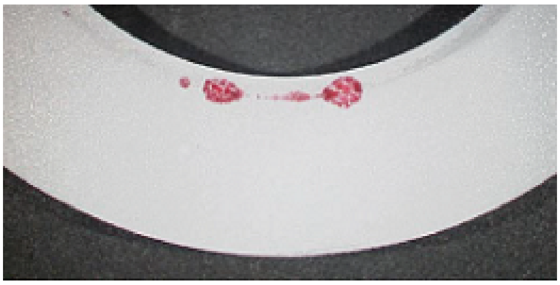

Fig.13 Result of dye penetrate testing

Alternative procedure is introduced. 3-D ultrasonic testing was performed on the large diameter cylinder coating so as to evaluate bonding of entire interface. Figure 14 shows over view of 3-D ultrasonic inspection machine. Inspection of entire interface is operated by rotating specimen on the stage and probe scans vertical direction. Whole coating layer is able to inspect by 3-D ultrasonic testing. This digitalized procedure reveals the defect size and defect location under non-destructive condition.

Figure 15 shows the results of ultrasonic testing of coated cylinder. This result shows as developed plane figure of cylinder after image processing. As shown in figure 15(a), sound interface was obtained in the top part and bottom ones of cylinder, whereas defect was observed widely in the middle of cylinder using inappropriate coating parameters. It was considered that the defect in center part of cylinder was caused by the deformation of cylinder with water jacket wall, because the deformation of cylinder to the direction of outward decreases the pressure of the coating material against cylinder. Decreasing the deformation of cylinder is required to progress the soundness of coated layer.

Figure 15(b) shows the results of ultrasonic testing of low-deformation coated cylinder after optimization of operating parameters. As a result of deformation control, defect was decreased and percentage of soundness weld area was more than 99%.

4.4.3 Bonded strength of coating layer

Destructive tests were also introduced to assess bonding strength of coating layer. Considering difficulties of evaluation of bonding strength, simple Die-punch test was used. Table 1 shows the result of shearing test. Die-punch shear tests were carried out on the sliced plates from coated cylinder. The material of tested cylinder was A5056, and coating layer was Al-25%Si. As shown in table 1, shear strength of sound interface was equivalent to the strength of base cylinder material (150MPa). Even when there was minute defect in part of interface, decrease of the share strength was small.

It is concluded that coating layer is metallurgically bonded.

4.5 Application for products

As described above, it was shown that the developed inner coating process could coat the large diameter cylinder and coated layer was sound without defect. Coating was tried to the actual engine cylinder block that is the target of this process from those results. Coating was carried out to the single cylinder aluminum engine block which is practical productions. Material of the block was AC2B cast aluminum alloy and the cylinder was 82mm diameter. A thickness of cylinder is asymmetry due to water jacket in side of cylinder. Therefore, the strength of cylinder was uneven in same level of cylinder during duration of coating. This caused the deformation of cylinder, and produced defects. However, as shown in figure 16, it was found that the thickness of coated layer was uniform.

Table 1 Results of shearing test

	With defect	Without defect
Shear strength [MPa]	100 - 120	140 - 160

Original target of the inner coating process was the aluminum engine block. However, principle of this process is available to another work that have cylinder. Figure 17 shows one of the applications. Al-Sn material was coated to the steel bore of connection rod. Thus, this inner coating process can apply to not only aluminum cylinder but also steel cylinder, and various applications is possible.

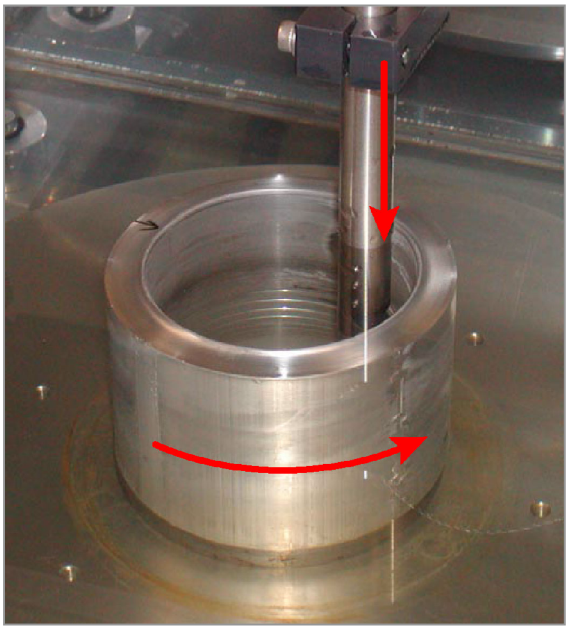

Fig.14 Over view of 3-D ultrasonic inspection machine

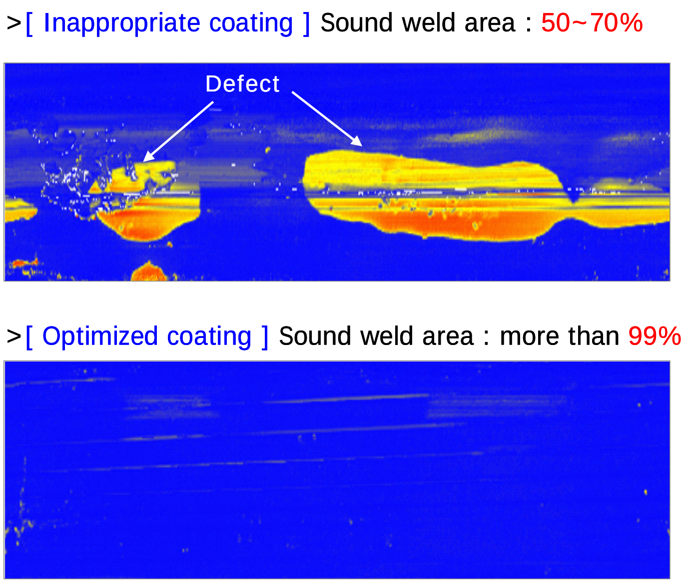

Fig.15 Results of ultrasonic inspection to surface defect of coated cylinder

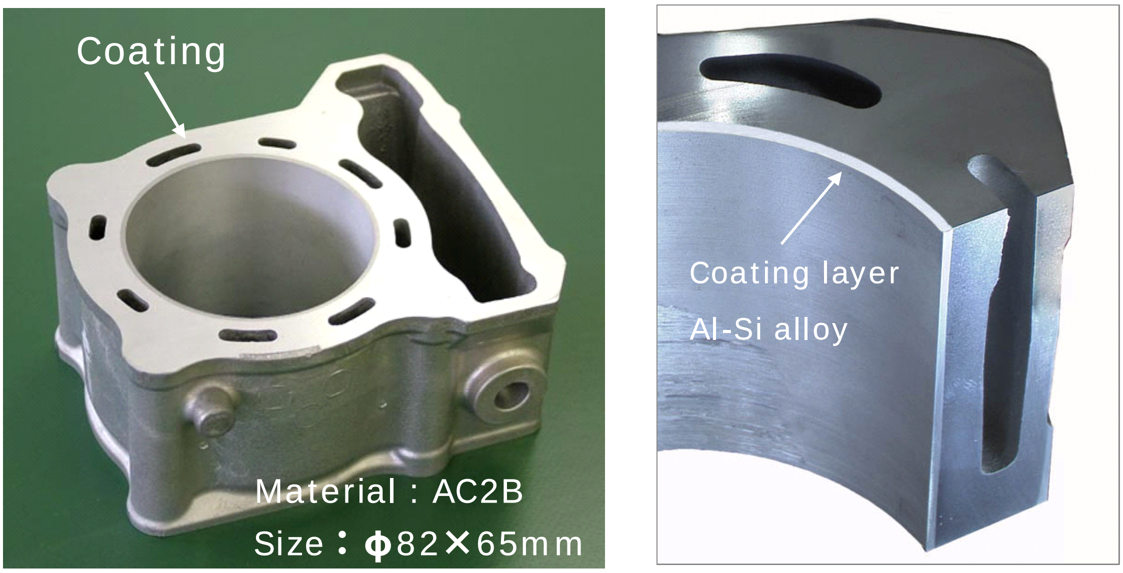

Fig.16 Cross sections of coated aluminum cast engine block

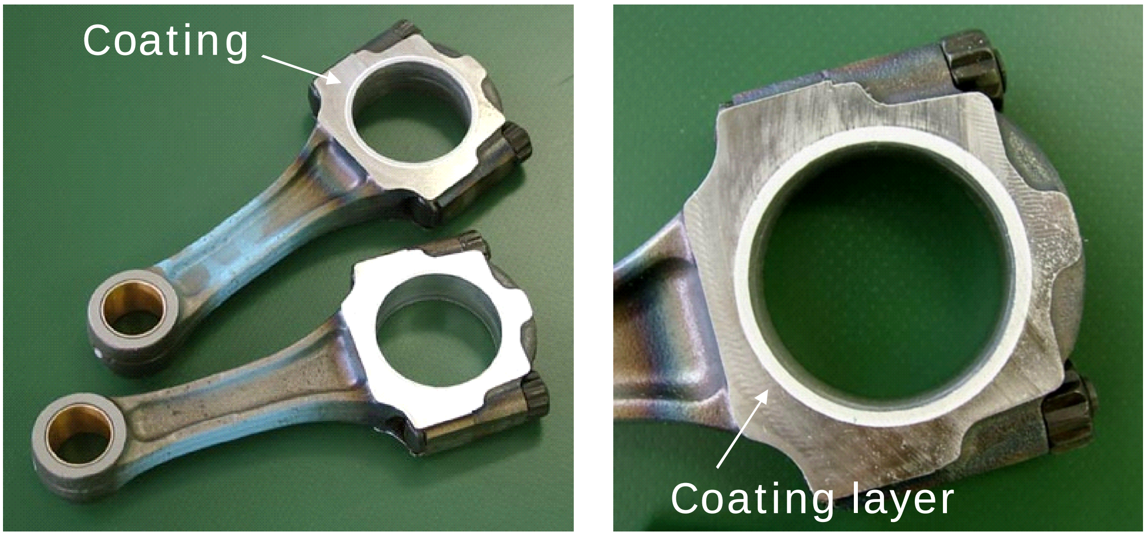

Fig.17 Application of coating process to connecting rod

5. Conclusions

Solving global warming problem, a novel coating process was successfully developed by support of Japan Science and Technology Agency. Following results are obtained.

1. A novel process was developed to coat the inner surface of aluminum cylinders with fine-grained material with modified hardness.

2. An actual engine block with 82mm diameter cylinder was satisfactory coated by Al-25%Si and the thickness of coated layer was uniform thickness and fine grains.

3. Shear strength of sound interface was equivalent to the strength of A5052 base cylinder material.

4. Soundness of entire coated interface was evaluated with 3-D ultrasonic testing and the results revealed that the percentage of sound weld area was more than 99%.

5. In this coating process, the maximum temperature reached was in the range of 673K-758K in case of small diameter, and 620-750K in case of large diameter.

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