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# Evaluation of ferrous powder thermal spray coatings on diesel engine cylinder bores

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**Abstract**

In order to reduce weight, a new liner-less technology without cast iron liner is anticipated to be put into practice in the field of aluminum cylinder block manufacture. Our target is diesel engines. However, diesel fuel contains the element sulfur which introduces the possibility of corrosive attack since sulfuric acid generated on the liner surface is higher than with gasoline fuel. Because of this disadvantage, higher wear and corrosion resistances of the inner surface of the cylinder bore are required to make practical a liner-less aluminum cylinder block. A newly developed ferrous powder (Fe–C–Ni–Cr–Cu–V–B alloy) revealed most excellent corrosion and wear resistances, compared with currently used bulk casting materials such as Fe–C–Si–B alloy and Fe–C–Si–Mo–B alloy for cylinder liners. To test the new ferrous alloy powder it was applied to actual engine bores by using Rota-Plasma spray coating. The results of the experiment showed a potential equivalent to current liner-equipped engine bores.


*Keywords:* Plasma; Thermal spraying; Corrosion; Wear; Diesel engine; Al alloy

## 1. Introduction

Aluminum alloy is currently gradually replacing ferrous casting materials in cylinder blocks for weight reduction in the automobile industry. In order to reduce the weight of automobile diesel engines, liner-less aluminum cylinder blocks without cast iron liners are expected to come into practical use in the near future. Yet, diesel fuel's impure element sulfur introduces the corrosive attack possibility, since sulfuric acid generated on the liner surface is higher than with gasoline fuel [1,2]. For that reason, higher wear and corrosion resistances on the inner surface of cylinder bores are required so that liner-less aluminum cylinder blocks can perform effectively. At present, coating technologies for cylinder bores have been investigated from the point of view of the coating material and the coating method [3–7]. This research is intended to examine both wear and corrosion performances using plasma thermal spray tech-

Table 1
Newly developed chemical compositions of spray powder for cylinder block

| Chemical composition (mass %) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C | Si | Mn | P | S | Ni | Cr | Cu | V | B | Fe |
| 3.10 | 2.89 | 0.08 | 0.004 | 0.004 | 8.95 | 2.46 | 4.80 | 0.74 | 0.075 | Bal. |

Table 2
Chemical compositions of current liner bulk materials

| | Chemical composition (mass %) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Mo | B | Fe |
| ST | 3.09 | 2.31 | 0.73 | 0.23 | 0.117 | – | 0.093 | Bal. |
| GT | 3.27 | 2.32 | 0.74 | 0.21 | 0.124 | 0.44 | 0.051 | Bal. |

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Table 3
Rota-Plasma spray parameters

| Substrate | Cylinder block |
|---|---|
| Paramete | |
| Powder name | ISUZU selected powder |
| Powder chemical composition | Fe–C–Ni–Cr–Cu–V–B |
| Plasma gun | SM-F210 |
| Current | 250 (A) |
| Recorded voltage | 30 (V) |
| Argon (Ar) | 40 (L/min) |
| Hydrogen ($H_2$) | 1 (L/min) |
| Powder carrier gas | Ar 3.8 (L/min) |
| Powder feed rate | 30 (g/min) |
| Spray distance | 45 (mm) |
| Rotation speed | 200 (rpm) |
| Forward speed | 6 (mm/rev) |
| | 20 (mm/sec) |
| Gun jet cooling | Ar 6 (bar) |
| No. of passes | 24 |

nology and to verify the feasibility of application to actual engine bores with a newly developed ferrous powder (Fe–C–Ni–Cr–Cu–V–B alloy) compared with currently used bulk casting materials such as Fe–C–Si–B alloy and Fe–C–Si–Mo–B alloy for cylinder liners.

## 2. Experimental details

### 2.1. Material

Al–11.1mass%Si–2.1mass%Cu–0.8mass%Fe–0.8mass%Zn–0.3mass%Mn–0.3mass%Mg alloy casting was used for the cylinder block. The spray material, a newly developed ferrous powder, Fe–C–Ni–Cr–Cu–V–B alloy [8], was used in our experiments. The powder size is 5–45 μm in diameter. The chemical composition of the powder is shown in Table 1, which shows austenitic structure. Two types of cast iron liner bulk materials, Fe–C–Si–B alloy (ST) and Fe–C–Si–Mo–B alloy (GT), were also used for comparing wear and corrosion performances. The chemical compositions of these bulk materials are shown in Table 2.

### 2.2. Spray conditions

Atmospheric Plasma Spraying (APS), Rotaplasma®, was utilized in the experiments. Before the spraying process, a blast treatment was performed on the aluminum alloy substrate with alumina and titania using particle sizes of 600–800 μm. The bore diameter and height of the test engine are 93.7 and 126.7 mm, respectively. Test pieces for evaluating wear and corrosion performances were also prepared in rectangular parallelepiped shape with sizes of 17 × 15 × 70 mm. Those test pieces were spray-coated with the same spraying process, Rotaplasma®, by using a cylindrical setting jig. The target coating thickness is 250–300 μm, and the spray conditions are shown in Table 3.

### 2.3. Wear testing

Wear resistances of coatings were examined using reciprocation motion type testing equipment under a wet condition of engine oil mixed with sulfuric acid water solution (3.6 vol.%). A chromium-plated pin with a coating thickness of 100–150 μm was used as a counter-part. Wear tests were performed at the condition of 240 m/min sliding speed, 50 mm per stroke, and 98 N load. The test pattern is 10 h wear test followed by 14 h stop/hold and then 10 h wear test again, so the actually total wear testing time is 20 h. The maximum wear depth was measured using "Talysurf S5C" picture image analyzing method by scanning the surface of the test pieces with a 2-μm radius of stylus tip.

### 2.4. Corrosion testing

Corrosion resistance of the coatings was evaluated after the test piece was immersed in 20 mass% sulfuric acid water solution for 95 h. In order to evaluate only the coating

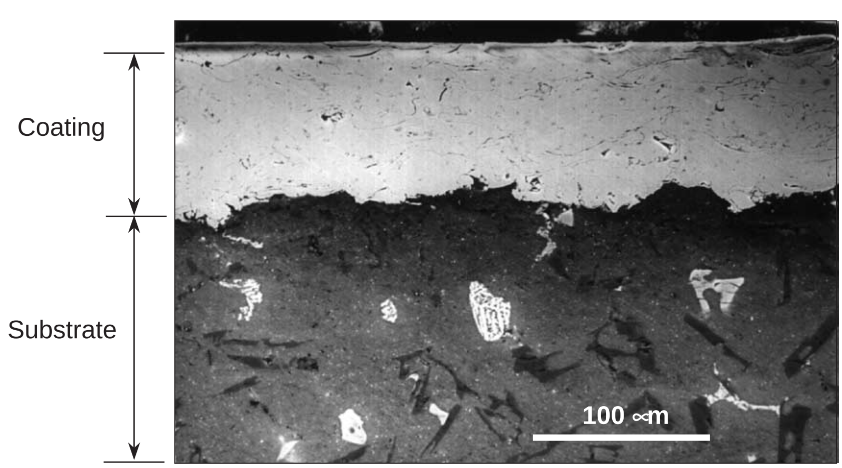


Fig. 1. Representative spray coating section with newly developed powder after grinding finishing.

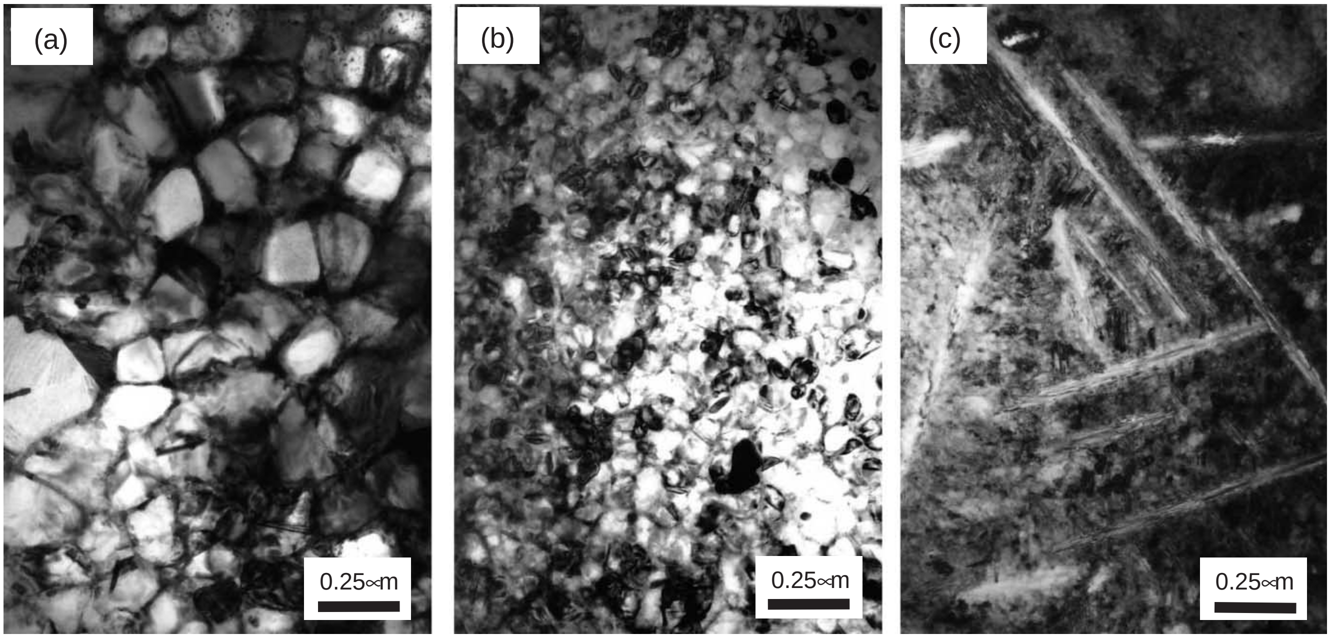


Fig. 2. Typical TEM microstructures of spray coatings, (a) Cellular structure, (b) Fine structure, (c) Twin structure.

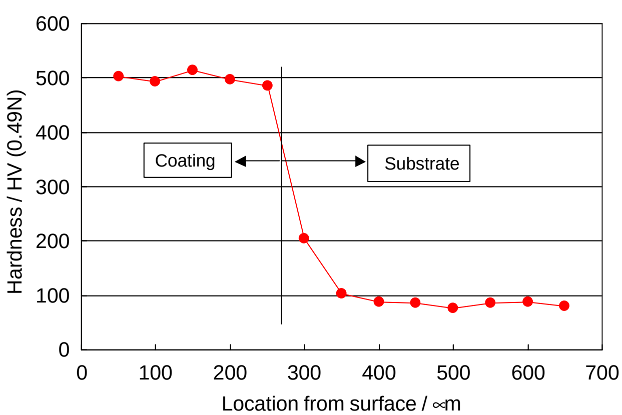


Fig. 3. Hardness profile on the cross section of the spray coating.

surface, the test piece was located into a special jig with sealing rubber to prevent sulfuric acid water solution from penetrating into the aluminum substrate part. During the test, weight of test pieces were measured at each appointed checking time.

### *2.5. Rigidity of cylinder block*

The inner diameter of each bore was measured by using a bore-gage in two conditions: with and without bolt fastening in order to compare the rigidity of the cylinder blocks between the spray coating cylinder block and the cast iron liner cylinder block. The rigidity was compared by the variance between with and without bolt

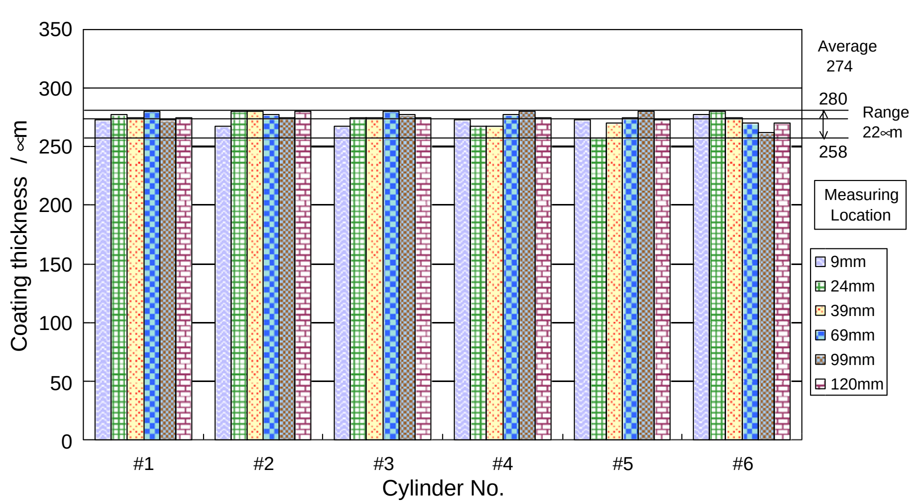


Fig. 4. Variation of coating thickness measured at each location in the bore for different cylinder bores.

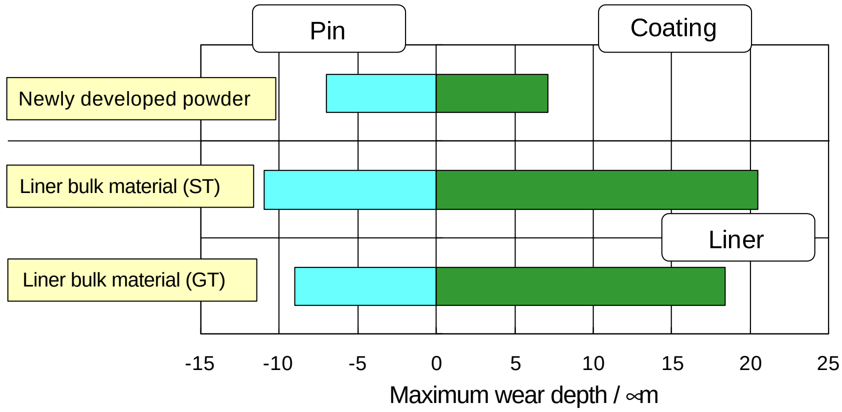


Fig. 5. Anti-wear property of the coating and counter pins in the condition of engine oil and sulfuric acid water solution in comparison with current liner materials.

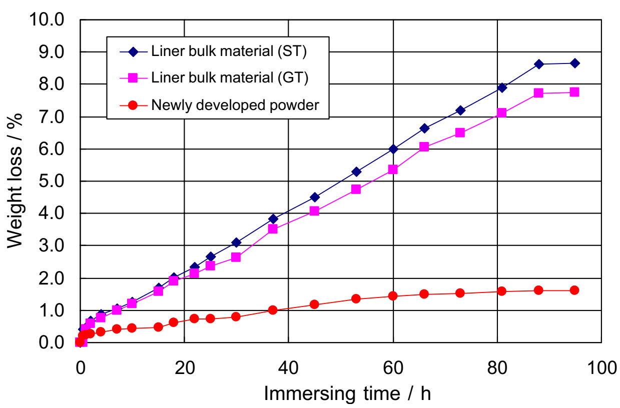


Fig. 6. Corrosion test results of newly developed powder coating and current liners after 95 h dipping in 20 mass% sulfuric acid solution.

fastening at each measuring height of 10 to 110 mm with 10 mm pitch from the top position of the cylinder block.

## 3. Results and discussion

### *3.1. Microstructure of the coating*

No cracking was found in the coating and no peeling was observed at the interface between the coating and the substrate in any of the coatings. A cross-section of the coating after grinding finishing is shown in Fig. 1. Porosity rate in the coating is 2%, less than that of the target value. Transmission electron microscopy (TEM) revealed that coating structure consists of austenite ($\gamma$-Fe) with a cellular structure, a fine structure, and a twin structure as shown in Fig. 2. Hardness profile on the cross- section of the spray coating is shown in Fig. 3, which indicates a uniform hardness distribution around HV 500.

### *3.2. Coating thickness*

Fig. 4 shows the variation in coating thickness measured at different heights from 9 mm at the bottom to 126.7 mm at the top of the bore for each cylinder bore. Coating thickness satisfied the target value of 250 µm at every position of the

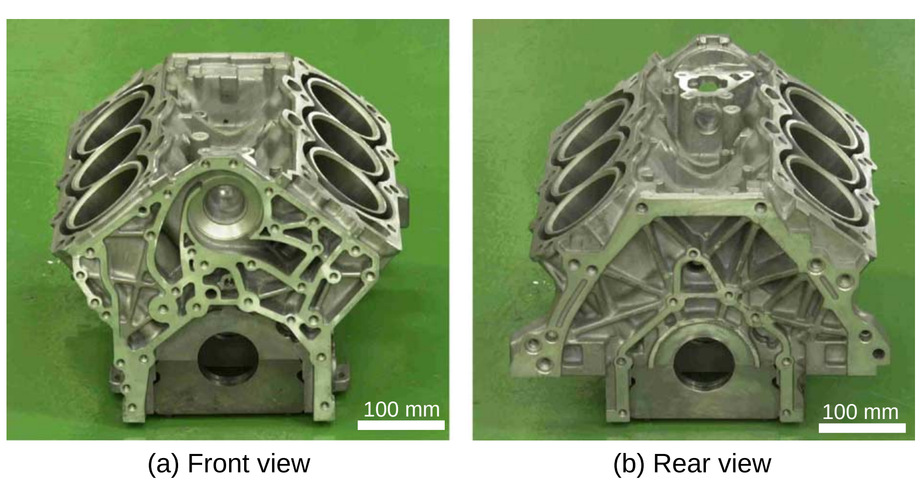


Fig. 7. External appearance of cylinder block.

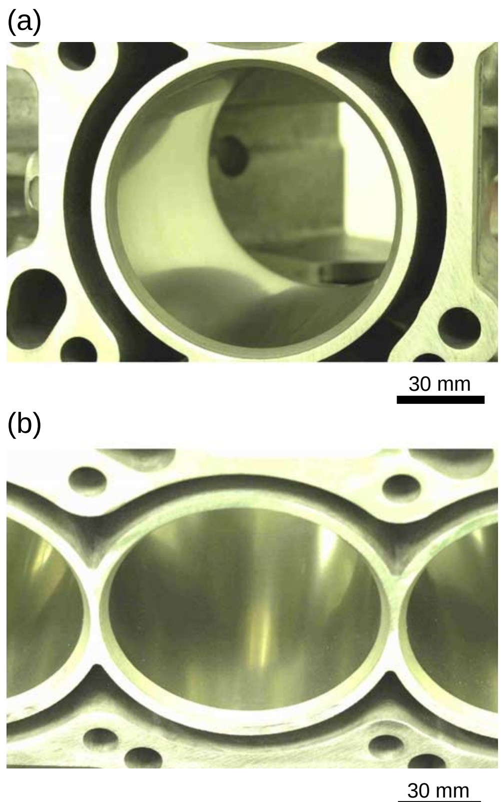


Fig. 8. Surface appearance of sprayed bore after honing finishing.

bore, and ranged between 258 μm in minimum and 280 μm in maximum. Therefore, the distribution of coating thicknesses can be considered to be very stable.

### 3.3. Wear resistance

Fig. 5 shows the wear test results at engine oil lubricant conditions mixed with sulfuric acid water solution (3.6 vol.%). The maximum wear depths of spray coating, counter pins, and bulk materials are compared between the newly developed powder and two types of liner bulk materials. The newly developed powder coating showed excellent wear performance compared with those of liner bulk materials currently used in actual engines. Especially, the maximum wear depth of coatings was less than half compared with those of liner bulk materials. Moreover the maximum wear depth of the counter pin against the spray coating also showed less than those of liner bulk materials.

### 3.4. Corrosion resistance

Corrosion test results of 95 h immersion in 20 mass% sulfuric acid water solution is shown in Fig. 6. Weight loss of the coating was about 2% after 95 h dipping, less than those of liner bulk materials, ST and GT, around 8–9%. A newly developed powder coating showed vastly superior corrosion resistance compared with liner bulk materials currently used in actual engines.

### 3.5. Rigidity of cylinder block

Figs. 7 and 8 show the external appearance of the cylinder block and the sprayed bore after honing finishing, respectively. Variation of bore diameter by bolt fastening is shown in Fig. 9. This figure indicates that no remarkable

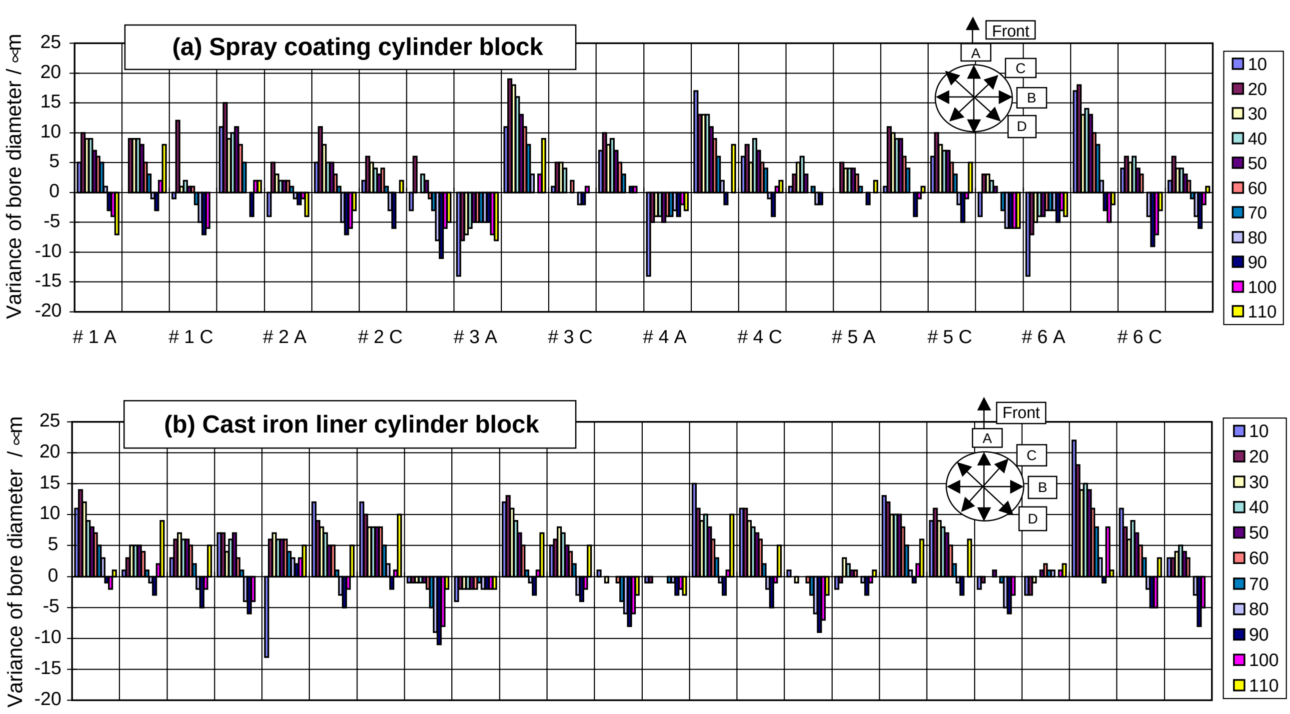


Fig. 9. Variation of bore diameter by bolt fastening.

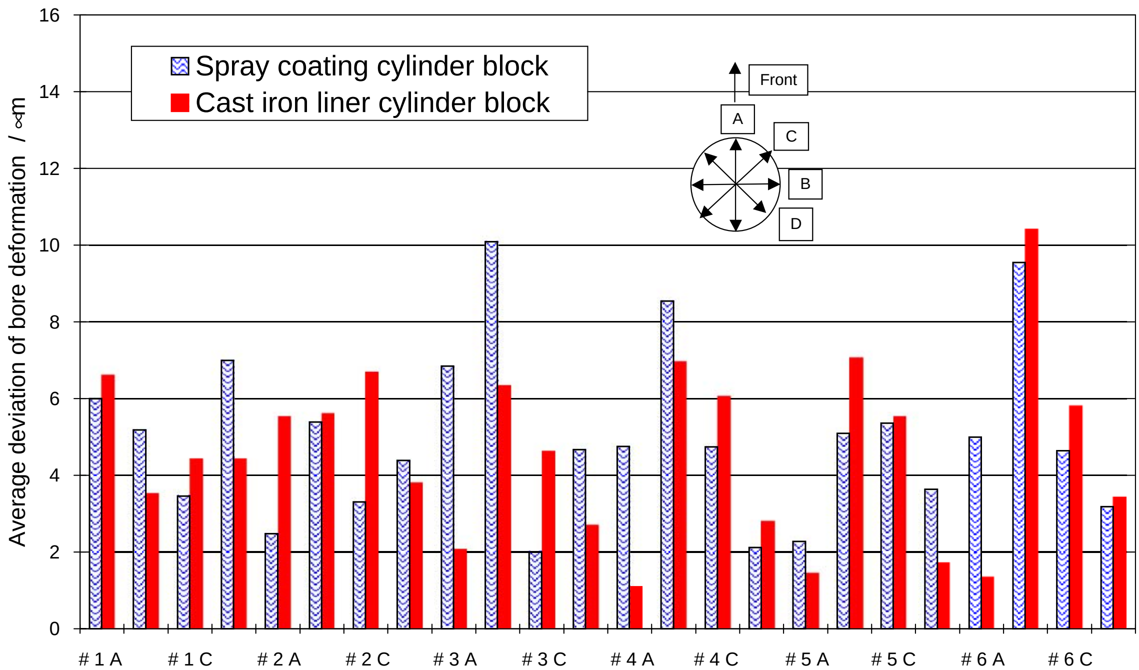


Fig. 10. Average deviation of bore deformation by bolt fastening on each bore.

difference is seen between the spray coating cylinder block and the cast iron liner cylinder block. Average deviation of absolute value on the variance of each bore is shown in Fig. 10, which also reveals no outstanding distinction on bore deformation between the two types of cylinder blocks. Overall average deviation of spray coating cylinder block is 6 μm, and that of cast iron liner cylinder block is 7 μm. From the results, it is proved that the rigidity of spray coating cylinder block is equivalent to, or greater than that of a cast iron liner cylinder block.

## 4. Conclusions

Thermal spray coating on cylinder bores in diesel engine has been done by using atmospheric plasma spraying with newly developed ferrous powders, and characteristics of the cylinder bore, wear, corrosion and rigidity have been evaluated.

The main conclusions obtained are as follows,

1. Coating thickness satisfied the target of 250 μm at every position of the bore. The variation of coating thickness measured at each position was small, ranged between 258 μm in minimum and 280 μm in maximum.
2. A newly developed powder coating showed excellent wear performance compared with liner bulk materials currently used in actual engines. Especially, the maximum wear depth of coatings was less than half compared with those of liner bulk materials. Maximum wear depth of counter pin against the spray coating also showed less than those of liner bulk materials.
3. Weight loss of the coating was about 2% after 95 h immersion in 20 mass% sulfuric acid water solution, less than those of liner bulk materials, ST and GT, around 8–9%. A newly developed powder coating showed extremely superior corrosion resistance compared with those of liner bulk materials currently used in actual engines.
4. Rigidity of spray coating cylinder block is equivalent to, or greater than that of a standard cast iron liner cylinder block.
5. It is confirmed that spray coating bores with the newly developed spray coating material made by using the Rotaplasma® process fills the essential performances required for practical use in actual diesel engines. Consequently, it is concluded that the liner-less aluminum cylinder block with spray coating bore has the possibility of practical use.

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