Thermally Sprayed Coatings for Protection of Fretting Wear

Hathaipat Koiprasert,[1*] Panadda Niranatlumpong[1] and Supattanapong Dumrongrattana[2]

Vibration often occurs in many types of engines and machinery during operation. Such vibration, apart from causing the usual nuisances like inaccuracy in production or noise pollution, also generates wear of the machinery parts and components. Fretting is a type of wear generally associated with vibration and is one of the major causes of failure in many components. Fretting itself may occur on a small scale but it can initiate other types of wear leading to severe damage of the components. High operating temperature, which is a common working condition in many engines, can also accelerate the wear mechanism resulting in a different wear behavior. Fretting wear protection at high temperature is therefore necessary particularly in high-cost components such as fuel nozzles and fuel nozzle collars in land based gas turbine engines which are used at high temperature.

This research was carried out to study fretting wear resistant coatings at elevated temperatures for gas turbine application. Four types of coating; namely WC-17%Co, Cr_3C_2-25%NiCr, AlSi-graphite and CoMoCrSi, were deposited on stainless steel substrates by thermal spraying techniques. Physical and mechanical properties of the coatings; such as adhesion strength, porosity and microstructure, were measured for comparison. The wear behavior of each type of coating was studied by using an in-house flat-on-flat wear tester which was designed to simulate the vibrating condition of the fuel nozzle at an operating temperature of 500°C. Wear tests were performed for various time durations for each set of specimens.

The results from the fretting wear tester showed that the HVOF coatings outperformed the plasma sprayed coatings of the same materials. CoMoCrSi exhibited excellent wear and oxidation properties. It was concluded that the CoMoCrSi coating is suitable to use as protection from fretting wear at 500°C for fuel nozzles and fuel nozzle collars in land based gas turbines.

Key words: fretting wear, high temperature wear, wear resistance coating and thermal spraying.

[1]*National Metals and Materials Technology Center (MTEC), Pathumthani 12120, Thailand.*
[2]*Department of Physics, Faculty of Science, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand.*
[*]*Correspondence to: e-mail: hathaik@mtec.or.th*

การเคลือบผิวด้วยเปลวความร้อนเพื่อป้องกันการสึกหรอแบบเฟรตติ้ง

หทัยพัฒน์ ค่อยประเสริฐ ปนัดดา นิรนาทล้ำพงศ์ และ สุพัฒน์พงษ์ ดำรงรัตน์ (2547)
วารสารวิจัยวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย **29(2)**

ขณะใช้งานเครื่องจักรกลหลายชนิดมักมีการสั่นสะเทือนเกิดขึ้น การสั่นสะเทือนของชิ้นส่วนต่างๆ มีผลต่อความแม่นยำในการผลิต การกระทบกันทำให้เกิดมลพิษทางเสียงและยังก่อให้เกิดการสึกหรอของชิ้นส่วนเครื่องจักรกล เฟรตติ้งเป็นการสึกหรอประเภทหนึ่งที่เกิดจากการสั่นสะเทือนและเป็นสาเหตุสำคัญอย่างหนึ่งของความเสียหายของชิ้นส่วนเครื่องจักรกล เนื่องจากเครื่องจักรกลหลายชนิดมีการใช้งานที่อุณหภูมิสูงซึ่งสามารถเร่งกลไกการสึกหรอทำให้มีพฤติกรรมการสึกหรอที่แตกต่างออกไป ดังนั้นการป้องกันการสึกหรอแบบเฟรตติ้งที่อุณหภูมิสูงจึงเป็นสิ่งจำเป็นโดยเฉพาะอย่างยิ่งชิ้นส่วนที่มีราคาแพง เช่น หัวฉีดเชื้อเพลิงและปลอกหัวฉีดเชื้อเพลิงในเครื่องยนต์ใบพัดกังหันก๊าซที่ใช้เป็นเครื่องผลิตไฟฟ้าซึ่งชิ้นส่วนดังกล่าวใช้งานที่อุณหภูมิสูง

งานวิจัยนี้ได้นำเสนอการศึกษาผิวเคลือบเพื่อป้องกันการสึกหรอแบบเฟรตติ้งที่อุณหภูมิสูงสำหรับใช้งานป้องกันการสึกหรอของหัวฉีดเชื้อเพลิงและปลอกหัวฉีดเชื้อเพลิงในเครื่องยนต์ใบพัดกังหันก๊าซ โดยศึกษาผิวเคลือบ 4 ชนิดคือ WC-17%Co Cr_3C_2-25%NiCr AlSi-graphite และ CoMoCrSi ที่พ่นเคลือบบนเหล็กกล้าไร้สนิมด้วยกระบวนการพ่นเคลือบด้วยเปลวความร้อน จากนั้นนำผิวเคลือบที่ได้มาทดสอบสมบัติทางกลและทางกายภาพต่างๆ เช่น ความแข็งแรงในการยึดเกาะระหว่างผิวเคลือบกับชิ้นงานเหล็กกล้าไร้สนิม ความพรุนของผิวเคลือบและโครงสร้างจุลภาค เพื่อเปรียบเทียบผิวเคลือบแต่ละชนิด นอกจากนี้ยังได้มีการทดสอบความต้านทานการสึกหรอแบบเฟรตติ้งที่อุณหภูมิ 500 องศาเซลเซียสในห้องปฏิบัติการ โดยสร้างเครื่องทดสอบการสึกหรอแบบเฟรตติ้งที่อุณหภูมิสูง ซึ่งเป็นเครื่องชนิด Flat-on-Flat ทำการทดสอบในเตาอบควบคุมอุณหภูมิที่ 500 องศาเซลเซียสเพื่อจำลองสภาวะที่เกิดการสึกหรอของชิ้นส่วนดังกล่าวและศึกษากลไกการสึกหรอของผิวเคลือบ

ผลการวิจัยพบว่าผิวเคลือบจากการพ่นเคลือบด้วย HVOF มีสมบัติดีกว่าผิวเคลือบที่พ่นเคลือบด้วยเปลวพลาสมาเมื่อพ่นเคลือบด้วยวัสดุชนิดเดียวกัน ผิวเคลือบ CoMoCrSi มีสมบัติต้านทานการสึกหรอและการเกิดออกซิเดชันที่ดีมาก ด้วยเหตุนี้ผิวเคลือบ CoMoCrSi จึงเหมาะที่จะใช้ในการต้านทานการสึกหรอแบบเฟรตติ้งที่อุณหภูมิประมาณ 500 องศาเซลเซียสของชิ้นส่วนหัวฉีดเชื้อเพลิงและปลอกหัวฉีดเชื้อเพลิงในเครื่องยนต์ใบพัดกังหันก๊าซ

คำสำคัญ การสึกหรอแบบเฟรตติ้ง การสึกหรอที่อุณหภูมิสูง ผิวเคลือบเพื่อป้องกันการสึกหรอ การพ่นเคลือบด้วยเปลวความร้อน

INTRODUCTION

Fretting wear is a surface degradation which occurs between two contracting surfaces that are subjected to a cyclic, relative motion with amplitudes ranging from 1 to 100 microns.[1,2] The movement is usually the result of external vibration.[3] The locations where fretting may occur are in riveted or bolted joints, hubs, in press fits on shafts, bearing housings, *etc*. Fretting wear can generate an accelerated failure if it becomes abrasive wear or other wear type. Fretting damage occurs in many applications including the jet engine disk and compressor blades in the jet engine[4] and the fuel nozzle and its collar in the land based gas turbine.[5] An elevated operating temperature can accelerate wear rate, resulting in different wear behaviors.

This research was carried out to study the fretting wear resistant coatings at elevated temperature for gas turbine applications. The fuel nozzle, made from stainless steel 304, is one of the critical parts in a combustor section of a gas turbine engine. During operation, the fuel nozzle, which is slotted inside its collar and held in place as shown in Figure 1, is subjected to high pressure from fuel combustion. This will cause these parts and the combustion chamber to vibrate. It is this vibration that causes fretting wear on the outer surface of the nozzle. Slight wear damage will result in reduction of gas pressure in the chamber which will affect the engine efficiency. The chamber is operated at a maximum temperature of 700 to 800°C and the temperature of the nozzle is below 500°C.[6]

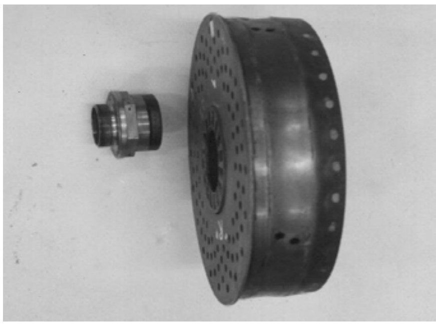

Figure 1. Fuel nozzle and its collar.

Thermal spraying methods, known as HVOF (High Velocity Oxy Fuel) and Plasma Spray, are the coating techniques proven to be successful at providing wear resistant surfaces. They are widely used for solving wear problems in the automobile, air craft and tooling industries. These techniques can provide dimensional restoration of worn parts and improve wear resistance. However, due to the complicated nature of wear, there is no certain rule of coating material selection. The objective of this investigation is to study the behaviors of different coating materials under fretting wear condition at 500°C in order to select the most suitable coating for the wear protection of fuel nozzles in gas turbine engines.

EXPERIMENTAL PROCEDURE

Sample preparation

Two types of specimen substrates were prepared from stainless steel 304 rod. For the first set of samples used in the pull-off test, the rod was cut into a cylinder of 25.4 mm in diameter and 45 mm in length. A 10 mm diameter hole was drilled through the side of the cylinder, 13 mm away from one flat end to enable the fixation of the samples during testing. For the second set of samples, stainless steel rods of 25.4 and 38.1 mm diameters were sliced into 5 mm thick discs. This set of samples was used for coating characterization and wear testing.

A flat surface of each sample, which was to be thermally sprayed, was roughened by grit blasting using a 740 micron alumina grit to obtain a sharp peaked surface contour and a roughness greater than 5-6 microns, which is essential to the adhesion of the coating[7] The air pressure used for grit blasting was 8 bar. The blasting nozzle was held perpendicular to the sample surface at a distance of 80 mm for 30 seconds. After the grit blasting process, the samples were cleaned in acetone using an ultrasonic bath for 15 minutes. The samples were then ready for HVOF and plasma spraying.

The coating materials chosen for this investigation were WC-17%Co, Cr_3C_2-25%NiCr, AlSi-graphite and CoMoCrSi. WC-17%Co cermet was chosen for its very high hardness and excellent wear resistance, but its maximum operating temperature is 500°C. Cr_3C_2-25%NiCr, also wear resistant, performs better against high temperature corrosion not exceeding 800°C.[8,9] These two coatings are commonly used for wear resistant coatings. AlSi-graphite contained flake graphite, which can act as a solid lubricant. Its maximum operating temperature is also around 500°C. CoMoCrSi is a hard, low friction material. It has good sliding wear and good oxidation resistance at a maximum operating temperature of 800°C. The HVOF and plasma spraying parameters for each material were optimized to achieve high coating density and low oxide content. These parameters are shown in Tables 1[10] and 2[11] (Modified from the standard parameters to suit the spray system used). Each coating was sprayed to a thickness of 300 to 400 microns. The coatings for the wear test were ground down using SiC paper, to a thickness of about 250 microns and a surface roughness of about 0.8 microns.[12]

After the coating fabrication, the samples were ultrasonically cleaned in acetone and were ready for testing.

Physical and mechanical testing

Microstructures of the cross-section of the as-sprayed coatings were studied using a JEOL-JSM 6301F SEM. Porosity percentage of the cross-sectioned coatings were obtained using a LEICA Q 600 image analyzer. The hardness of the coatings was also tested on the cross-sections, using a Vickers indenter and a Shimadzu HVM-2000 microhardness tester with a load of 300 grams and hold-on time of 10 seconds. The results were averaged from 10 indents. X-ray diffraction was performed to identify the chemical compositions of the coatings, using CuK_α radiation and 2θ angle between 5-90°C.

A "pull-off" technique was used to evaluate adhesive or cohesive strength of the coatings. The test was carried out according to ASTM C633-79. The coated surfaces of the cylindrical samples were covered with 0.5 mm thick Plasmatex Klebbi glue and stuck onto flat surfaces of uncoated cylinders. The glue was cured at 200°C for 2 hours to strengthen the bonding. The specimens were then loaded into a Shimadzu AG-10TB universal testing machine for the tensile test, using a 10,000 kg load and a 1 mm per minute pulling rate, shown in Figure 2.

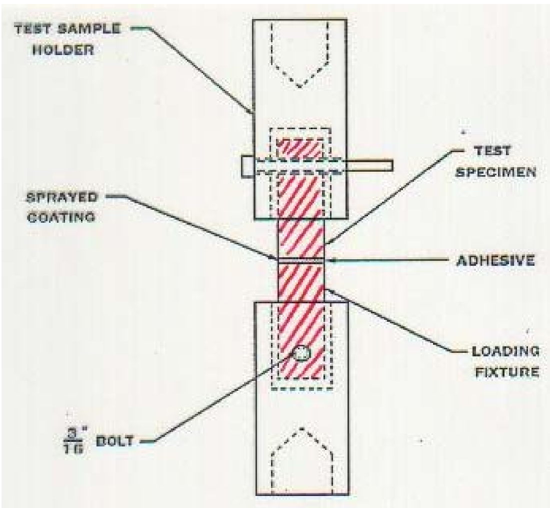

Figure 2. Schematic diagram of the pull-off test.[13]

Table 1. Spray parameters for HVOF spraying technique.

Coating	Pressure(bars)				Flow meter (Standard Liters per Minute (0ºC))				Spray distance (mm)	Spray rate (g/min)
	O_2	H_2	N_2	Air	O_2	H_2	N_2	Air		
WC-17%Co	11.7	9.6	10.3	6.2	214	684	396	343	228.6	50
Cr_3C_2-25%NiCr	11.7	9.6	10.3	6.2	214	684	396	343	228.6	50
AlSi-graphite	11.7	9.6	9.6	6.9	214	684	396	344	228.6	30
CoMoCrSi	11.7	9.6	9.6	6.6	214	750	396	351	228.6	43

Table 2. Spray parameters for plasma spraying technique.

Coating	Pressure (bars)		Flow meter (Standard Liters per Minute (0ºC))		DC (amp.)	DC (volt)	Spray distance (mm)	Spray rate (g/min)
	Ar	H_2	Ar	H_2				
WC-17%Co	6.9	3.4	73.2	8.5	400	50-55	76.2	83
Cr_3C_2-25%NiCr	6.9	3.4	48.8	4.8	500	60-70	76.2	42
AlSi-graphite	6.9	3.4	92.7	6.6	500	75-85	127	60
CoMoCrSi	6.9	3.4	73.2	5.7	500	70-75	101.6	45

An in-house wear test rig was designed to simulate the operating condition of the fuel nozzle. In this test rig, a disc sample of 38.1 mm diameter was held coating-side up at the bottom and attached to a Quantum air vibrator type VP10, using 30 psi air pressure. The 25.4 mm diameter sample was positioned coating-side down on the top of the large disc of the same coating with 6 kg. load pressing down. As the samples vibrated, the coated surfaces moved relative to each other. The relative sliding movement was 40 to 80 microns and the vibration speed was 3 to 4 mm per second, monitored by a Riovibro VM 63a pocketable vibration meter. The tester was positioned inside a furnace to obtain an operating temperature of 500°C.

Weight changes of the test samples, calculated per unit area using subtraction technique of the specimen before and after testing, were recorded every 24 hours. After 96 hours of wear test, the planar surfaces of the coatings were observed using SEM.

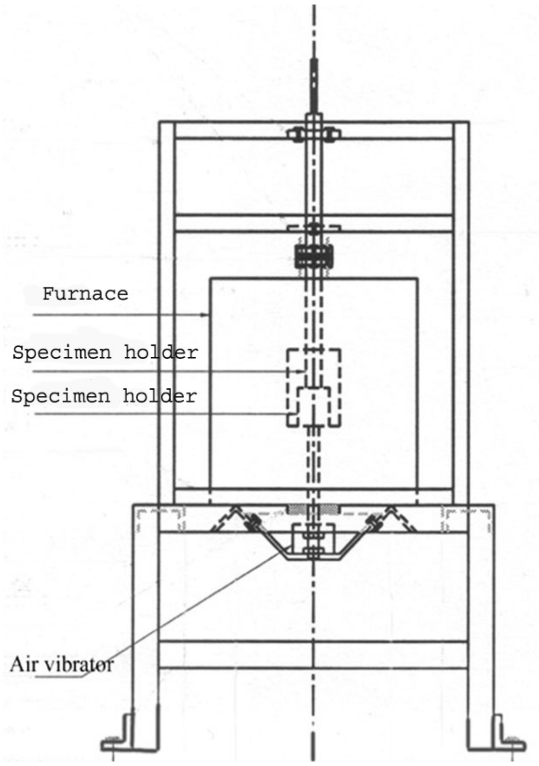

Figure 3. Schematic diagram of a fretting wear tester.

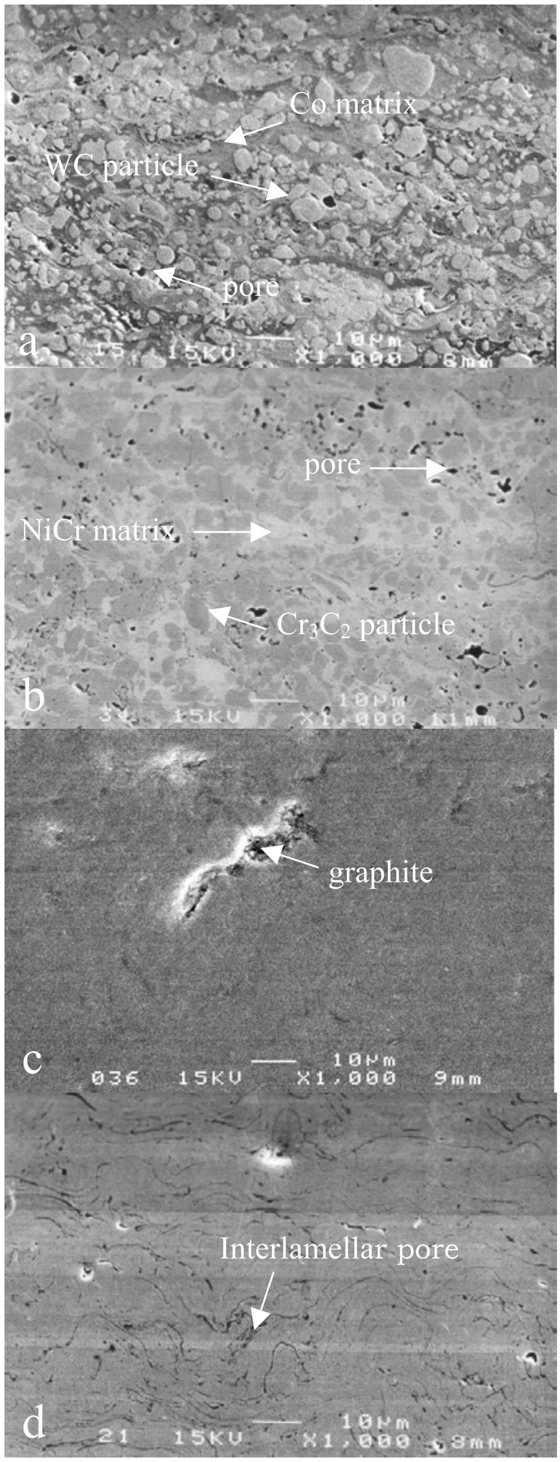

Figure 4. HVOF coating microstructures at 1000x magnification of (a) WC-17%Co, (b) Cr_3C_2-25% NiCr, (c) AlSi-graphite and (d) CoMoCrSi.

RESULTS AND DISCUSSIONS

Microstructures of the HVOF and plasma sprayed coating cross-sections are as shown in Figures 4 and 5.

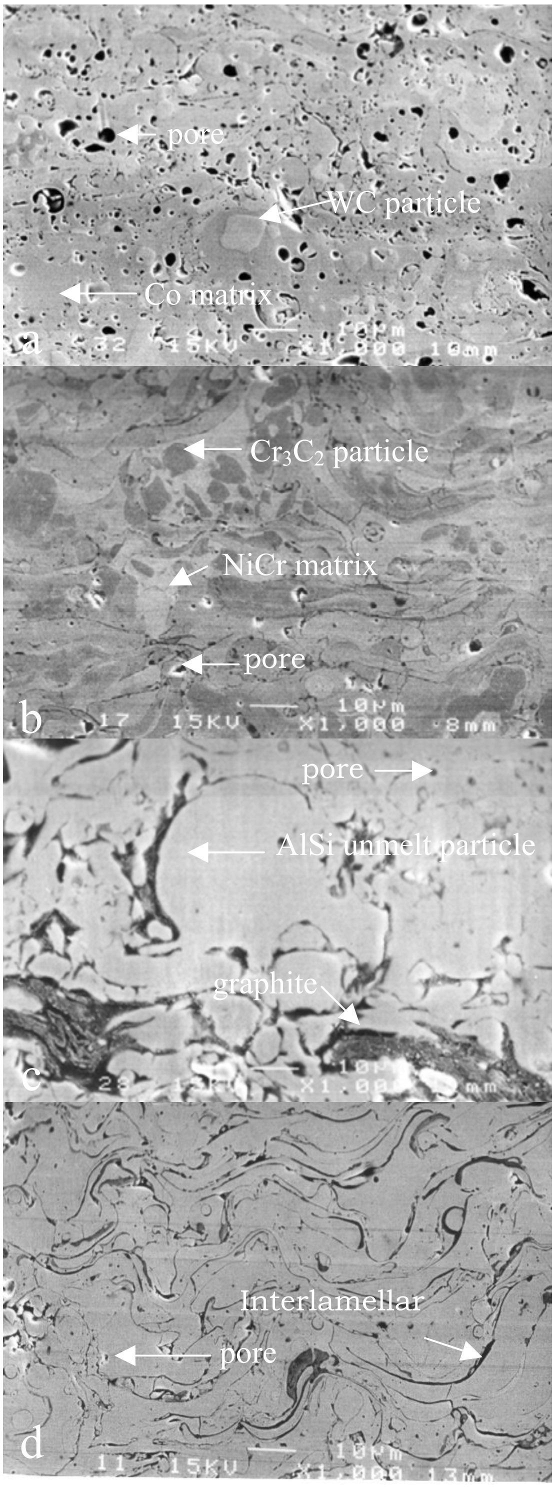

Figure 5. Plasma sprayed coating microstructures at 1000x magnification of (a) WC-17%Co, (b) Cr_3C_2-25%NiCr, (c) AlSi-graphite and (d) CoMoCrSi.

WC-17%Co and Cr_3C_2-25%NiCr HVOF sprayed coating have similar high density structures. WC-17%Co and Cr_3C_2-25%NiCr coatings consist of WC or Cr_3C_2 particles scattered in Co or NiCr matrix. Some rounded pores can be observed as dark color, these are suspected to be due to particle pull-out during polishing. The AlSi-graphite HVOF sprayed coating shows a very high density AlSi phase matrix with large flakes of unmolten graphite (very dark color) contained within the structure-the splat boundary cannot be identified. The AlSi-graphite plasma sprayed coating has a lower density, larger pores and a higher number of unmolten AlSi particles than the HVOF coating. The splat boundary can be identified more easily. HVOF and plasma sprayed CoMoCrSi coatings consist of a single phase with the splat boundary clearly defined. The interlamellar pores in the CoMoCrSi plasma sprayed coating are larger than those in the HVOF coating. Some porosity is present between splats, which implies that the degree of melting during spraying is less than that of the previous coatings. The plasma sprayed coating has a lower density and larger pores than the HVOF coating because it has a lower velocity of molten particles (250-500 m/s)[2] than HVOF (750-1350 m/s).[14,15] From $F_{(impact)} = ma$, HVOF particles have a higher impact force, which therefore results in a higher density.

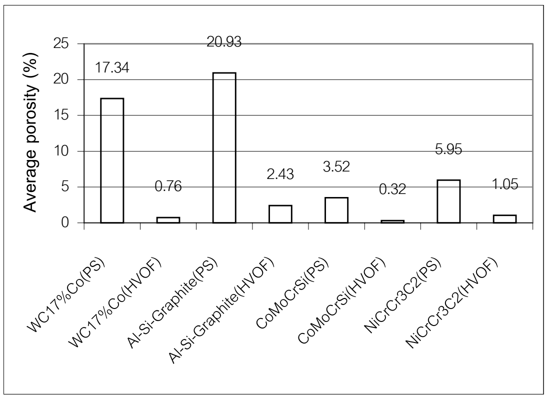

Figure 6. The average porosity of the coatings.

Averaged porosity of the coating cross-sections is summarized in Figure 6. It is to be noted that the porosity of the AlSi-graphite coating measured is higher than the actual value because the image analyzer technique employed in this investigation uses color differentiation to detect pores. Since graphite has a very dark color, some graphite flakes were identified as pores during this measurement.

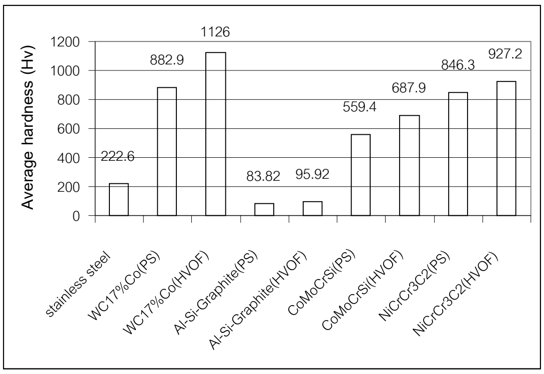

Figure 7. Graph showing the average hardness of the coatings.

Figure 7 shows the average hardness of the coatings. The HVOF coatings are harder than the plasma sprayed coating because of the higher density. WC-17%Co coatings have the highest hardness value due to the carbide particles. The hardness of the Cr_3C_2-25%NiCr coating is lower due to a lower percentage of softer carbide.[16] Al-Si Graphite exhibits the lowest hardness value due to large % of soft graphite.[17]

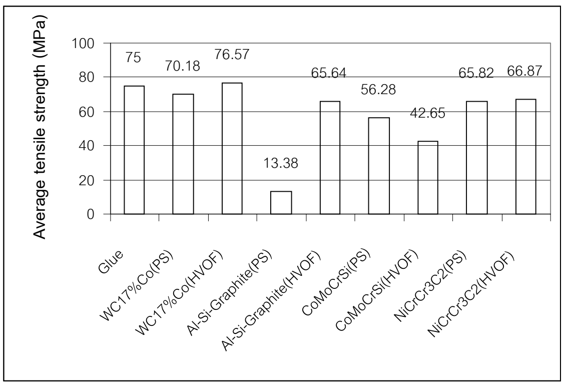

Figure 8. Adhesive or cohesive bond strength of the coatings to stainless steel substrates.

Bond strength of the coatings is reported in Figure 8 with reference to the glue adhesive strength to the stainless steel, which varies between 70 and 75 MPa. From the results, the WC-17%Co and Cr_3C_2-25%NiCr in both HVOF and plasma sprayed coatings showed very high cohesive and adhesive strengths. Since the test samples were debonded at the glue, it can be concluded that the cohesive and adhesive strengths of these coatings are higher than 70 MPa. AlSi-graphite coatings debonded in a cohesive manner due to the graphite flakes acting as a defect. Among those coatings, the HVOF sprayed coating had a higher bond strength than the plasma sprayed coating because the latter has lower density and the pores act as a defect. CoMoCrSi possesses the lowest bond strength of all four coatings. CoMoCrSi HVOF coating also debonds cohesively, but the plasma sprayed coating is adhesively debonded. In the CoMoCrSi HVOF coating, the surface roughness of the coating reduces as the coating thickness increases, partly due to the higher impact force. At a certain distance away from the interface, the roughness may not be high enough for the coating to obtain a good adhesion. For this reason, CoMoCrSi HVOF coating had a lower bond strength than the plasma sprayed coating. The failure of CoMoCrSi coating is shown in Figure 9.

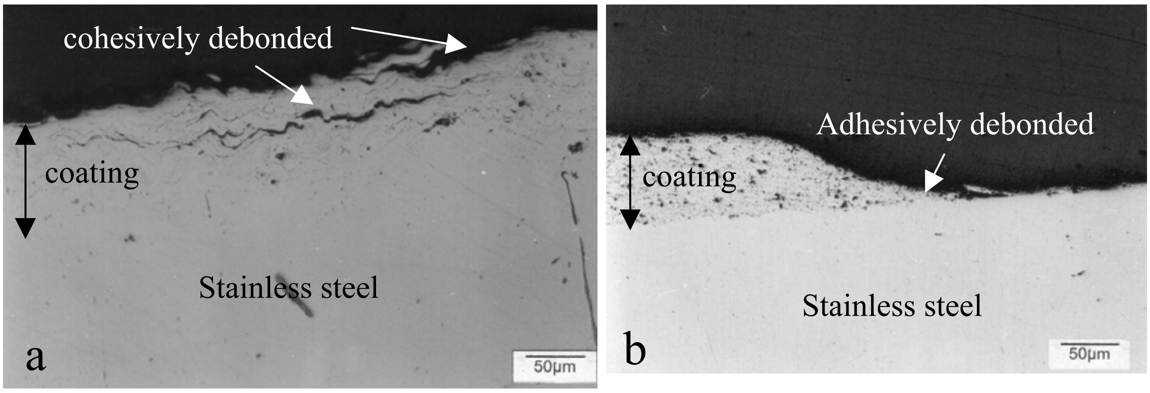

Figure 9. Optical micrograph after pull off test of (a) cohesive failure of HVOF sprayed CoMoCrSi coating (b) adhesive failure of plasma sprayed CoMoCrSi coating.

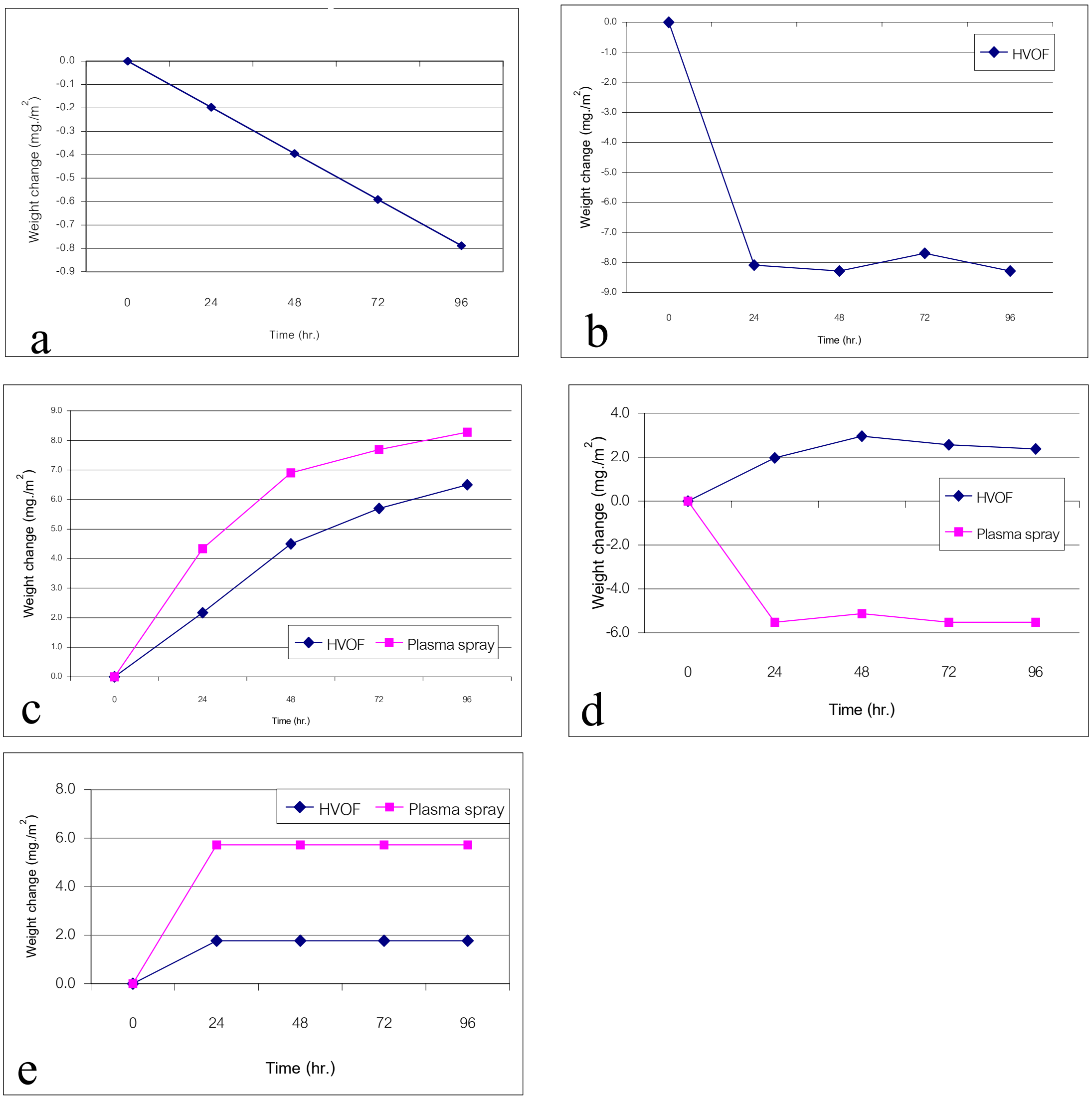

Figure 10. Wear testing of (a) stainless steel, (b) WC-17%Co, (c) Cr_3C_2-25% NiCr, (d) AlSi-graphite and (e) CoMoCrSi.

Results from wear tests are reported in Figure 10, in terms of weight changes of the 25.4 mm diameter samples with respect to the test duration. The stainless steel sample shows a gradual decrease in weight (Figure 10(a)). Observation of the planar surface after 96 hours of testing reveals plastically deformed areas with some wear debris present (Figure 11).

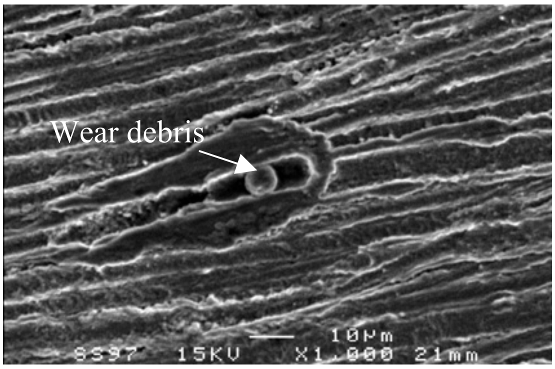

Figure 11. Optical micrograph of the planar surface of the stainless steel sample after 96 hours of wear test.

Formation of a third body film, consisting of a mixture of wear debris from contacting surfaces building up to form a layer,[18,19] was suspected. However, since the two surfaces are of the same material, it was not clear whether there was a material transfer and a build up of the wear debris on the surfaces. Moreover, the cross-section of the sample surfaces does not show any distinct third body film.

Figure 10(b) shows a reduction in weight of the WC-17%Co coating at an early stage of testing due to the loss of WC particles from the coating surface. Detachment of the hard particles is possibly due to the oxidation of the coating, forming a brittle product of $CoWO_4$.[20] This will cause a decrease in ductility around the WC particle and hence, the particles can become detached easily. XRD results in Figure 12 confirm this conclusion. After the initial loss of loose particles on the surface, the weight of the coating remains stable due to the high wear resistant properties of the WC-Co coating, although the loss of loose particles can cause a further three-body abrasion on the coating, see Figure 13 (three-body abrasion occurs when abrasive particles can move freely between two contacting surfaces). WC-17%Co plasma sprayed coatings were severely fractured when removed from the test rig for weighing, shown in Figure 14, due to damage caused by oxidation and decarburization. The wear information was, therefore, not obtainable and is not presented in Figure 10(b). The W_2C phase has a larger number and larger size of unstable pores, which promote oxygen absorption. This leads to the formation of oxidation products, such as $CoWO_4$ and WO_3, due to wettability and surface energy change, with resultant coating break down.

A sub-parabolic increase in weight of Cr_3C_2-25% NiCr coating, as shown in Figure 10 (c), indicates the oxidation of NiCr to form Cr_2O_3. Further testing could cause the thickening oxide layer to crack and produce hard oxide debris which will accelerate the wear process.

The change in weight of the AlSi-graphite coating during wear testing is summarized in Figure10 (d). AlSi-graphite HVOF coating has an initial increase in weight of the coating, which is possibly due to oxygen absorption.

After the test, the splat boundary in AlSi-graphite plasma sprayed coating could not be identified because of the diffusion at high temperature, but the splats of AlSi-graphite plasma sprayed coating are still present. This results in a higher weight reduction in the plasma sprayed coating than the HVOF coating. Both the HVOF and plasma sprayed coatings consist of AlSi matrix, graphite flakes, some porosity and fine Si particles, shown in Figure 15. The slow cooling in the furnace at the end of the testing allows enough time for the precipitation of Si particles from the eutectic Al-Si alloy to take place as shown by previous research work.[21-23] The presence of Si particles was thought to help improve the resistance to plastic deformation of the coating.[24]

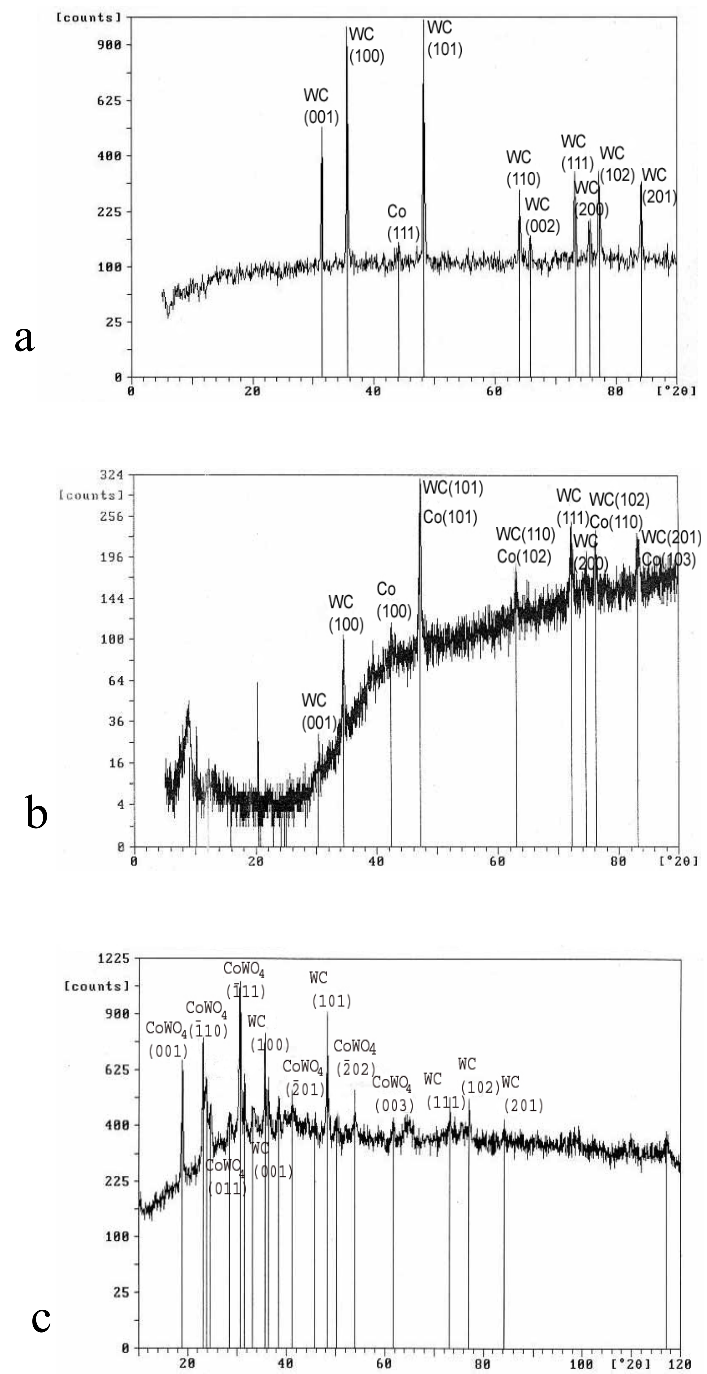

Figure 12. X-ray diffraction graph showing chemical compositions of (a) WC-17%Co powder, (b) as-sprayed WC-17%Co coating and (c) WC-17%Co coating after 96 hours of wear test.

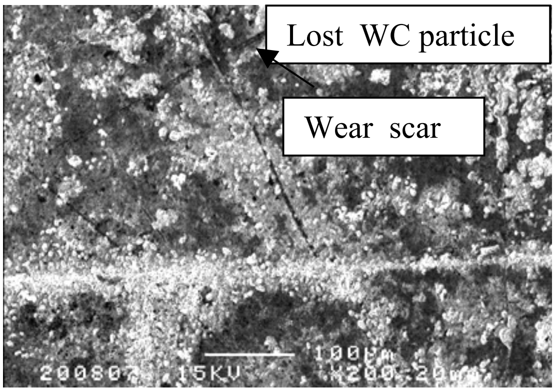

Figure 13. WC-17%Co HVOF coating surface.

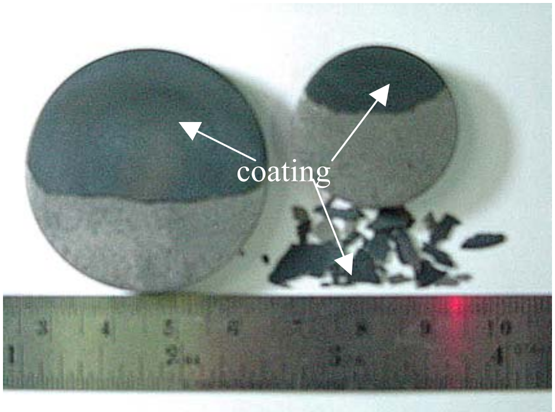

Figure 14. WC-17%Co Plasma Sprayed coating failure after 24 hours of wear test at 500ºC.

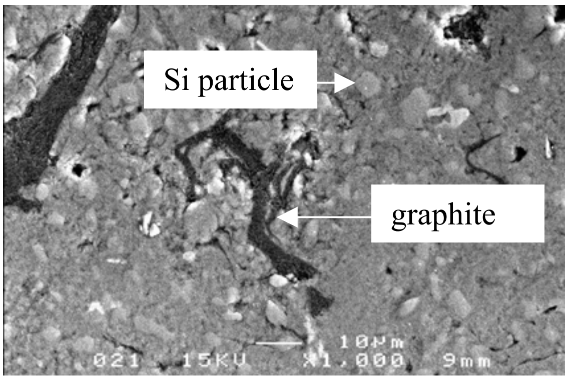

Figure 15. Micrograph of the cross-sectioned surface of the AlSi-graphite coating after 96 hours of wear test at 500ºC.

In addition, AlSi-graphite coatings formed a third-body film on each surface, which protects the surface from further wear.(18,19) However, the result still displays high weight loss in comparison to the stainless steel. The third-bodies of AlSi-graphite HVOF coating are shown in Figure 16.

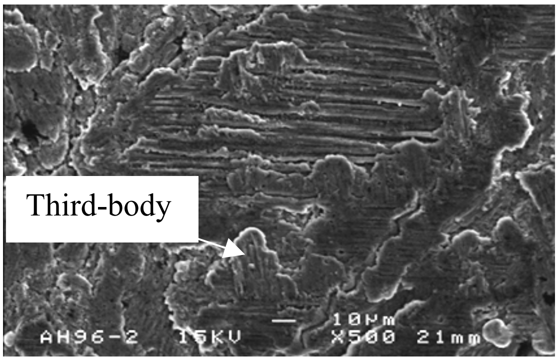

Figure 16. Third-body film on the AlSi-graphite coating surface.

Figure 10 (e) shows the weight change of CoMoCrSi during testing. The coating has a small increase in weight at the start of the test, possibly due to oxygen absorption. There is no obvious oxide layer observed. The weight of the sample remains constant after the initial increase, there is no weight loss detected. This is largely because of the hard, self-lubricating properties of the coating. It was this mechanical and chemical stability of the coating in the fretting wear condition at 500°C that makes CoMoCrSi the most suitable coating among all the coatings tested to be used to protect from fretting wear problems in fuel nozzles in gas turbine engines.

From Figure 10, the Cr_3C_2-25% NiCr and CoMoCrSi plasma sprayed coatings have larger weight gains than the HVOF coatings because of the larger number and bigger size of pores that cause more oxygen absorption.

CONCLUSIONS

For wear resistant coatings at high temperature, oxidation-corrosion properties become an important factor as well as the wear properties. HVOF coatings outperformed the plasma sprayed coatings of the same materials due to their higher coating hardness, higher coating fracture strength, higher adhesion to the stainless steel substrate, higher phase stability to oxidation and decarburization and minimal porosity, which obstructs oxygen absorption. The HVOF coatings are also less oxidation-active, type of coating is also important. The WC-17% Co coating, though very resistant to wear at ambient temperature, does not perform well at 500°C. The Cr_3C_2-25% NiCr coating has better wear and oxidation resistance than WC-17%Co, but its continuous oxidation may cause rapid wear damage. The AlSi-graphite coating has a third-body film and precipitates primary Si particles, which improve the wear resistance of the coating. However, the weak composite structure between AlSi and graphite cannot withstand such severe wear condition and, therefore, did not perform satisfactorily. The CoMoCrSi coating also exhibited excellent wear and oxidation properties. The oxidation almost ceased within 6 hours of testing in the HVOF coating and 14 hours in the plasma sprayed coating. Thus, CoMoCrSi HVOF coating is the most appropriate coating among the materials tested to be used for the protection of the fuel nozzles and fuel nozzle collars in gas turbine engines from fretting damage at 500°C.

ACKNOWLEDGMENTS

The authors would like to thank the Electricity Generating Authority of Thailand (EGAT) for the information on the fuel nozzle and fuel nozzle collar and for providing the stainless steel sample. We are also very much grateful to King Mongkut's University of Technology Thonburi for the support in tools and machinery for testing and building the fretting wear tester at high temperature.

REFERENCES

1. Krueger, F. E. (1975) "Failure Analysis and Prevention" Metals Handbook, 10, 8th edition, *American Society of Metals*, *U.S.A.*, 154-155.
2. Hutchings, I. M. (1992) "Tribology: Friction and Wear of Engineering Materials" *Edward Arnold, London,* 109-110.
3. Waterhouse, R. B. (1992) "Friction Lubrication and Wear Technology" *ASM Handbook, Henry, S.D. (Eds.), 18, ASM International. U.S.A.* 242.
4. Freimanis, A. J., Segall, A. E., Conway Jr, I. J. C. and Whitney, E. J. (2000) "Elevated Temperature Evaluation of Fretting and Metal Transfer between Coated Titanium Compounds" *Tribology Transactions.* **43**, 653-657.
5. Koiprasert, H. (2003) "Development of Thermally-Sprayed Coatings to Improve Wear Resistant of Fuel Nozzle and Fuel Nozzle Collar in Land Based Gas Turbine" M. D. thesis, King Mongkut's University of Technology Thonburi.
6. Personal communication. (2001) "Sammated, P., Head of Maintainance Division, Electricity Generating Authority of Thailand."
7. Gill, B. J. and Tucker, R. C. Jr. (1986) "Materials Science and Technology" **2**, 207-213.
8. Guilemany, J. M. and Calero, J. A. (1997) "Thermal Spray: A United Forum for Scientific and Technological Advances" Berndt, C.C., ed., ASM International, Materials Park. OH, 717-21.
9. Lai, G.Y. (1978) "Thin Solid Films" **53**, 343-51.
10. METCO LTD, Hydrogen spray parameters using DJ2600 Hybrid hardware, New York.
11. METCO LTD. (1992) Metco perkin elmer type 3MB-II plasma spray gun, New York.
12. Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus ASTM Gas, (1997) *Annual Book of ASTM Standard*, Section **3**, 3.02 392-396.
13. Kitpanidchavisase, A. (1998) "Plasma Spray Coating of Hydroxyapatite for Medical Applications", M. D. Thesis, King Mongkut's University of Technology Thonburi.
14. Thrope, R., Kopech, H. and Gagne, N. (2000) "Advanced Materials and Processes" **157**, 27-32.
15. Frank, M. J. VandnBerge (1998) "Thermal Spray Processes: An Overview" *Advance Materials and Processes*, **154**, 31-36.

16. Ding, C., Li, J., Zhang, L. and Yu, X. (1998) "Proceedings of the 15th International Thermal Spray Conference" 25-29 May 1998, France, 275-280.
17. Chu, H. S., Liu, K. S. and Yeh, J. W. (2000) "An in situ composite of Al (graphite, Al_4C_3) produced by reciprocating extrusion" *Materials Science and Engineering*. **A277**, 25-32.
18. Bayer, R. G. (1994) "Mechanical Wear Prediction and Prevention" *Marcel Dekker, Inc., New York*. **27(73)**, 90-91.
19. Descartes, S. and Berthier, Y., (2002) Wear **252**, 546-556.
20. Basu, S. N. and Sarin, V. K. (1996) Materials Science and Engineering. **A 209**, 206-212.
21. Bäckerud, L., Chai, G. and Tamminen, J. (1990) Solidification characteristics of aluminum alloys. **2**, 25-79.
22. Zhang, R., Cao, Q., Pang, S., Wei, Y. and Liu, L. (2001) "Dissolution kinetics of primary silicon in hypereutectic Al-Si melt" *Science and Technology of Advanced Materials*. **2**, 3-5.
23. Stoichev, N., Petrov, K., Yaneva, S., Kovachev, P. and Tzvetanova, N. (2002) "Micro-structural development in Al-Si microcrystalline allloys" *Materials Science and Engineering*. **A337**, 12-16.
24. Prasad, B. K., Venkateswartu, K., Modi, O. P., Jha, A. K., Das, S., Dasgupta, R. and Yegneswaran, A.H. (1998) "Sliding Wear Bahavior of Some Al-Si Alloys: Role of Shape and Size of Si Particles and Test Conditions", *Metallurgical and Materials Transactions*. **29A**, 2747-2754.

Received: January 13, 2004
Accepted: June 29, 2004