SEM – Invaluable and practical tool for casting defect analysis before a DOE

Introduction

Many foundries have experienced costly outbreaks of high reject rates due to metallurgical casting defects. A defect may arise from a single clearly defined cause or may be a result of a combination of factors, so that the necessary preventive measures are initially unclear. However, to prevent recurrence it is necessary to correctly diagnose the defect as well as to find the root cause of the defect.

Several approaches are being used in foundries to diagnose metallurgical casting defects. In most cases, a simple visual evaluation of the defect is conducted. Nevertheless, metallurgical casting defect analysis is also accomplished by chemical analysis, microscopic examination, destructive testing, and non-destructive testing. The logical classification of the origin of a casting defect presents great difficulty because of the wide range of inter-related molten metal and casting process contributing factors. In a broader classification, the metallurgical defects may be grouped under four generic origin sources: melting, moulding, pouring, and finishing. Casting defects are very often the result of these variables not being properly controlled.

The elimination of casting defects requires the collection and analysis of data. There are many statistical techniques to help us control process variables, correlate the effects of variables, analyse problems and establish priorities for problem solving. Perhaps the Pareto chart is the most common tool used to pinpoint major causes of scrap in a foundry. Still, all of these techniques are of little use if the defect is improperly diagnosed.

Attempting a corrective action without knowing exactly what the problem is may prove very expensive. In certain instances application of experimental designs have been applied in aluminum foundries for scrap reduction programs. However, for a Design Of Experiment (DOE) technique to succeed, it is imperative that the defect be properly diagnosed. Unfortunately, it is not uncommon practice that a foundry tries to eliminate a casting defect based on an improper diagnosis.

It is a fact that the size and type of a foundry (i.e., large high-production foundry, medium, or jobbing foundry) as well as the cultural thinking of its management influence the methodology to diagnose casting defects, and the manner in which corrective actions are implemented. To correctly diagnose casting defects, it is imperative to fully document the defects by illustration, description, analysis, and accurate data. Attempting a corrective action without knowing exactly what is the problem may prove very expensive. Once a corrective action is found, it must be implemented. In jobbing foundries the corrective action usually takes place during the next production run, mainly because sampling will be cost prohibitive or because of production requirements. On the other hand, in the large high-production foundries the corrective action takes place almost immediately.

It has been known for two decades that the statistical approach to experimentation provides an orderly way to collect, analyze, and interpret significant effects of foundry process variables (1, 2, 3). One might initially think that full-scale DOE have been more widely used in foundry scrap reduction programmes. However, it appears not to be the case. In addition, most of the few published design of experiment methods in the foundry industry seem to be suited for the large high-production foundries (4, 5, 6, 7).

For design of experiments techniques to be successful on the foundry floor, senior foundry management has to commit adequate manpower and resources as well as to be actively involved in the process. In addition, foundry management must set the cultural climate for:

- ❏ improving communication and cooperation among the persons involved in the experimental design programme.
- ❏ understanding that both experiment and interpretation of results would take time.
- ❏ keeping experimental castings segregated.
- ❏ making sure that results are presented with graphical display, and adequate explanation in practical foundry floor language without being bothered by statistical complexity.

The present article was written with the purpose of presenting a case study reflecting the methodology and cultural thinking of a jobbing foundry to eliminate metallurgical defects in a particular automotive green sand casting. For confidentiality reasons, both the foundry name and the casting shape will not be revealed. Nevertheless, for the benefit of this article, it is important to mention that the casting process involves a cope and drag moulding machine, the molding material is olivine green sand, while the dry sand core making process uses the SO_2 system. The gating system of the casting has two independent downsprues and one foam filter per sprue base. In addition, insulating sleeves are used in the moulding process.

This article includes both the results from a design of experiment technique, and scanning electron microscopy for evaluation of the metallurgical defects. In addition, it provides practical knowledge regarding correlation of casting defects with scanning electron photomicrographs. It is important to mention that this study is not, and should not be viewed as an exhaustive discussion of either DOE or Taguchi methods.

Background

This paper illustrates a methodical report from an aluminium jobbing foundry in its quest to eliminate a high scrap rate due to metallurgical defects in a green sand automotive casting. Because of the unsuccessful scrap reduction through traditional approaches, e.g., one person trying to eliminate the scrap by varying single variables, or by trial and error, senior management pushed for a design of experiment technique to eliminate the scrap. Thus, the approach to tackle the scrap consisted first of all in establishing a multi-disciplinary team approach in which key representatives from all the departments were invited to participate.

The first step was to analyze the historical data accumulated by the quality control department and to develop an immediate action plan. However, the data available at that time was inconclusive with respect to defect analysis and the location of the defects. From the historical scrap data, the only obvious information was that the scrap was due to metallurgical problems.

Trying to obtain better data, a second meeting was conducted almost immediately to visually assess typical scrap rejects by each member of the team. For that purpose, several representative rejected sections of castings, before and after machining, were available at the meeting. At that time, it was evident that the castings had two different types of defects. One defect could be observed in the as-cast condition by the naked eye while the second type of defect could only be seen after the machining operation. In order to distinguish the defects they were identified as defect 1 and defect 2. The characterization of the defects was as follows:

- ❑ Defect 1 was visually characterized as an oxide without defining the type of oxide or inclusion. This defect was present mainly along external casting surfaces.
- ❑ Defect 2 was characterized as a laminated surface or metal folding; possibly influenced by a cold shut and/or a blow condition. This defect was located near the casting surface at the top surface of the casting being made by the cope mold.

Brainstorming of the process identified factors or variables that might be related to the occurrence of the defects in question. Seven factors were thought to have the greatest influence affecting such metallurgical defects. Based on the number of variables to be analyzed, an L8 orthogonal array was chosen.

Experimental set up

The variables and the levels that were used are depicted in Table 1 while Table 2 shows the assignment of the array columns.

It is important to mention that during the experiments, enough human resources were allocated on the floor to co-ordinate, measure, and record all the related activities that were deemed necessary to run the experiments under the following controlled conditions:

- ❑ All cores were made the same day.
- ❑ Core surface appearance was 100% visually inspected.
- ❑ Only crucible furnaces were used.
- ❑ Metal specific gravity and chemistry were taken just before each experiment.
- ❑ Green sand and dry sand properties were monitored and recorded.
- ❑ Proper drilling and location of mold vents was 100% visually assured.
- ❑ Placement of proper filter size and proper casting identification was 100% visually assured.
- ❑ Two patterns were used, each with its respective gating system.
- ❑ Adherence to molten metal fluxing procedure was monitored.
- ❑ Metal temperature and mould filling time were monitored for each casting.
- ❑ Exactly the same number of castings were made for each experiment.
- ❑ Experiments 1, 2, 5, and 6 were conducted on the same day.
- ❑ Experiments 3, 4, 7, and 8 were conducted on the same day.
- ❑ Adherence to the DOE was one hundred percent.
- ❑ Each casting was stamped according to the experiment number.
- ❑ Even though sixteen castings were made for each experiment, only fifteen castings were used for machining purposes because one casting would be used for mechanical property evaluation.
- ❑ All castings were grouped in pallets based on the experiment number.
- ❑ All castings were heat treated in-house.
- ❑ All castings were sent together to the machining source. Foundry personnel monitored the machining and scrap at the machining facility.
- ❑ Only the DOE manager was allowed to physically dispose of the scrap.
- ❑ To concur on the casting defects, all the team members reviewed all the scrap.

PROCESS VARIABLE	LEVEL	
	1	2
A= Gating Ratio	1:4:4	1:2:2
B= Metal Temperature (ºF)	1340-1360	1380-1400
C= Drill Vents	NO	YES
D= Metal Fluxing	NO	YES
E= Sr Level (%)	NONE	.011-.018
F= Filter Porosity (PPI)	20	10
G= Core (% LOI)	1.1	0.8

Table 1: Variables and levels used for the design of experiment

EXPERI-MENT	GATING RATIO	METAL TEMPERATURE	DRILL VENTS	FLUX	Sr LEVEL	FILTER POROSITY	CORE (%LOI)
1	1:4:4	1340-1360	NO	NO	NONE	20	1.1
2	1:4:4	1340-1360	NO	YES	.011-.018	10	.8
3	1:4:4	1380-1400	YES	NO	NONE	10	.8
4	1:4:4	1380-1400	YES	YES	.011-.018	20	1.1
5	1:2:2	1340-1360	YES	NO	.011-.018	20	.8
6	1:2:2	1340-1360	YES	YES	NONE	10	1.1
7	1:2:2	1380-1400	NO	NO	.011-.018	10	1.1
8	1:2:2	1380-1400	NO	YES	NONE	20	.8

Table 2: Levels and settings used for the experiment

Design of experiments results

As the experimental castings were being machined, the scrapped castings were collected. The scrap was sorted in two groups: one group for the oxides (defect 1) and one group for laminated surfaces or metal folding (defect 2).

The group of scrap castings due to oxides showed that the oxide defect was present in only four different specific areas of the castings. Though the origin of such oxides or foreign material was still unknown, there were several opinions and assumptions about the potential source of the defect: crucible furnace wall, molten metal dross, and refractory material from the insulating sleeves.

Close monitoring and evaluation of the machined scrap castings revealed that defect 2 was in reality due to a core breakage problem and not due to laminated surfaces or gas blowholes. It was found that depending on the severity of the core break, the machined casting surface could expose a superficial lamination or an elongated void. Such exposed defects were due to the lack of machining stock (thin wall) that was caused by the core breakage. Therefore, the accurate scrap breakdown after the machining operation is given in Table 3. After all the machining scrap data was collected and sorted, three different approaches were considered to analyze the data via the Taguchi method.

1) Good versus scrap castings

2) Good castings versus broken core scrap castings

3) Good castings versus scrap castings due to oxides

It was recognized that with the approaches taken for the scrap analysis, each of the quality characteristics such as good casting, bad (scrap) casting, broken core, and oxide would have to be treated as an attribute data. Even though, the quality control department proposed an alternative way to convert the qualitative scale to an artificial quantitative scale (e.g., from 1 to 5), it was agreed to keep the attribute analysis since no major measurement difference could be obtained among defects.

Analysis of the results was performed with a commercial computer software package. For each of the three approaches, an analysis of variance (ANOVA) table and a mean analysis response graph were obtained. Even though it was pointed out earlier in the article that the purpose of this paper was not to discuss how to analyze or interpret the ANOVA table, it is probably appropriate to mention that the purpose of the ANOVA table is to list the contributions of each factor to the total experimental data variance, while the mean analysis graph depicts more clearly the most significant factor levels. In addition, it may be also appropriate to define the meaning of the column headers of the ANOVA table.

Source--the process variable assigned to each column.
Pool-----contains pool or unpool factors.
DF-------degrees of freedom.
S---------factor variation.
V---------factor variance.
F---------factor variance ratio.
S'--------factor pure variation.
p---------factor contribution ratio.
e---------experimental errors.

Evaluation based on good versus scrap castings

When the experimental results were evaluated based on how many good and how many scrap castings were obtained, the resulting ANOVA table indicated that factors C and F were insignificant. The results from the ANOVA table are given in Table 4.

EXPERIMENT	GOOD CASTINGS	SCRAP CASTING BY DEFECTS		% OF GOOD CASTINGS
		BROKEN CORE	OXIDES	
1	13	0	2	87
2	14	0	1	93
3	8	4	3	53
4	13	0	2	87
5	14	0	1	93
6	10	0	5	67
7	14	0	1	93
8	2	13	0	13

Table 3: Scrap break down after the machining operation.

The mean analysis indicated that the best levels are A1, B1, D1, E2 and G1 while factors C and F are insignificant.

Evaluation based on good castings versus broken core scrap castings

For this type of evaluation it was considered that the scrapped castings due to oxides were good, since oxides do not have anything to do with broken cores. Therefore, experiment 3 rendered 73% good castings, experiment 8 rendered 13 % good castings while each of the rest of the experiments yielded 100% good castings.

In this situation, the ANOVA table given in table 5 indicated that all factors were important particularly factors B, E, and G. However, the influence of factor E (Sr level) could not be metallurgically or physically explained.

The mean analysis indicated that the best levels are A1, B1, C2, D1, E2, and G1.

Evaluation based on good castings versus scrap castings due to oxides

For this type of evaluation it was considered that the castings scrapped due to broken cores were good castings. Again in this case, a dimensional defect does not have anything to do with an oxide defect. Therefore, experiments 1 and 4 rendered 87% good castings; experiments 2 and 5 rendered 93 % good castings. In the remaining of the experiments, the percentage of good castings was 80%, 67%, 93%, and 100% for experiments 3, 6, 7, and 8 respectively.

In this situation, the ANOVA table given in table 6 indicates that factors C, E, F, and G are important while factors A, B, and D are not significant.

The mean analysis indicated that the best levels are A2, B2, C1, D1, E2, F1 and G1.

Table 7 summarizes the best casting variable levels found for each of the three previous approaches. As this table illustrates, none of the variable levels obtained for any of the three approaches could have eliminated the source of the casting defects. First of all, because the DOE was established to solve a blow or misrun defect and not a defect influenced by a broken core condition. Secondly, because the oxide defect was never properly identified as to what type of oxide it was.

At this point, it was apparent that at least two more independent designs of experiments would have to be run: one DOE to eliminate the core breakage problem and another DOE to eliminate the oxide problem. In both cases, it was obvious that if the proper defect analysis had been made before running the first experiment, results would have been more valuable. Besides, it was also clear that in order to eliminate the "educated" assumptions made on the oxide type and origin, it would be imperative to have more accurate interpretation by stereoscopy and scanning electron microscope analysis.

Even though the experimental results did not turn out to uncover the factors that were expected, the experiment was still considered a partial success: partly because of the major cultural breakthrough for the foundry with regard to proper data collection and teamwork. In addition, senior management recognized that good experimental results could only be obtained by precise statement of the defect to be solved, so that the factors affecting such defect be analyzed and it is imperative to commit technical and well trained manpower and resources to obtain proper data collection and defect analysis before any undertaking be made to diagnose any kind of defect. Finally, it was also clear that the approach of trying to eliminate a defect out of impatience or desperation was usually costly in time, money, and resources.

Microscopic analysis

Stereoscopic binocular microscope analysis and scanning electron microscope analysis (SEM) were conducted on each of the metallurgical defects that resulted from the design of experiment. The scanning electron microscope analysis consisted in obtaining the surface topography and the surface chemical composition via energy dispersive x-ray analysis (EDX).

The dimensional, and the handling damage scrap castings were not considered for the SEM analysis. The scrap castings due to the broken core problem were easily segregated after the machining operation.

In addition, several representative sections of foreign foundry and moulding materials were analyzed under the SEM. The objective of the analysis was to be able to compile photomicrographs illustrating the

Source	Pool	DF	S	V	F	S'	p
A		1	364.5	364.5	6.7	310.0	5.51
B	1		1,104.5	1,104.5	20.3	1,050.0	18.66
C	E	1	24.5	24.5			
D		1	544.5	544.5			
E		1	2,664.5	2,664.5	48.9	2,610.0	46.38
F	E	1	84.5	84.5			
G		1	840.5	840.5	15.4	786.0	13.97
e1		1	544.5	544.5	10.0	490.0	8.71
e2							
(e)		2	109.0	54.5		381.5	6.78
Total		7	5,627.5	803.9			

Table 4. ANOVA table indicating that factors C and F are not significant.

Source	Pool	DF	S	V	F	S'	p
A		1	450.0	450.0			
B		1	1,624.5	1,624.5			
C		1	450.0	450.0			
D		1	450.0	450.0			
E		1	1,624.5	1,624.5			
F		1	450.0	450.0			
G		1	1,624.5	1,624.5			
e1		1	450.0				
e2							
(e)							
Total		7	6,673.5	953.4			

Table 5. ANOVA table indicating that all factors are important.

Source	Pool	DF	S	V	F	S'	p
A	e	14.5	4.5				
B		1	50.0	50.0	11.1	45.5	6.28
C		1	264.5	264.5	58.8	260.0	35.91
D	e	1	4.5	4.5			
E		1	128.0	128.0	28.4	123.5	17.06
F		1	144.5	144.5	32.1	140.0	19.34
G		1	128.0	128.0	28.4	123.5	17.06
e1							
e2							
(e)		2	9.0	4.5		31.5	4.35
Total		7	724.0	103.4			

Table 6. ANOVA table indicating that factors C, E, F, and G are important,while factors A, B, and D are not significant.

GOOD	VARIABLE LEVEL						
VS	A	B	C	D	E	F	G
SCRAP	1	1	⬍	1	2	⬍	1
B. CORE	1	1	2	1	2	2	1
OXIDE	⬍	2	1	⬍	2	1	2

Table 7. Summary of best variable levels found for each of the three approaches. (⬍= No significant level).

characteristic form and morphology of known inclusions. Once the photomicrographs were available, the next step was to compare and to discuss the inclusion topography of such foreign foundry materials against the topography of the defective casting in question. The foundry materials that were analyzed were:

- ❑ Sections of the crucible furnace wall.
- ❑ Skims and dross from the molten metal surface.
- ❑ Pieces of insulating sleeves.
- ❑ Pieces of green sand molds.
- ❑ Pieces of dry sand cores.

Scanning electron microscope analysis

Figure 1 shows the typical shape and microstructure of the surface of the silicon carbide crucible wall. This structure is composed of two phases shown in dark (area 1) and white colours (area 2). EDX spectrum analysis of the dark and white areas revealed the concentration of carbon and silicon elements respectively. Figures 2 and 3 have their respective EDX spectrum embedded into the photograph. Figure 2 shows that the white area is rich in silicon, while figure 3 shows that the dark area is rich in carbon. These types of particles, if present in the casting, would be considered as exogenous inclusions. The individual high concentrations of silicon, and carbon may be attributable to the glazed coated crucible. It is known that such glazed coating often contains metallic silicon and graphite to reduce oxidation and improve non-wetting properties of the crucible.

Figure 4 shows the typical morphology of the dross layer floating on the top surface of the molten metal bath. This condition would represent an improperly skimmed metal. Two different colours: white (area 1) and gray (area 2) represent typical major dross particles. The EDX spectrum of the white area is shown in Figure 5. As it can be seen, the white particles are chlorine, potassium, aluminium and magnesium rich particles resulting from fluxing salts. These particles would be present as non-metallic inclusions in the casting. The EDX spectrum of the gray particle is embedded in Figure 6. Figure 6 shows that the gray area is made mainly out of aluminium with some traces of magnesium and potassium.

The morphology of the refractory material of the insulating sleeve is depicted in Figure 7. This material does not melt down during pouring. If this material would get entrapped into the casting during pouring, the defect in the casting would look like the structure shown in this figure.

Figure 8 depicts the typical green sand grains that are part of the green sand mould. The chemical analysis shows that the sand is mainly silica base sand.

Figure 9 shows the typical grain structure of the dry sand core that is in contact with the casting surface. The chemical analysis shows that the sand is silica sand.

Metallurgical casting defects

Each of the 15 rejected castings, which were visually characterized as oxides, was analyzed under stereoscopic binocular microscope and SEM. Once the defects were properly located, it was found that the defects occurred in one of four different defined areas along external
casting surfaces. As previously mentioned, the casting shape will not be disclosed. Therefore, for presentation purposes, these areas will be identified as A, B, C, and D. An important aspect to consider is that the pictures of the casting defect locations are irrelevant as compared to the microscopical analysis of the defects.

Figure 10 is a representative SEM picture of one of the four "oxide" defects that appeared at location "A" (lower surface of casting in contact with dry sand). As a result of the magnification, a better detail of the casting defect (void) can be observed. The casting surface around the void is very uniform: smooth surfaces without any breaking edge. It can also be noticed that the internal bottom surface of the void looks the same as the outside casting surface: relatively smooth. The similar appearance among surfaces would indicate that the same material that makes the outside surface created the defect (void). To confirm this theory, a surface topography and chemical analysis of both surfaces was conducted.

Figure 11 (for the inside hole) and 12 (for the outside surface) show that both surfaces are the same. By comparing Figure 10 with Figure 9 we can conclude that the dry sand grains caused the defect (void). Based on the analysis we must conclude that stickers in the dry sand core are causing voids in the casting surface. Therefore, the casting defect at location "A" should not be considered as an oxide.

Figure 13 is another SEM picture from a different casting having a similar casting surface defect along location "A". For a more in depth analysis, the defect was sectioned also perpendicular to the outside casting surface. As before, by comparing this surface against the surface shown in Figure 9, it can be concluded that the same material that makes the outside surface caused the defect. Again, we must conclude that stickers in the dry sand core are causing the defect.

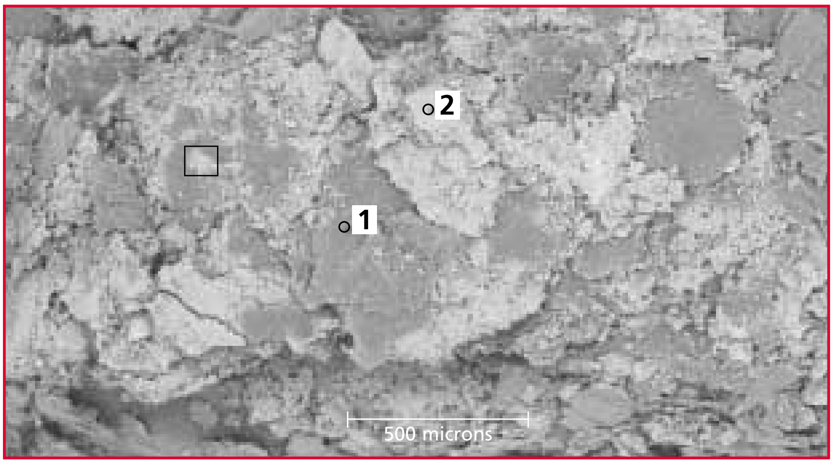

Figure 1: SEM image from a silicon carbide crucible wall section showing two different areas.

Figure 14 is a representative SEM picture of any of the seven "oxide" defects that appeared at locations "B" and "C". These locations are from upper and lower sections of the castings in contact with green sand mould material respectively. This picture clearly shows that the defect is due to green sand particles embedded in the casting. By comparing Figure 14 and Figure 8, it is clear that the defect is due to sand inclusions and not oxides.

Figure 15 is a representative SEM picture of any of the four "oxide" defects that appeared at location "D" (upper surface of the casting in contact with green sand mould material). However, this picture shows that the appearance of the defect is different from the one shown in Figure 14. Figure 15 also shows that the morphology of the defect is quite different as compared to any of the previous morphologies shown in Figures 1, 4, 7, 8 and 9. A close up of Figure 15 is shown in Figure 16. Figure 16 depicts the defect topography as well as the elements present and their relative intensity. Based on these findings, this defect could be associated with molten metal turbulence.

Conclusions

The initial results from the DOE clearly indicated that even before the statistical analysis was performed, the defects had not been accurately identified. However, due to the fact that proper scrap analysis was conducted, it became obvious that, to solve the actual scrap problems, at least two independent designs of experiments would be needed: one to solve the broken core problem and one to solve the oxides or inclusion defects. In summary:

- ❑ The use of design of experiments is a team effort.
- ❑ Every team member recognized the importance to properly diagnose a defect before any corrective action takes place.
- ❑ Even educated assumptions are not as good as actual microscopic evaluation.
- ❑ Metallurgical defects in location "A" were due to dry sand core stickers.
- ❑ Metallurgical defects in locations "B" and "C" were due to green sand inclusions.
- ❑ Metallurgical defects in location "D" were due to metal turbulence.

Finally, it is important to mention that, based on these findings, corrective actions were implemented, and new designs of experiments were conducted according to new selected factors.

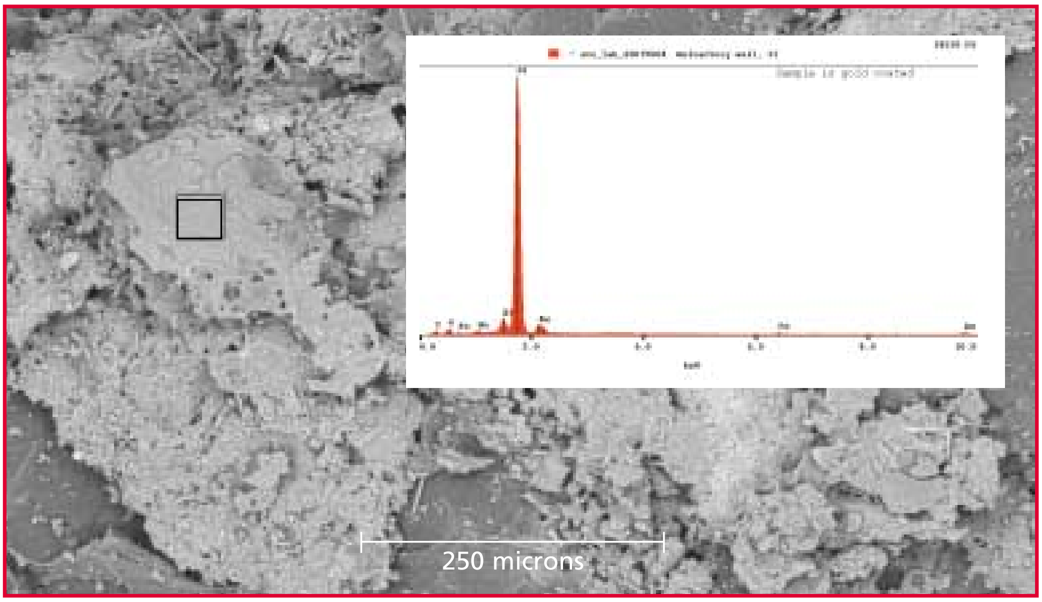

Figure 2: SEM image, and EDX spectrum of area 2 (white area from figure 1) showing high concentration of silicon.

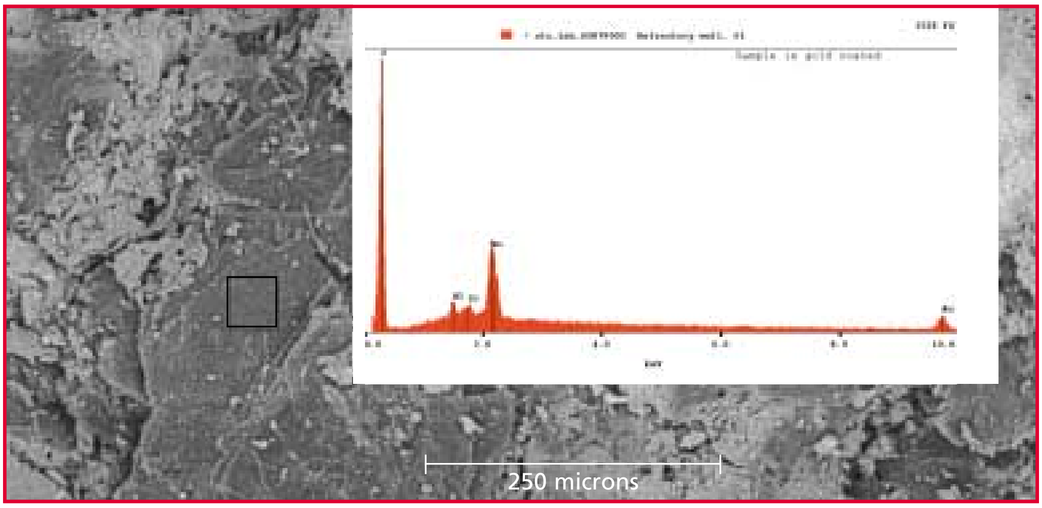

Figure 3: SEM image, and EDX spectrum of area 1 (dark area from figure 1) showing high concentration of carbon.

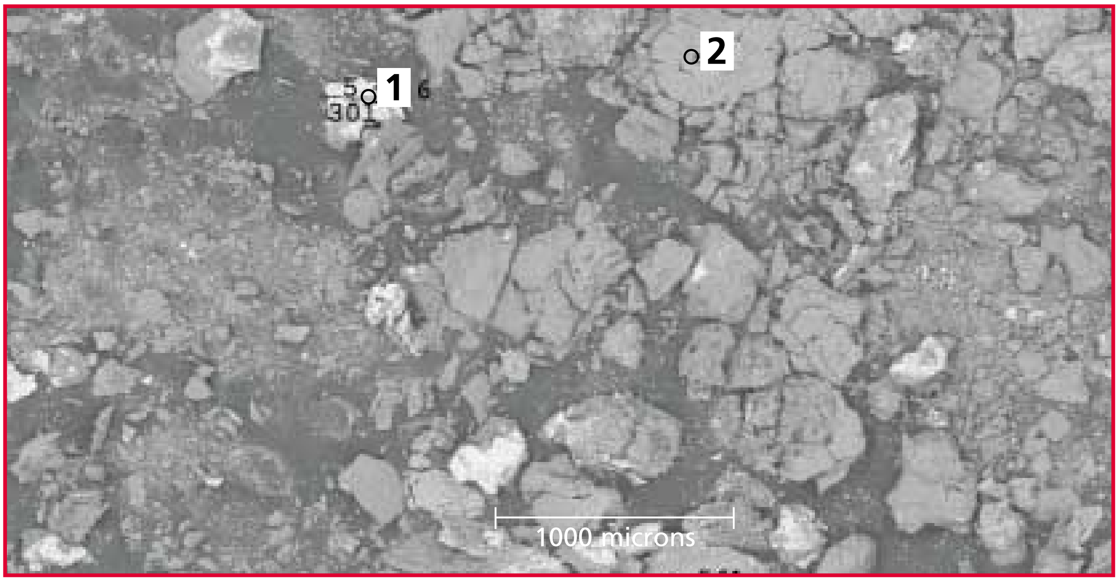

Figure 4: SEM image from dross layer floating on top of the surface of the molten metal inside the crucible furnace.

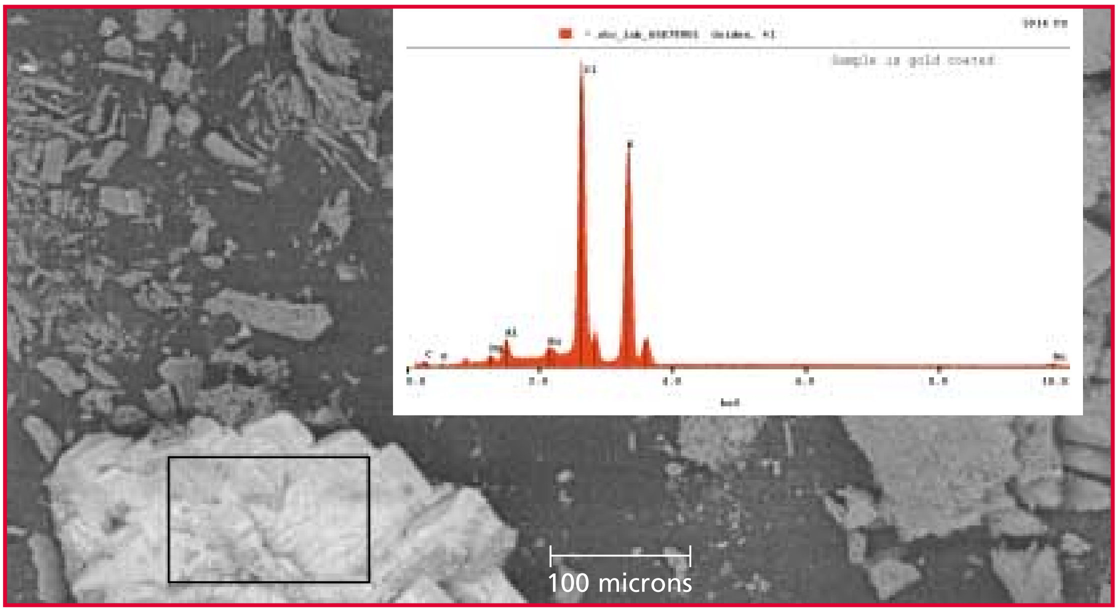

Figure 5: SEM image, and EDX spectrum of area 1 (white area from figure 4) showing chlorine, potassium, aluminium and magnesium rich particles.

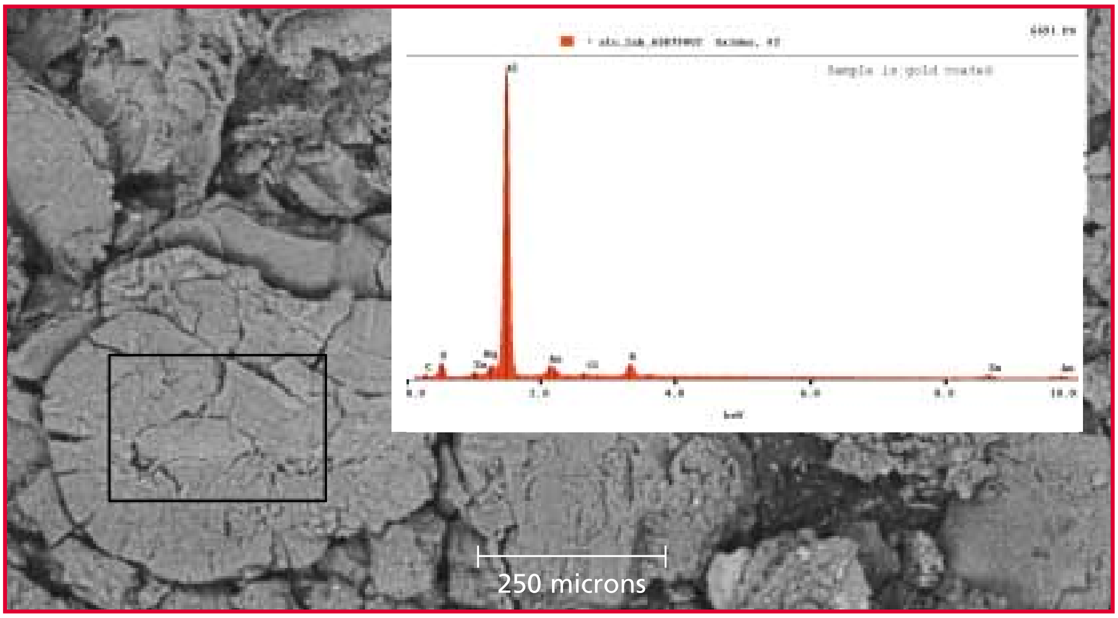

Figure 6: SEM image, and EDX spectrum of area 2 (dark area from figure 4) showing aluminium and traces of magnesium, and potassium particles.

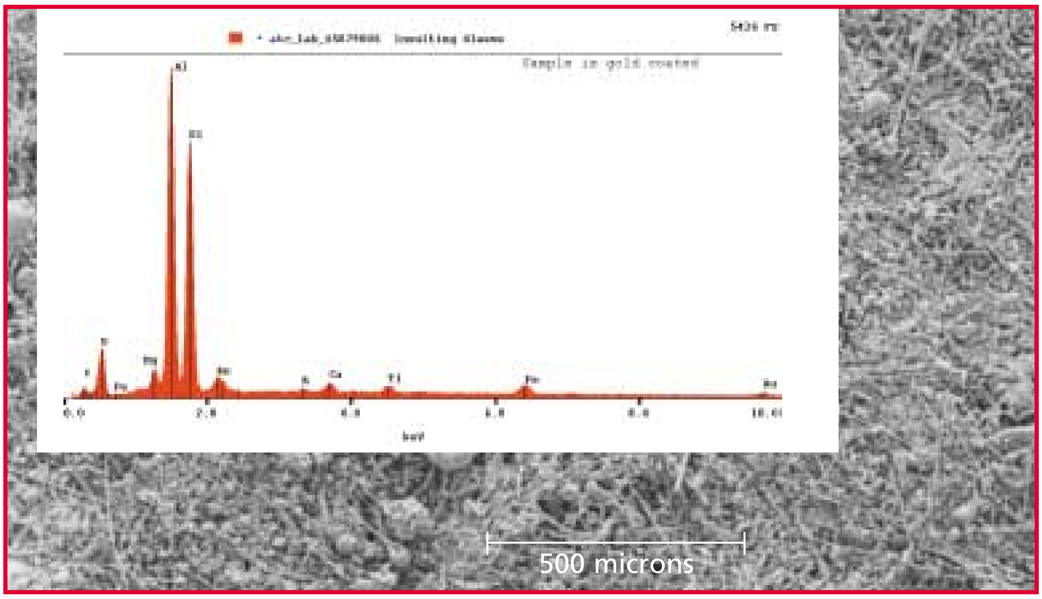

Figure 7: SEM image, and EDX spectrum of the insulating sleeve structure.

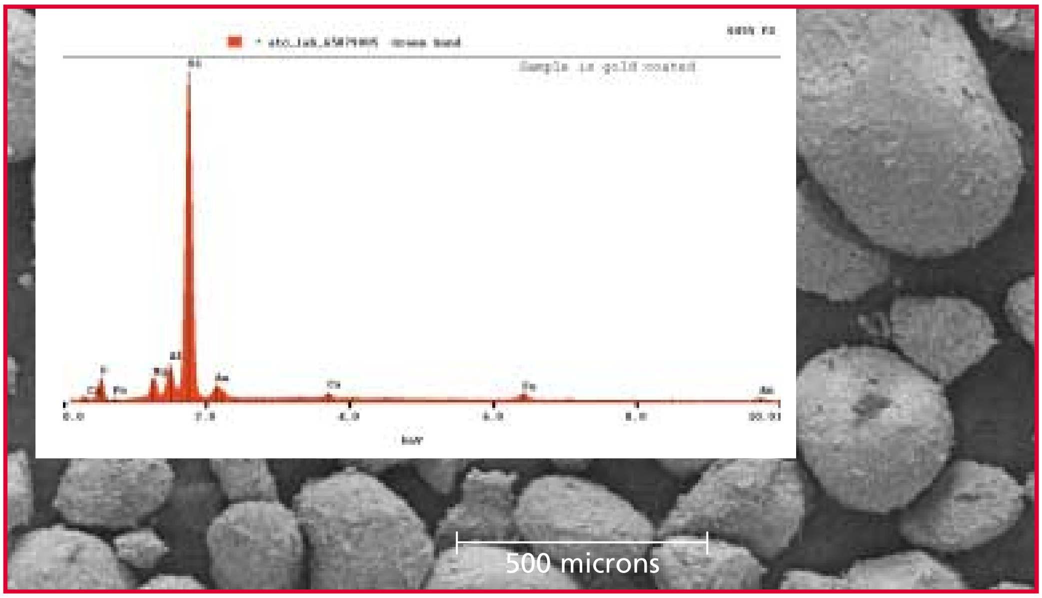

Figure 8: SEM image, and EDX spectrum of green sand grains coming from the faces of the cope and drag moulds.

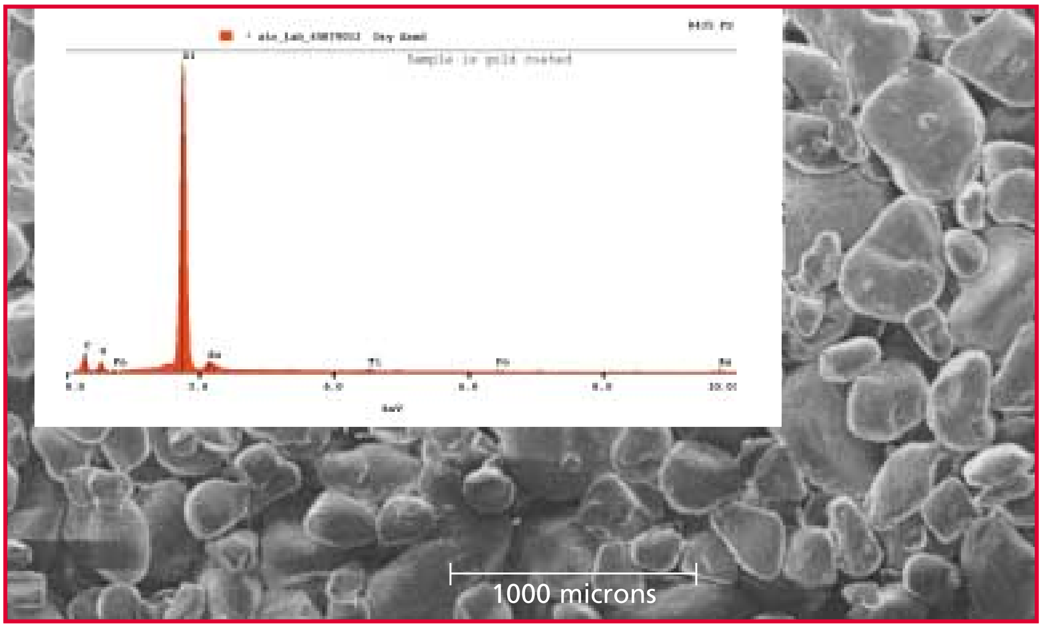

Figure 9: SEM image, and EDX spectrum of dry sand grains coming from the external surfaceof the dry sand core.

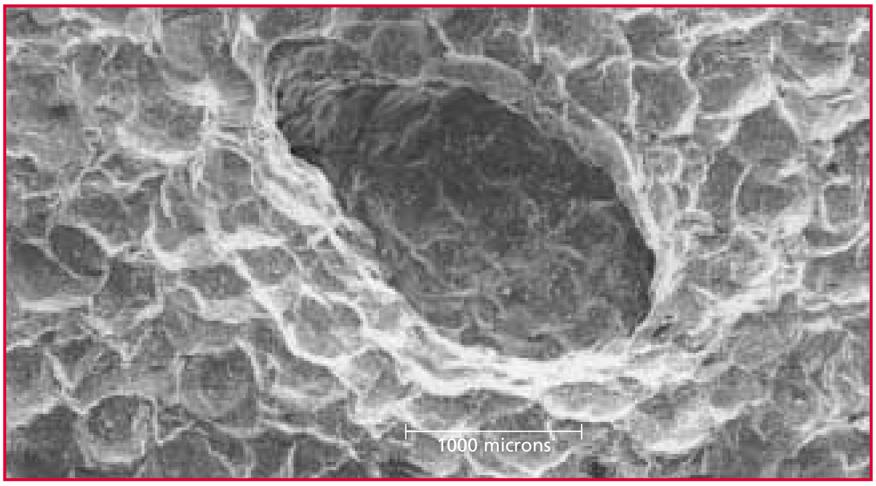

Figure 10: SEM image of the typical defect (void) and surrounding areas. This defect (hole) is a typical representation of similar defects in other castings. Photo is from a section of the casting in contact with dry sand core.

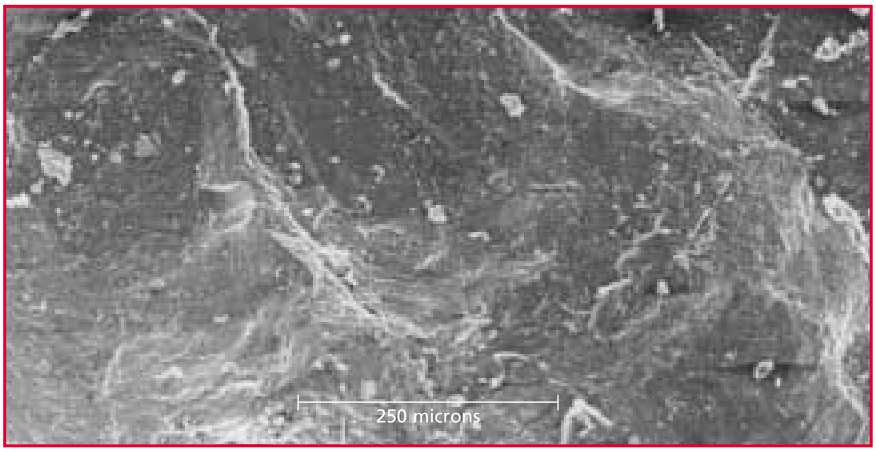

Figure 11: SEM image of the inside area of the defect (void) depicted in figure 10.

Figure 12: SEM image of the outside area of the defect (void) depicted in figure 10. This image is a typical representation of the surrounding areas.

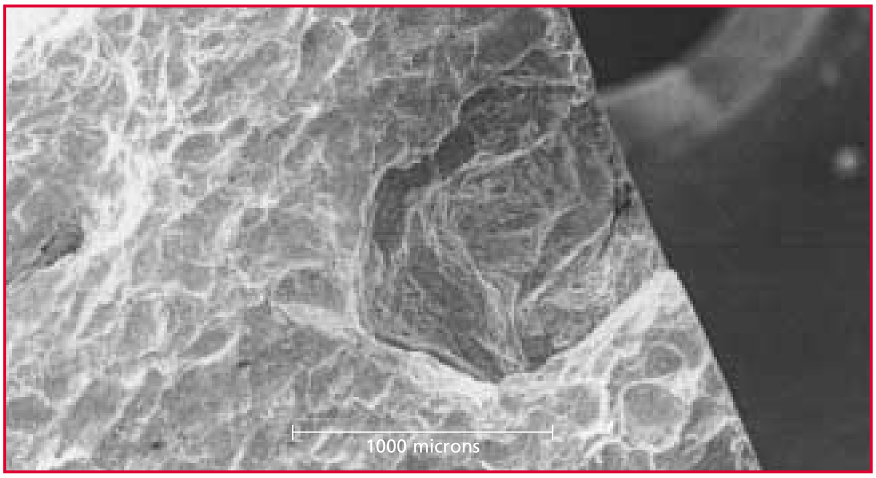

Figure 13: SEM image of a similar defect (void), as the one shown in figure 10, but in a different casting.

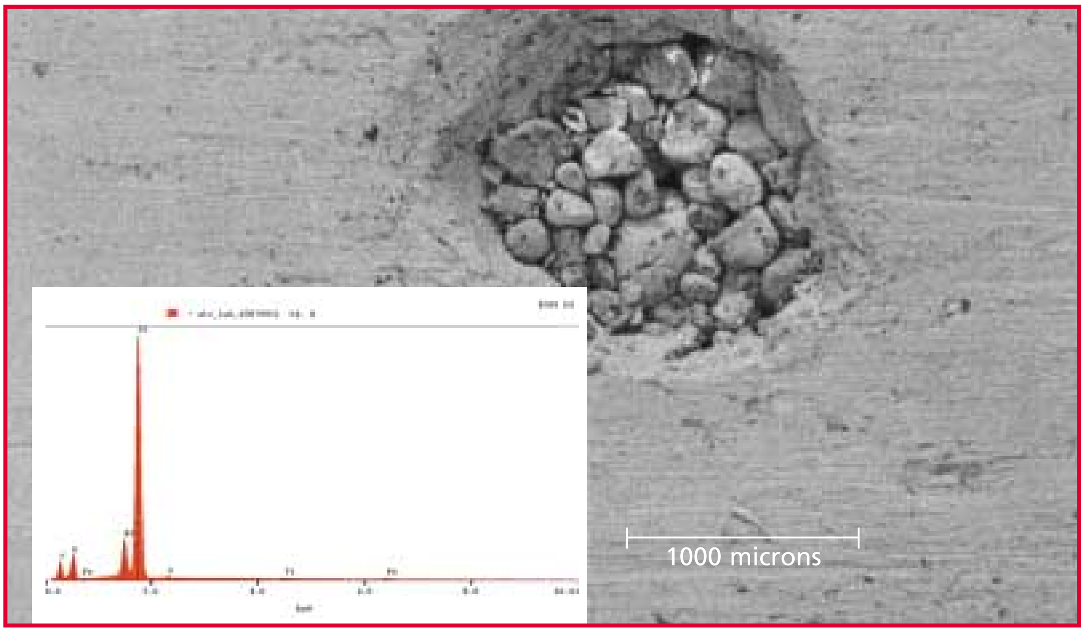

Figure 14: SEM image, and EDX spectrum of the castings being scrapped for"oxides".Photo is from a section of the casting in contact with green sand mould material.As it can be seen the actual defect is green sand inclusions.

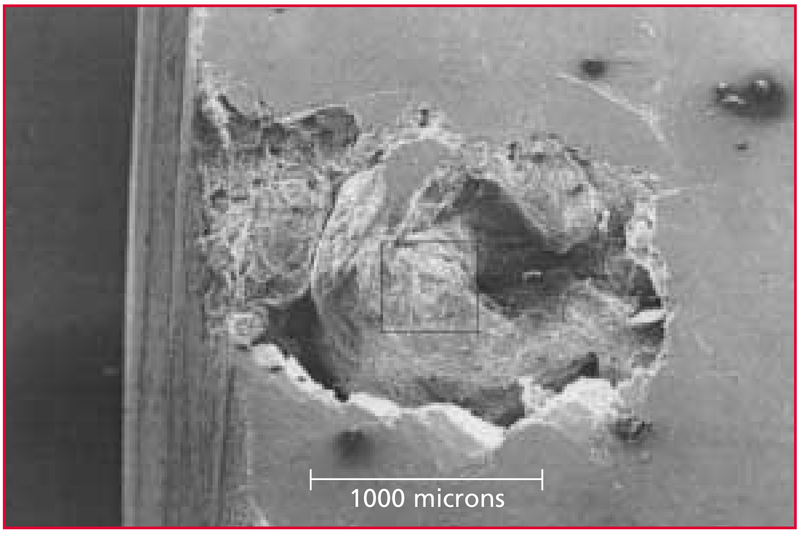

Figure 15: SEM image of an open cavity (defect) normally being identified as oxide.

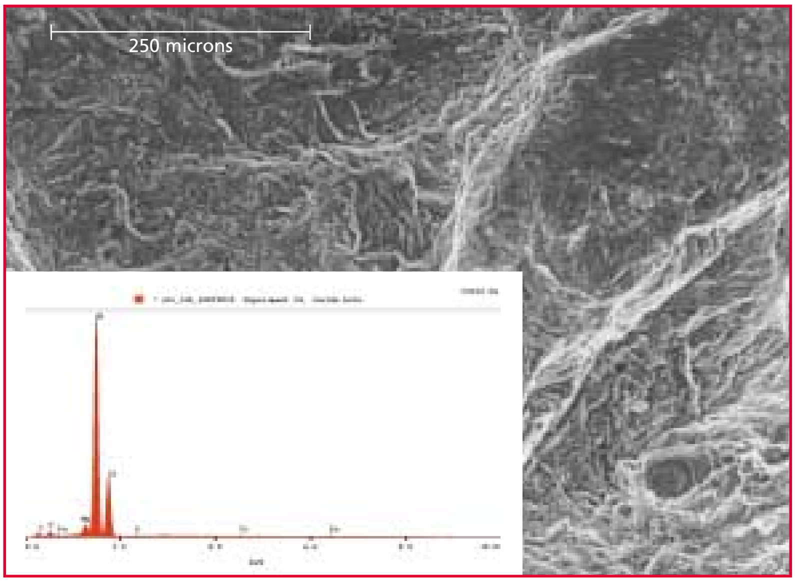

Figure 16: SEM image, and EDX spectrum of the defect shown in Figure 15, Indicating an oxide film.

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