

Optical Emission Spectrometry

Thermo Scientific ARL iSpark Plus OES Metal Analyzer: Inclusion analysis in iron and steel with Spark-DAT

Standard inclusion analysis

Introduction

OES (Optical Emission Spectrometry) is a common technique for elemental analysis of solid steel samples. It is used in most steel plants and by companies that need to control the composition of steel products. The Thermo Scientific™ ARL iSpark™ Plus OES Metal Analyzer is an advanced optical emission spectrometer built on trusted technologies that measures every element necessary to steel production with high precision and accuracy regardless of the elements' concentration levels. The Spark-DAT* (Spark Data Analysis and Treatment) inclusion analysis adds an important dimension to the ARL iSpark Plus, allowing ultra-fast evaluation of non-metallic micro-inclusions.

The Standard Inclusion Analysis option allows close to real-time monitoring of inclusions in steel manufacturing. This analysis could help, for example, a steel plant that wants to control and minimize the occurrence of inclusion problems that might affect the quality of the steel or upset the smooth running of the manufacturing process.

Significantly faster than other inclusion analysis methods such as SEM/EDX, Spark-DAT inclusion analysis was introduced in 1995 on ARL spectrometers. Continuously improved since then, it has become a reference for ultra-fast inclusion analysis and is utilized by many steel companies who use our optical emission spectrometers.

Benefits of the Standard Inclusion Analysis

- Provides inclusion data and elemental concentrations simultaneously, for the duration of a normal OES analysis
- Suitable to check inclusions during steel manufacturing, in up to several hundred samples per day
- Normal operation and maintenance of the ARL iSpark Plus
- Normal OES sample preparation
- Low investment cost
- Perfectly adapted for automation with ARL SMS systems



Figure 1:
Thermo Scientific
ARL iSpark Plus.

*Also referred to as OES/PDA (Pulse Discrimination Analysis) in the literature.

Inclusions

Inclusions are small particles that are always present in steel. Their composition, size and number largely depend on the steel grade and manufacturing process. Inclusions disrupt the metallic matrix and strongly influence steel properties. Though some of them are needed, as they confer desired properties (e.g., fatigue resistance, hardness, and machinability) to the steel, they frequently have detrimental effects: They can be responsible for steel properties not complying with requirements, for steel defects that appear in the rolling mill, for failures of products made of steel, or for process issues like nozzle clogging.

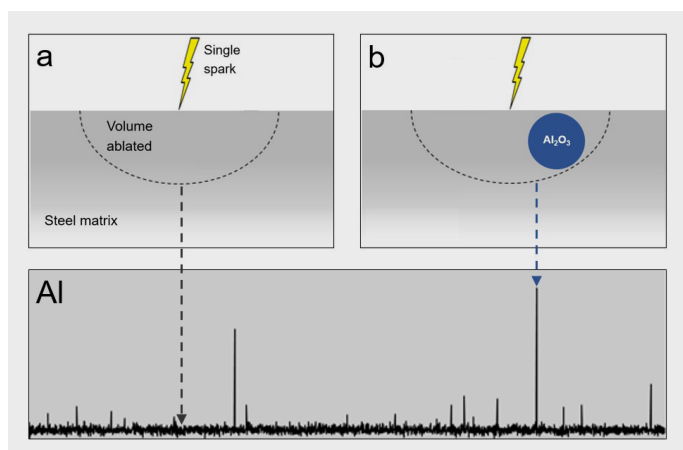
To a steel plant, quality and production costs caused by inclusions can easily amount to several hundred thousand dollars per year. Rapidly assessing inclusions' composition, size and number during steelmaking is therefore necessary when producing quality steels, and Spark-DAT inclusion analysis offers unique opportunity to do this.

Principles of Spark-DAT inclusion analysis

Single Spark Acquisition (SSA) and single spark signals

SSA is the acquisition mode of the ARL iSpark Plus. Its name refers to the very short spark, which is repeated thousands of times within seconds in the different phases (i.e., in pre-burn and integration phases) of the OES analysis sequence. The principle of SSA is the following: Each single spark ablates a small volume of sample material, breaks that small bit down into atoms, and excites electrons to higher energy levels. The electrons rapidly return to stable equilibrium state, causing an emission of light whose wavelength components depend on the elemental composition of the small volume of material analyzed. The light emitted at every single spark by each element present in the sample is converted by the photodetectors into electrical signals, which are acquired individually.

To understand the principles of the Spark-DAT inclusion analysis, let us consider the run chart of the single spark signals collected on the Al photodetector when sparking a low alloy steel sample containing aluminum oxide inclusions (Figure 2).



The intensity of the Al signal depends on the number of Al atoms present in the small volume ablated by the single spark. When no Al-bearing inclusion is present (Figure 2a), the signal is proportional to the number of Al atoms present in the metallic form (also known as soluble form). When an Al-bearing inclusion is present, such as aluminum oxide (Figure 2b), a signal proportional to the number of Al atoms in the inclusion adds to the background signal from the Al atoms in the metallic form. As the concentration of Al is much higher in the inclusion (about 53% in Al_2O_3) relative to the surrounding steel sample, this gives rise to an identifiable peak on the run chart of the Al single spark signals. The net intensity of the peak is proportional to the number of atoms present in the inclusion—in other words, to the volume of the inclusion.

Signal processing

For elemental analysis the single spark signals are averaged and converted into concentrations through calibration curves. For inclusion analysis the single spark signals are stored individually and processed based on statistical principles using OXSAS, the analytical software of the ARL iSpark Plus. Figure 3 shows a diagram of this process. The key components of signal processing in inclusion analysis are the Spark-DAT algorithms, which allow fast computation of the inclusion data.

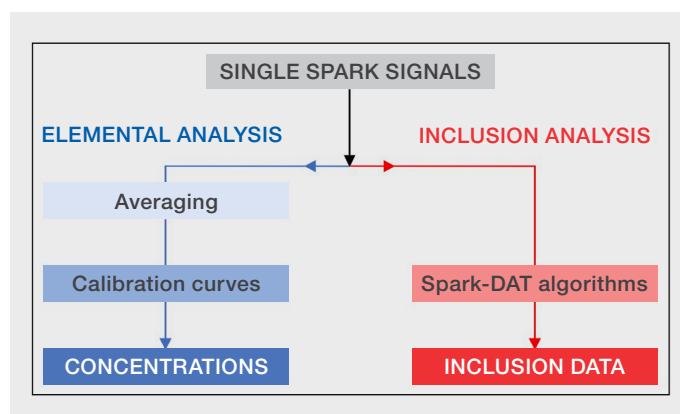


Figure 3: Signal processing in elemental and in inclusion analyses.

Inclusion data available with the Standard Inclusion Analysis option

The Standard Inclusion Analysis method produces the so-called standard inclusion data, which allow for the characterization of inclusions in terms of composition and number and, to some extent, size. The two primary types of standard inclusion data are peak counts and peak coincidence counts. A secondary type of standard data is SML counts, which allow to evaluate the number of small (S), medium (M) and large (L) inclusions.

◀ Figure 2: Example of run chart of Al single spark signals in a low alloy steel sample illustrating the cases where no inclusion (a) and an Al_2O_3 inclusion (b) is present in the volume ablated by the single spark.

The different types are explained and exemplified hereafter. The samples used for illustration are three samples from the company voestalpine Stahl in Linz (Austria):

- VRM 22, a sample from a steel treated with CaC_2 and alloyed in Cr and Ni
- VRM 27, a sample from a low alloy steel treated with CaSi
- VRM 28, a sample from a low alloy steel obtained without Ca treatment

Some information about their inclusion content can be found in the final report* of a project of the European Research Fund for Coal and Steel.

Peak counts (pc)

The parameters of the Spark-DAT method are optimized so that it can be expected that “one peak corresponds to one inclusion and one inclusion gives rise to one peak.” Counting the peaks of an element is then assumed to be equivalent to counting all the inclusions that contain that element (for example, Al_2O_3 , $\text{Al}_2\text{O}_3\text{--CaO}$ and $\text{Al}_2\text{O}_3\text{--MgO}$ in the case of aluminum peaks).

From a statistical point of view, a peak is an outlier; in other words, it is a signal whose intensity does not follow the normal signal distribution, or a signal with an abnormally high intensity compared to the background signal from the element in the metallic form. Counting inclusions generally consists of counting the signals whose intensity exceeds a threshold placed at 3σ above the average value of the signal of the metallic form of the element, where σ is the standard deviation of this background signal (see Figure 4).

The counts are given in number of inclusions per mm^3 . This makes them independent of the number of single spark signals used for processing, and also, to a certain extent, of the instrument and analytical conditions used.

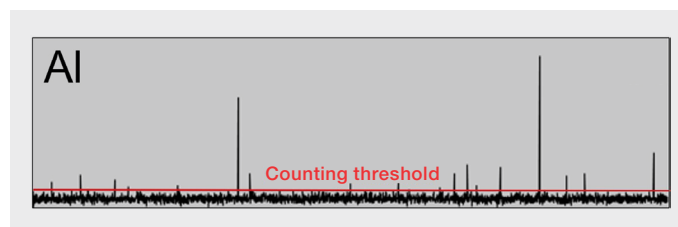


Figure 4: Run chart of Al single spark signals in a low alloy steel sample. The signals with an intensity higher than the threshold are peaks and they are therefore counted as inclusions.

The single spark diagrams obtained for Al, Ca, Mg and S (four elements of major interest in many steel grades) in the three VRM samples are presented in Figure 5. They clearly show that the three samples have different inclusion contents, in terms of the elements that make up the inclusions as well as in the number of inclusions.

Visual inspection of the run charts allows one to draw the following conclusions:

- Even if (given the relatively high concentration of Al in metallic form; see section “limiting parameters”) it is not possible to affirm that all small inclusions present are observable, the three samples have apparently similar amounts of Al-bearing inclusions.
- VRM 22 and VRM 27, the two samples of steel that have undergone calcium treatment, contain a very large number of Ca-bearing inclusions. Numerous coincidences of Ca peaks with peaks of the other elements indicate that a large proportion of the Ca-bearing inclusions also include the elements Al, Mg and S. As O is also present in the samples, there is a high probability that the inclusions consist of a mix of oxides and sulfides of Al, Ca and Mg.
- In VRM 28, the non-calcium-treated steel sample, the inclusions contain almost no Ca and only a small amount of Mg. Given the high S content and the certain presence of O, it is very likely that most of the inclusions consist of a mixture of Al oxides and sulfides, with some also containing Mg in small proportions.

Peak counts displayed in Table 1 confirm the observations.

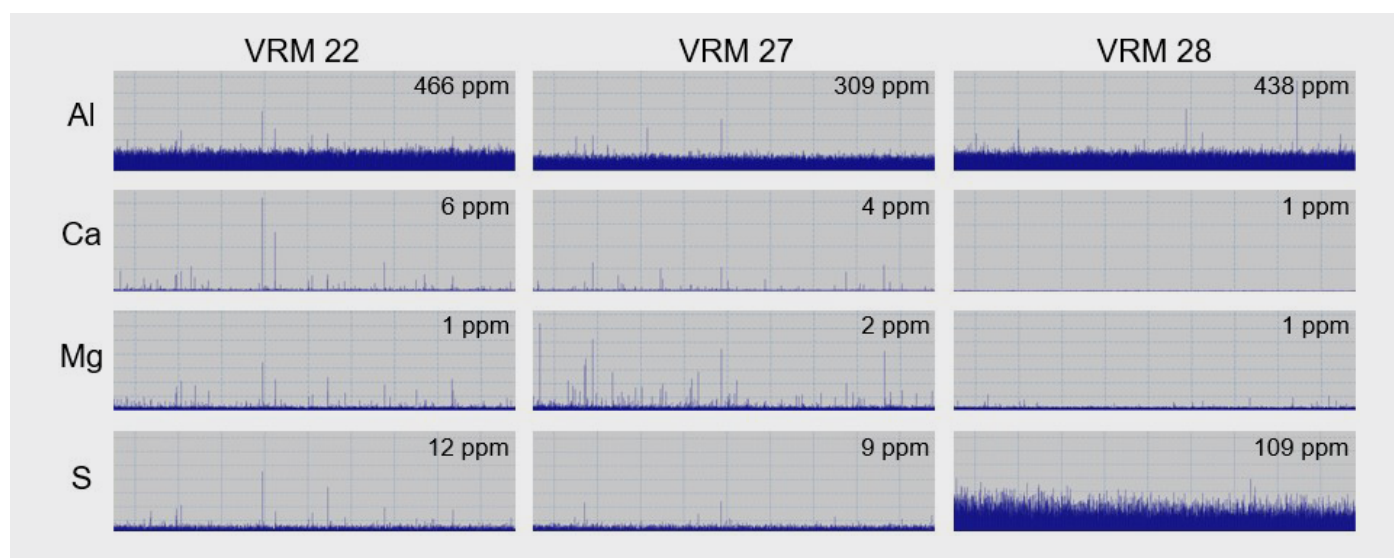


Figure 5: Single spark signal run charts of Al, Ca, Mg and S in run #1 of the analyses of samples VRM 22, VRM 27 and VRM 28. 2'360 single spark signals collected in 5.9s, but only the last 1'860 displayed, corresponding to the signals used for processing. The same vertical scale is used in the three run charts of each element. The concentrations in ppm are the bulk concentrations of the elements.

* EUR 25153 – “Process-based steel cleanliness investigations and rapid metallurgical screening of inclusions by modern PDA techniques (Ramsci)”, A. Bengtson, M. Sedlakova, H.-U. Schmitz, A. Pissenberger, M. Schuller, R. Didriksson, G. Runnsjö, T. Engkvist, A. Tremea, S. Fera, F. Ferro, M. Pérez-Alonso, R. Pizarro, J. Albarran, P. Jönsson, O. Ericsson, R. Wester, R. Noll, V. Sturm, V. Colla, G. Nastasi, Publications Office of the European Union, Luxembourg, 2012.

Parameter	Inclusion type	Inclusions / mm ³		
		VRM 22	VRM 27	VRM 28
Al pc	Al inclusions	539	745	838
Ca pc	Ca Inclusions	6123	3891	262
Mg pc	Mg inclusions	2651	3834	773
S pc	S inclusions	1112	838	3267

Table 1: Peak counts of Al, Ca, Mg and S (reported in number of inclusions per mm³) in samples VRM 22, VRM 27 and VRM 28. Average of 6 measurement runs acquired under conditions described in Figure 5 and counting threshold at 3 σ above the background.

Peak coincidence counts (pcc)

With peak counts, all inclusions of the types where the element is present are counted. For example, with Al pc all the Al family inclusions are counted. This includes inclusions like aluminum oxides Al₂O₃, calcium aluminates Al₂O₃-CaO, and spinels Al₂O₃-MgO.

Contrary to peak counts, peak coincidence counts are inclusion type specific. The specificity is obtained by checking the presence or the absence of multiple elements in the inclusions—in other words, checking the coincidences and non-coincidences of peaks of multiple elements. The principle is illustrated with calcium aluminate and aluminum oxide inclusions (Figure 6). When a calcium aluminate inclusion is ablated by a single spark, a coincidence of Al and Ca peaks is observed, which confirms the presence of the two elements in the inclusion. When an aluminum oxide inclusion is ablated, we observe a non-coincidence, i.e., an Al peak but no coincidence with a Ca peak. This confirms the presence of Al and the absence of Ca in the inclusion. The following principle can therefore be applied to distinguish the two types of inclusions:

- **Aluminum oxides:** count the Al peaks that have no coincidence with a Ca peak
- **Calcium aluminates:** count the Al peaks that do have a coincidence with a Ca peak

The number of elements that can be checked simultaneously is not limited by the Spark-DAT algorithm. This means that the presence or the absence of any potential other inclusion element can be checked, allowing very high specificity on the type of the inclusions.

Parameter	Checked elements		Unchecked common inclusion elements	Possible inclusion types	Inclusions / mm³		
	Coincidences with Al peaks	Non-coincid. with Al peaks			VRM 22	VRM 27	VRM 28
Al_CaMgS pcc	–	Ca, Mg, S	O, Mn, Si, Ti	Al oxides	82	189	441
AlCa_MgS pcc	Ca	Mg, S		Ca aluminates	48	20	12
AlCaMg_S pcc	Ca, Mg	S		Al-Ca-Mg-O	108	157	8
AlCaMgS pcc	Ca, Mg, S	–		Al-Ca-Mg-S(-O)	281	258	32
AlMg_CaS pcc	Mg	Ca, S		Spinels	16	121	153
AlS_CaMg pcc	S	Ca, Mg		Al-S(-O)	4	0	72
AlCas_Mg pcc	Ca, S	Mg		Al-Ca-S(-O)	0	0	20
AlMgS_Ca pcc	Mg, S	Ca		Al-Mg-S(-O)	0	0	100
				Al inclusions (sum)	539	745	838

Table 2: Peak coincidence counts (pcc) in number of inclusions per mm³ in samples VRM 22, VRM 27 and VRM 28 (same conditions as Table 1). In the name of the parameter, the element before the “_” sign are the elements whose presence is checked, while the elements after the “_” sign are the elements whose absence is checked. Regarding possible inclusion types, “-O” means that it is very likely that the inclusion is an oxide, while “(-O)” means that oxygen may also be present in the inclusion. As all possible combinations of Al with Ca, Mg and S are evaluated, the sum of the different types of inclusions is equal to the number of Al inclusions in Table 1.

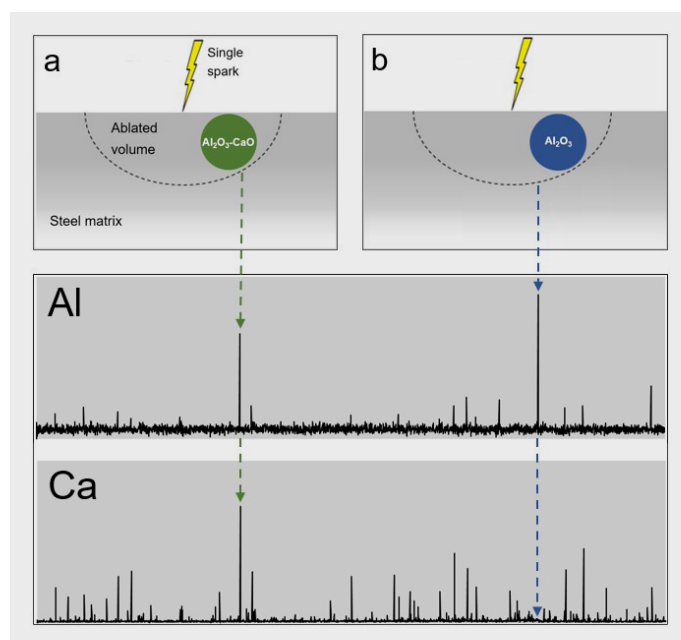


Figure 6. Single spark signal run charts of Al and Ca in a low alloy steel sample. Al peak with coincidence of Ca peak for an Al₂O₃-CaO inclusion (a) and without coincidence for an Al₂O₃ inclusion (b).

The number of different types of Al inclusions, containing or not the elements Ca, Mg and S, measured in samples VRM 22, VRM 27 and VRM 28 are shown in Table 2. The elements whose presence or absence in the inclusion were checked are listed. The elements whose presence or absence were unchecked can of course be present or absent in the inclusion. This is the case in particular for Mn, S, Si, Ti and especially O, which is always present in steel in the form of inclusions.

The results of Table 2 confirm the conclusions drawn after observation of the run charts:

- The inclusions in VRM 22 and VRM 27 are mostly oxides and mixes of oxides and sulfides of Al, Ca and Mg. Al oxides, spinels and Ca aluminates are also present in different quantities.
- The inclusions in VRM 28 are mainly Al oxides, spinels, sulfides of Al and Mg, and mixes of oxides and sulfides of Al and Mg.

The results are also coherent with the results published in the report of the European Research Fund for Coal and Steel mentioned above.

SML counts

The effect of inclusions on steel properties depends not only on their number, but also on their size. Generally speaking, the larger the inclusion, the greater its effect; in other words, larger inclusions are more critical. It is therefore sometimes necessary to assess the number of large inclusions in addition to or instead of the total number of inclusions. This is possible with SML counts.

SML counts allow counting peaks and peak coincidences that belong to different intensity classes, which, because the signal intensity is proportional to the volume of the inclusion, is equivalent to counting inclusions that belong to different size classes.

The name of the method comes from the fact that three classes are normally considered: S for small inclusions, M for medium size inclusions, and L for large inclusions. The SML classes are defined with three peak count thresholds, for example, at 3σ , 10σ and 30σ above the background signal (Figure 7):

- S class → small inclusions: peak intensity between 3σ and 10σ
- M class → medium-size inclusions: peak intensity between 10σ and 30σ
- L class → large inclusions: peak intensity above 30σ

At low concentration of the metallic form, if we consider that the inclusions are spherical, at 10σ and 30σ they are respectively about 1.5 and 2.2 times larger than at 3σ .

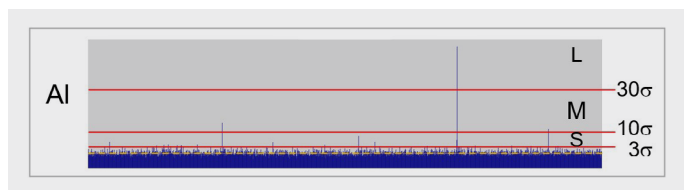


Figure 7: Single spark signal run charts of Al in run #6 of the analysis of sample VRM 22 with detection thresholds at 3, 10 and 30σ for SML classification. The dashed orange line is the average intensity value of the background signal.

Parameter	Size	Inclusions / mm ³		
		VRM 22	VRM 27	VRM 28
Al_CaMgS pcc	S	82	177	392
	M	0	12	45
	L	0	0	4
	Total	82	189	441
AlCa_MgS pcc	S	48	20	12
	M	0	0	0
	L	0	0	0
	Total	48	20	12
AlMg_CaS pcc	S	16	121	145
	M	0	0	8
	L	0	0	0
	Total	16	121	153
AlS_CaMg pcc	S	4	0	52
	M	0	0	12
	L	0	0	8
	Total	4	0	72

Table 4: SML peak coincidence counts in samples VRM 22, VRM 27 and VRM28 corresponding to peak coincidence counts of Table 2, obtained with thresholds for Al at 3, 10 and 30σ .

In practice, it is possible to adapt the SML classes according to the requirements on the final product. For example, all the inclusions (i.e., S, M and L inclusions) can be considered for steel grades or products made of steel with the most demanding specifications, while only the largest inclusions (i.e., L inclusions) can be considered for those with the least demanding specifications. In order to best meet the control requirements in different steel grades or products made of steel, the peak detection threshold values can be adjusted using samples classified as good and bad according to the usual control methods and criteria.

Tables 3 and 4 show the SML counts corresponding to the peak counts and peak coincidence counts given in Tables 1 and 2.

Parameter	Size	Inclusions / mm ³		
		VRM 22	VRM 27	VRM 28
Al pc	S	487	673	729
	M	44	64	89
	L	8	8	20
	Total	539	745	838
Ca pc	S	4185	2791	234
	M	1257	733	28
	L	681	367	0
	Total	6123	3891	262
Mg pc	S	2026	2634	6628
	M	524	902	133
	L	101	298	12
	Total	2651	3834	737
S pc	S	951	741	3267
	M	133	80	0
	L	28	16	0
	Total	1112	837	3267

Table 3: SML peak counts of Al, Ca, Mg and S in samples VRM 22, VRM 27 and VRM28 corresponding to peak counts of Table 1, obtained with thresholds at 3, 10 and 30σ .

Parameter	Size	Inclusions / mm ³		
		VRM 22	VRM 27	VRM 28
AlCaMg_S pcc	S	108	149	8
	M	0	8	0
	L	0	0	0
	Total	108	157	8
AlCaS_Mg pcc	S	0	0	20
	M	0	0	0
	L	0	0	0
	Total	0	0	20
AlMgS_Ca pcc	S	0	0	76
	M	0	0	24
	L	0	0	0
	Total	0	0	100
AlCaMGS pcc	S	229	206	24
	M	44	44	0
	L	8	8	8
	Total	281	258	32

Software aspects

Analytical software

All the features and algorithms necessary for the Spark-DAT inclusion analysis are fully integrated in OXSAS, the analytical software of the ARL iSpark Plus. OXSAS manages most aspects of the inclusion analysis: it allows users to set up the method and the parameters for the inclusion analysis; run the analysis; process the single spark signals; and as for concentrations, display, print, store and transmit the results of the inclusion analysis.

Handling of the inclusion data

The inclusion data can be handled exactly like elemental concentrations. This means that the following operations can be performed with them in OXSAS analytical software:

- Pseudo-element calculations. i.e., mathematical formulas, can be applied to results to evaluate additional inclusion data. For example, the total number of oxides can be calculated by summing the counts of the different types of oxides
- Inclusion data can be compared to specification limits introduced by the user in OXSAS grade limits table
- Transmission to a statistical process control software (see SPC hereafter), a LIMS or a remote computer
- Recalculation of the results. Inclusion data can be reprocessed after adding algorithms or modifying their parameters (e.g., the peak counting threshold)
- Storage and printing of the results.

Furthermore, the single spark signals data can be stored in .txt or .csv files. These files can be visualized with the Spark Viewer included in OXSAS, a simple tool that displays sparks run charts, distributions of intensities and signal statistics, and with the more advanced Spark Explorer optional software module (see software options hereafter). The .txt or .csv files can also be imported in common commercial software programs like Excel.

Practical aspects

Analysis method

The Standard Inclusion Analysis option includes an analytical method that combines inclusion analysis and standard elemental analysis, and a method that performs inclusion analysis only.

Analysis time

In combined analysis, signal acquisition and processing for inclusion analysis take just a fraction of a second. The analysis time is therefore very close to that of elemental analysis alone.

Surface preparation of the sample

Normal OES sample preparation by milling or grinding can be used for Standard Inclusion Analysis. However, grinding should be used with care, as contamination of the sample by the grinding material can affect the inclusion counts. In particular, it is recommended to use an Al_2O_3 -free grinding paper such as SiC paper for a reliable evaluation of the aluminum oxides. Milling, which is used nowadays in many steel plants, guarantees a contamination-free analysis surface.

Customization of the method

The inclusion analysis method can be customized to your needs by our experts before your ARL iSpark Plus is delivered. The customization is ideally performed with a set of samples containing the inclusions of concern for your company. Otherwise, a comprehensive method that includes peak counts and peak coincidence counts (some of them with SML classification) for different types of inclusions is delivered with the instrument.

Upgrades

The Standard Inclusion Analysis method is also provided as upgrade for existing ARL iSpark or ARL iSpark Plus instruments.

Element	Units	AVG	SD	SD%	6	5	4	3	2	1
Al	%	0.02979	0.000385	1.29	0.02948	0.02937	0.03027	0.03013	0.02951	0.03000
Al pc S	n/mm ²	673	237	35.30	846	435	435	604	677	1039
Al pc M	n/mm ²	64	40	61.62	72	121	24	24	48	97
Al pc L	n/mm ²	8	20	244.95	0	48	0	0	0	0
Al pc	n/mm ²	745	244	32.80	918	604	459	628	725	1136
Ca	%	0.00063	0.000110	17.60	0.00055	0.00054	0.00083	0.00057	0.00061	0.00066
Ca pc	n/mm ²	3891	2249	57.80	3166	3407	3335	2441	8409	2586
Mg	%	0.00028	0.000043	15.59	0.00028	0.00023	0.00027	0.00026	0.00025	0.00036
Mg pc	n/mm ²	3834	728	18.98	4712	4736	3311	2996	3649	3601
S	%	0.00066	0.000037	5.61	0.00068	0.00068	0.00061	0.00068	0.00063	0.00070
S pc	n/mm ²	838	173	20.67	1039	894	532	797	942	822
Al CaMgS pcc S	n/mm ²	177	146	82.56	193	97	48	121	145	459
Al CaMgS pcc M	n/mm ²	12	20	167.33	24	0	0	0	0	48
Al CaMgS pcc L	n/mm ²	0	---	---	0	0	0	0	0	0
Al CaMgS pcc	n/mm ²	189	165	87.44	217	97	48	121	145	507
AlCa MgS pcc	n/mm ²	20	18	90.33	24	0	24	0	48	24
AlCaMg S pcc	n/mm ²	157	66	42.24	266	121	145	72	145	193
AlMg CaS pcc	n/mm ²	121	79	65.67	97	24	97	217	72	217
C	%	0.06760	0.000932	1.38	0.06715	0.06863	0.06609	0.06781	0.06846	0.06745
Si	%	0.31615	0.002873	0.91	0.31643	0.32085	0.31181	0.31602	0.31614	0.31563
Mn	%	1.58767	0.011676	0.74	1.58866	1.60160	1.57007	1.57787	1.59276	1.59508
P	%	0.00933	0.000320	3.43	0.00914	0.00958	0.00893	0.00920	0.00932	0.00982
Cr	%	0.0184	0.00021	1.14	0.0184	0.0185	0.0184	0.0187	0.0185	0.0181
Ni	%	0.0139	0.00026	1.83	0.0137	0.0137	0.0137	0.0143	0.0141	0.0139

Figure 8: Part of OXSAS result display of a 6-run combined elemental and inclusion analysis of sample VRM 27. Parameters from elemental analysis in grey and from Standard Inclusion Analysis, including peak counts and peak coincidence counts, in green.

Limiting parameters

Many inclusion types can be measured. This includes oxides (Al_2O_3 , MgO , CaO , MnO , TiO_2 , SiO_2 ...), calcium aluminates (Al_2O_3 – CaO ...), spinels (Al_2O_3 – MgO ...), and sulfides (CaS , MnS ...). The ability to accurately detect and assess inclusions is subject to limitations that include the types and sizes of the inclusions, sample composition, and instrument performance. Some of the limiting parameters are detailed hereafter.

- **Detection limit of the elements**

The lower the detection limit of the elements composing the inclusions, the easier it is to detect the inclusions, characterize their type, and count them all. Al, Ca, Mg, S and Ti have low detection limits, while O (an important inclusion element) has a higher detection limit. O therefore does not always give rise to an observable peak. Because of that, O is normally not used in Spark-DAT algorithms. This is the case in the examples presented in this document.

- **High concentration of the metallic form**

The higher the concentration of the metallic form of an element composing the inclusion, the larger the smallest detectable inclusion. For example, at an Al concentration of 50 ppm, the smallest detectable Al_2O_3 inclusion has a diameter of about 1 μm , while at 0.2% it has a diameter of about 4.5 μm . At relatively high concentrations, all the elements are barely detectable, if at all. In low alloy steel, this is in general the case for Mn and Si.

- **Small inclusions**

Under optimal conditions, inclusions smaller than 1 μm can be detected. This is typically possible when the inclusions have a globular shape, and the detection limits of the elements that make them up and the concentrations of their metallic form are very low.

- **Large inclusions**

The limited energy of the single spark and its erratic behavior do not allow it to fully ablate inclusions larger than typically 10–15 μm . An inclusion larger than this can be detected, however, multiple single sparks are required to complete its ablation. This causes the inclusion to be counted multiple times, exactly like if several inclusions were present.

- **Shape of the inclusion**

Although optical emission is not capable of determining the shape of inclusions, it is a critical parameter in the detection of inclusions. In general, the inclusions with a compact shape are the easiest to detect, whereas long or thin inclusions are the most difficult.

- **Low content of the metallic form**

This is typical for Ca, which is totally insoluble in steel even at ppm level. Numerous very small inclusions (likely $\ll 1 \mu\text{m}$) give rise to signals that merge with the background signal and cannot be detected. Counting Ca-containing inclusions should therefore be understood as counting relatively large inclusions.

Conclusion

The Standard Inclusion Analysis considerably increases the versatility and the benefits of the ARL iSpark Plus OES Metal Analyzer. It is easy-to-use and low-cost, and it allows for the characterization of inclusions during elemental analysis, without noticeably increasing analysis time or reducing the number of samples that can be analysed in a day.

The Standard Inclusion Analysis is extremely beneficial in steel manufacturing. Not only are the inclusion data available in close to real time (a few minutes after sampling the liquid steel), which allows for the opportunity to take a rapid corrective action if needed, for example when the inclusion content excessively deviates from the optimal situation. The inclusion data also can be obtained for a very large number of samples. This enables efficient continuous control of inclusions which in turn helps to guarantee the smooth running of the steel production process and reduce the frequency of issues caused by inclusions like clogging of the submerged entry nozzle.

Furthermore, the inclusion information available on large numbers of production samples brings rich information—information that is complementary to that available with SEM/EDX systems—that helps metallurgists and process engineers improve the steel manufacturing process.

Finally, the Standard Inclusion Analysis is also useful as a low-cost check of inclusions in finished steel or in many products made of steel, thereby reducing number of failure analyses and costly customer claims



Thermo Scientific ARL iSpark Plus.

Other options available for inclusion analysis

Analytical options

- **Basic Inclusion Analysis**

The Basic Inclusion Analysis is the entry-level inclusion analysis. It delivers the peak and peak coincidence counts for a few common inclusions and comes with a report specific for inclusions. See the dedicated product specifications (AN41218) for more details.

- **Advanced Inclusion Analysis**

The Advanced Inclusion Analysis delivers the inclusion data generated by the Standard Inclusion Analysis and, in addition, advanced inclusion data. This advanced data is more quantitative, including inclusion size in micrometer, inclusion concentration, and inclusion volume fraction. A dedicated product specifications (AN41220) is available.

- **Spark-DAT soluble/insoluble**

The soluble and insoluble concentrations (i.e., the concentrations of the element in the metallic form and in the form of inclusions, respectively) of Al, B and Ti can be determined with the ARL iSpark Plus. The insoluble part is sometimes called Beta factor or B factor. Similar to inclusion analysis, the method uses processing of single spark signals by a dedicated Spark-DAT algorithm. More details are given in a dedicated product specifications (AN41217).

Software options

- **Spark Explorer**

The Spark Explorer is a software module that can be used on the instrument's computer or on a remote computer. It offers all the visualization tools necessary to explore in detail and understand the single spark signals, or to optimize the parameters of the Spark-DAT algorithms. For example, it allows comparison of the single spark run charts of several elements with analysis runs, in one or several samples. It also includes very useful functions, such as statistics on single spark signals, insoluble ratio calculation, and it allows optimizing the inclusion counting threshold.

- **Inclusions Report**

Inclusions Report allows users to generate a well-structured customizable report containing elemental concentrations and all the measured inclusions data. It is an essential tool when inclusion analysis results need to be archived or transmitted to the specialists who deal with inclusions (e.g., defectologists and process engineers).

- **SPC**

SPC (Statistical Process Control) software is the perfect complement to Spark-DAT inclusion analysis. It allows real-time charting, monitoring, analysis, communication, and reporting of any inclusion analysis result. SPC software is also able to warn if the number of inclusions is higher than the limit of the specification and to provide trends on inclusion contents.

See the brochure "Options for ultra-fast inclusion analysis" (OE-BR41375) for more details on these options.

Acknowledgments

We would like to thank Dr. Andreas Pissenberger, voestalpine Stahl Linz, for enlightening discussions and for reference values he kindly provided us regarding inclusions in the VRM and the CKD samples. Because of the absence of "inclusion CRMs," reference values for inclusion parameters were particularly helpful in the preparation of this application note.

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