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E21B 44/00 (2006.01)

(56) Documents Cited:
GB 2566068 A **WO 2019/160859 A1**
WO 2011/095600 A2 **US 20190323332 A1**
US10385619

(58) Field of Search:
INT CL **E21B**

(71) Applicant(s):
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(54) Title of the Invention: **Methods to monitor the efficiency of casing milling operations**
Abstract Title: **Control of casing milling using analysis of debris**

(57) A method of controlling wellbore casing milling includes providing a tool for milling a wellbore casing and delivering a milling fluid to the milling tool. A milling operation is performed on wellbore casing in a first milling stage using the milling tool. Debris is collected from the wellbore, including debris generated during the milling operation. At least one physico-chemical property of the collected debris is measured using a measurement apparatus and a first condition associated with the milling operation is determined based on the physico-chemical property. A second stage of the milling process is devised based on the first condition. Another milling operation is performed on the wellbore casing according in a second stage of the milling process. Debris may be analysed by infra-red or x-ray spectroscopy to determine a wear characteristic. The second milling stage may involve change of cutting speed, depth, or angle or by changing tool.

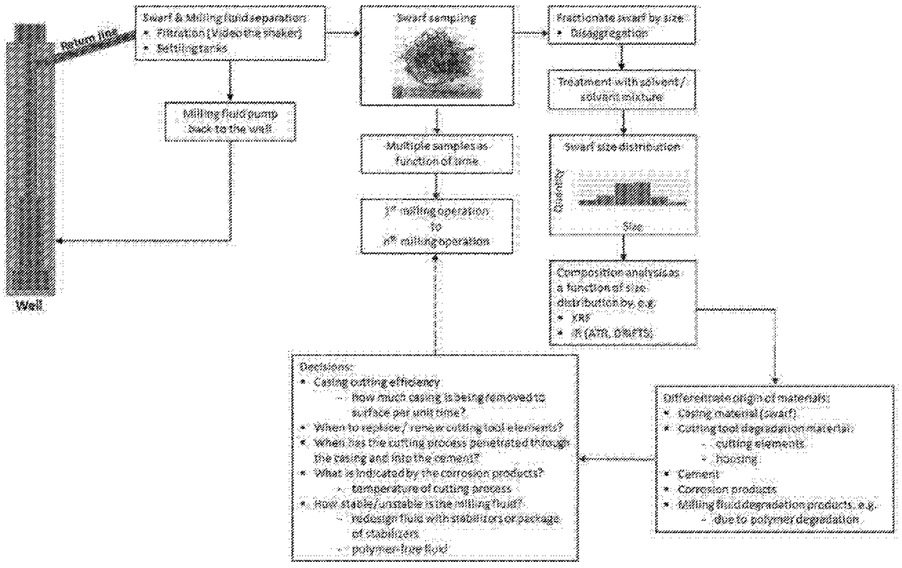


Figure 1

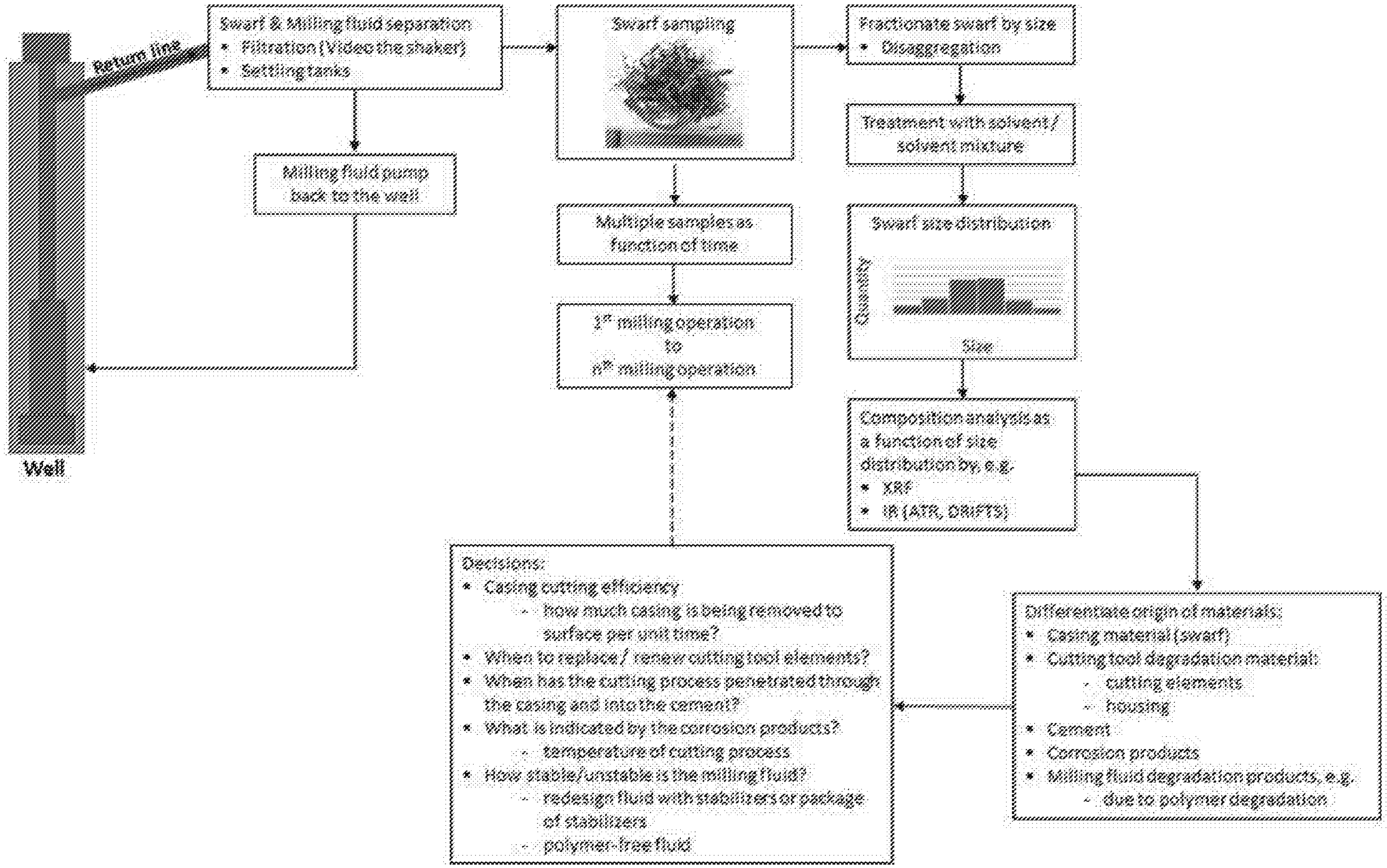
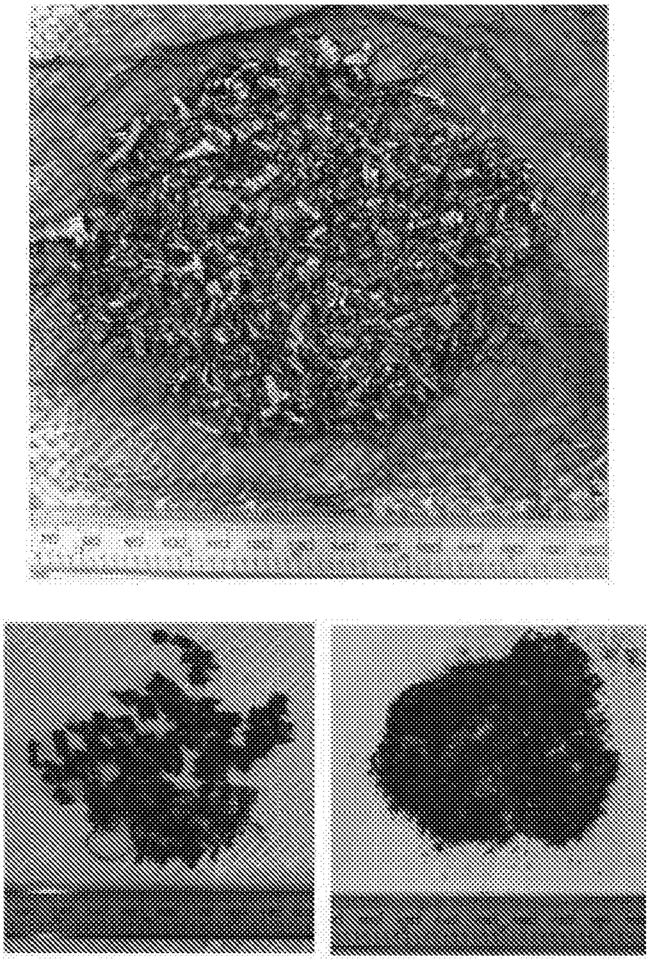
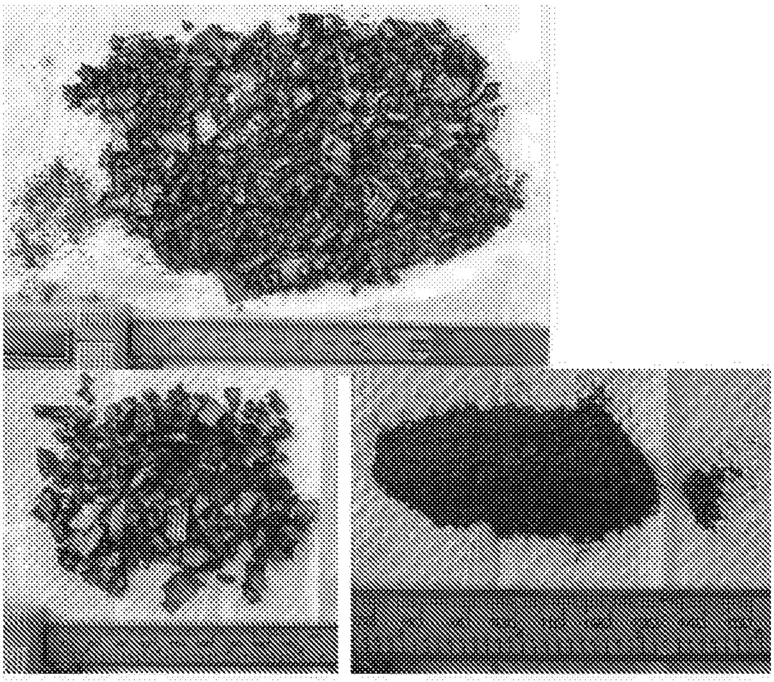

Well
Return line
Swarf & Milling fluid separation
• Filtration (Video the shaker)
• Settling tanks
Milling fluid pump back to the well
Swarf sampling
Multiple samples as function of time
1st milling operation to nth milling operation
Fractionate swarf by size
• Disaggregation
Treatment with solvent / solvent mixture
Swarf size distribution
Quantity
Size
Composition analysis as a function of size distribution by, e.g.
• XRF
• IR (ATR, DRIFTS)
Differentiate origin of materials:
• Casing material (swarf)
• Cutting tool degradation material:
- cutting elements
- housing
• Cement
• Corrosion products
• Milling fluid degradation products, e.g.
- due to polymer degradation
Decisions:
• Casing cutting efficiency
- how much casing is being removed to surface per unit time?
• When to replace / renew cutting tool elements?
• When has the cutting process penetrated through the casing and into the cement?
• What is indicated by the corrosion products?
- temperature of cutting process
• How stable/unstable is the milling fluid?
- redesign fluid with stabilizers or package of stabilizers
- polymer-free fluid

Figure 1



>2.8mm <0.7mm

Figure 2

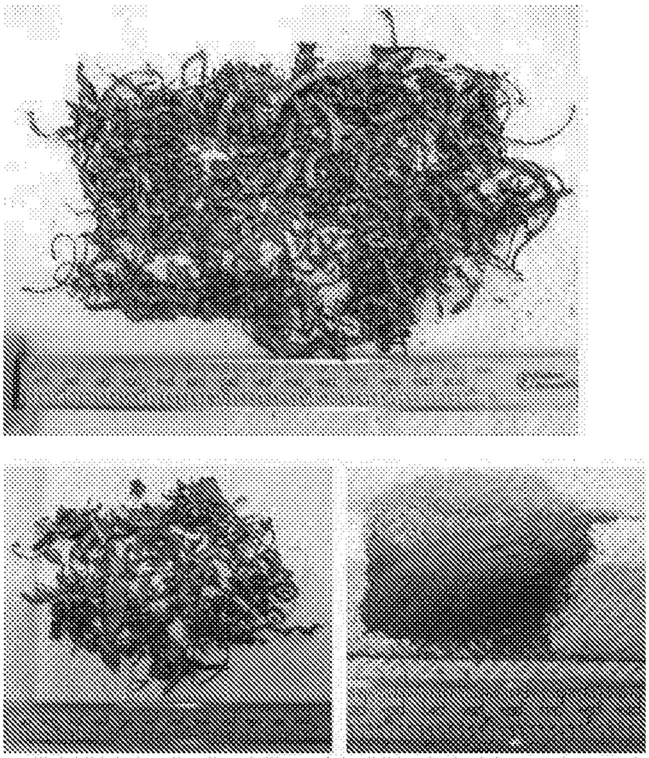


>2.8mm <0.7mm

Figure 3

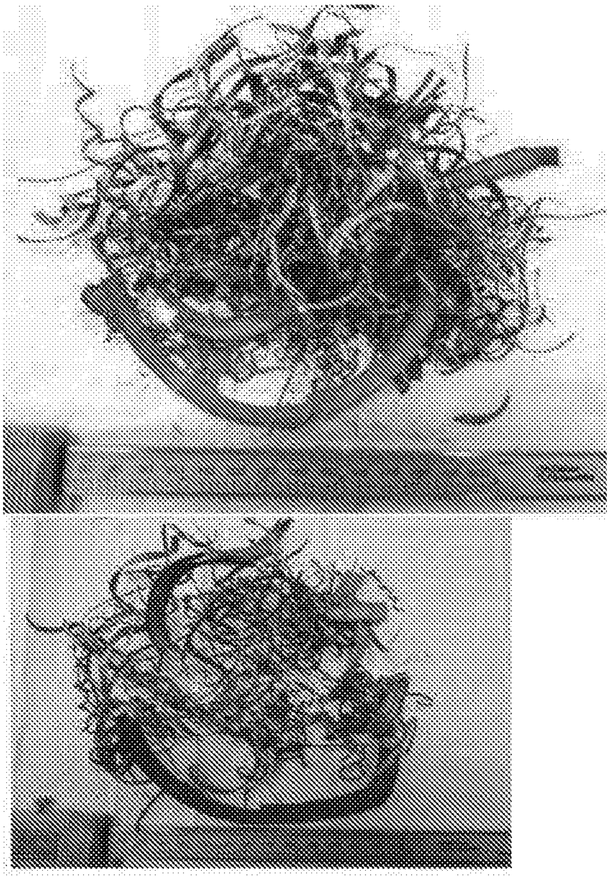
>8mm >2.8mm

Figure 4



>2.8mm <0.71mm

Figure 5



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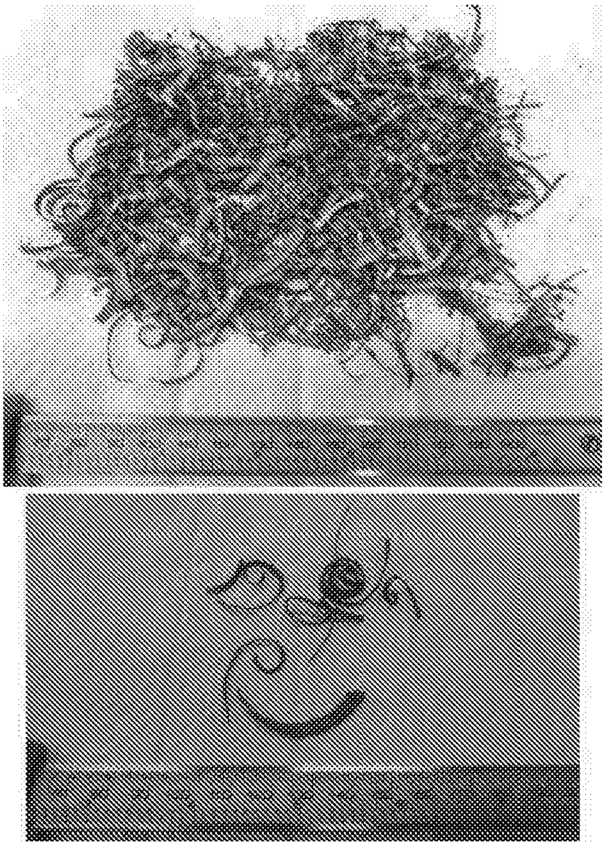

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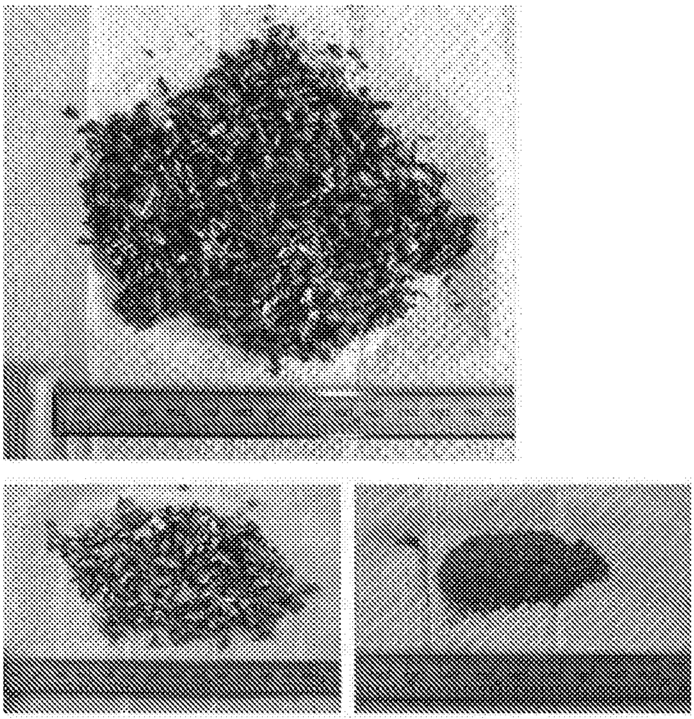

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<0.71mm

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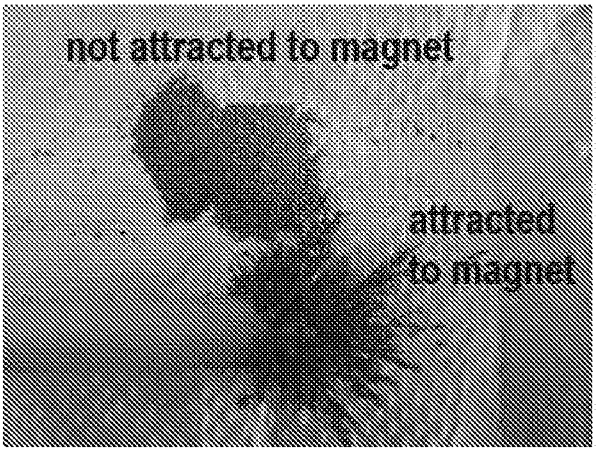

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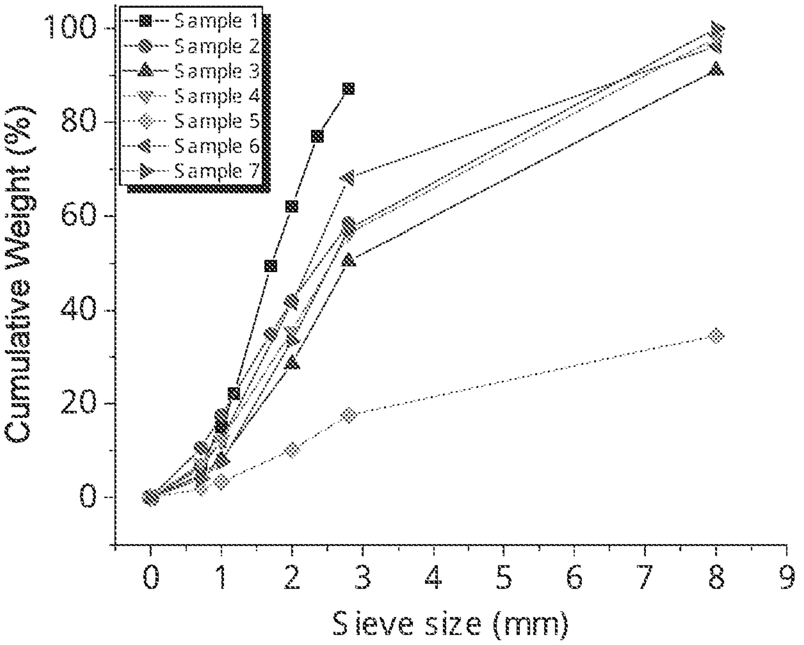

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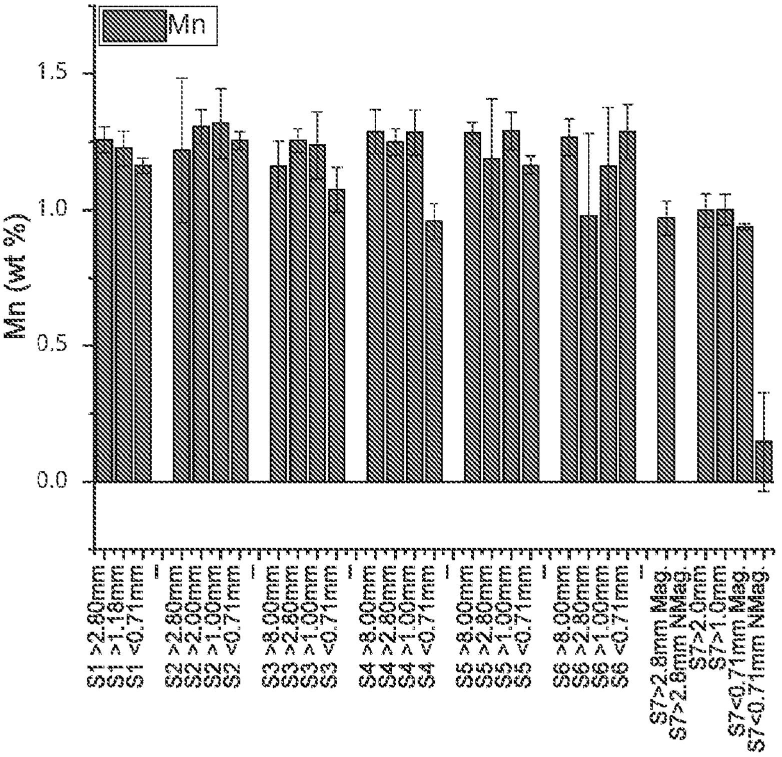

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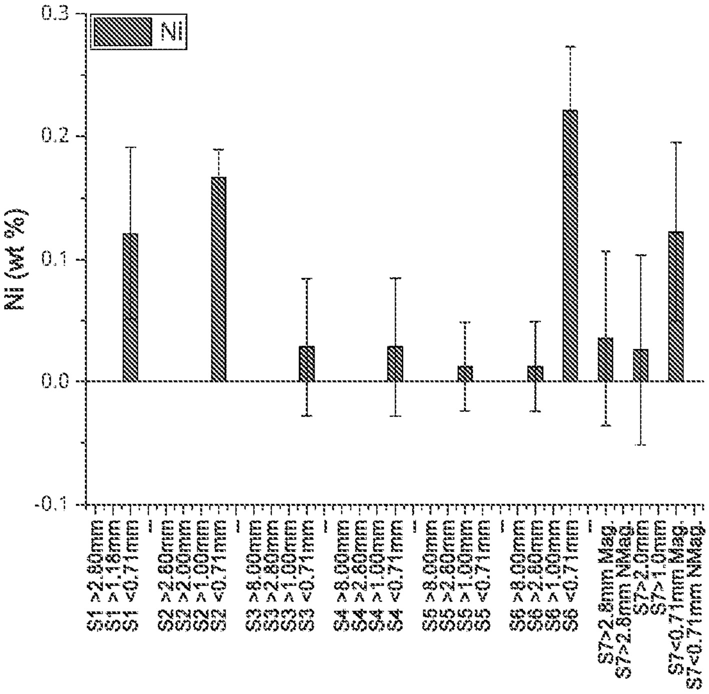

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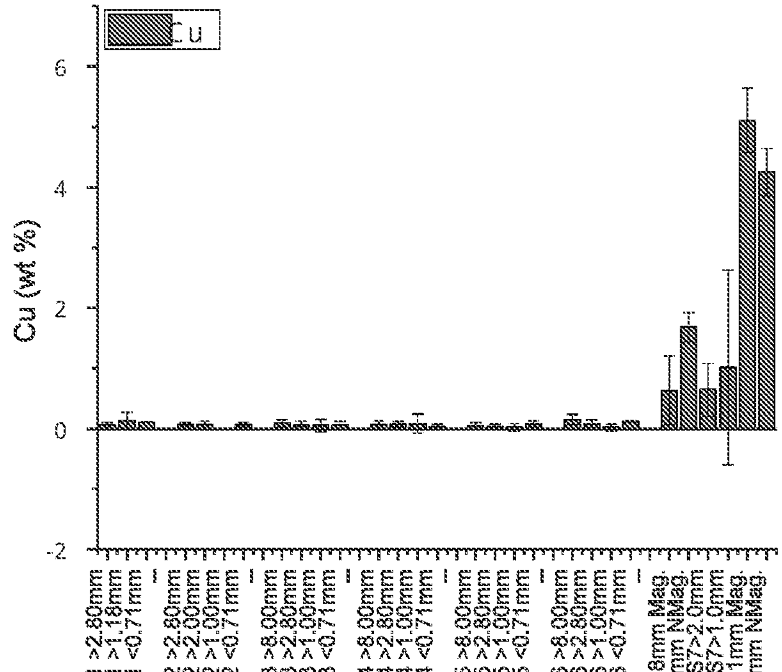

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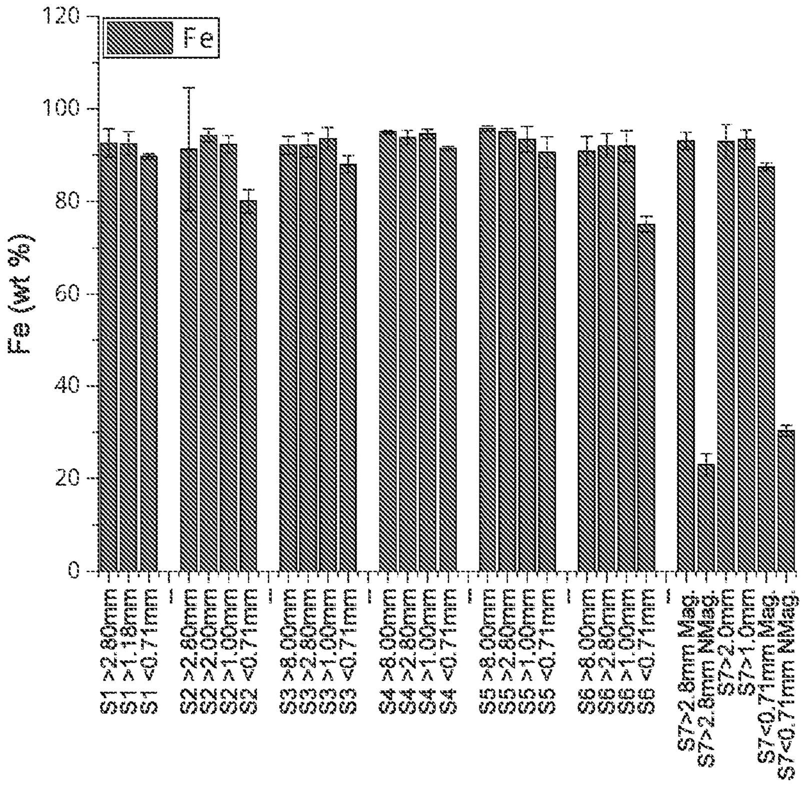

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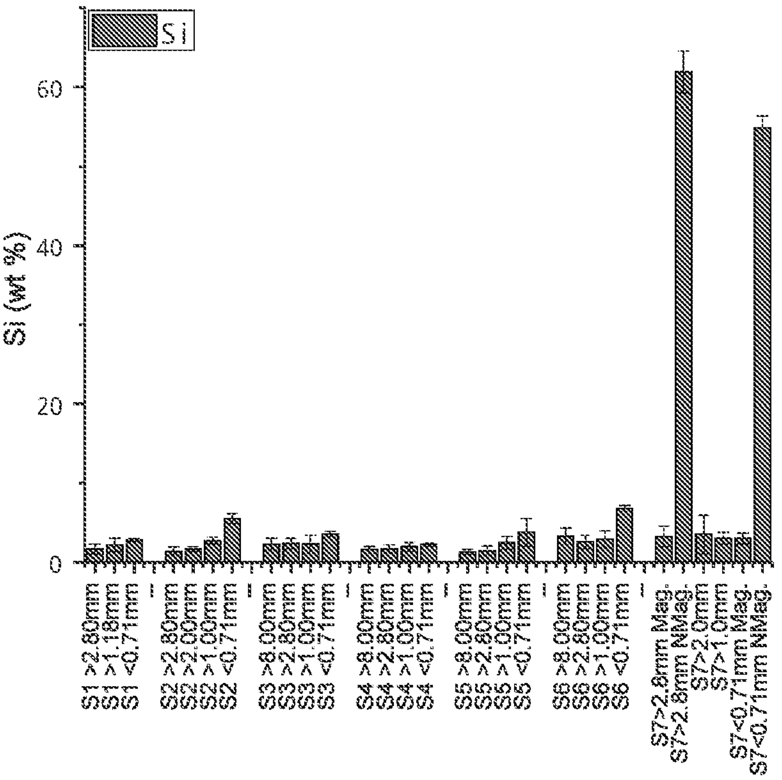

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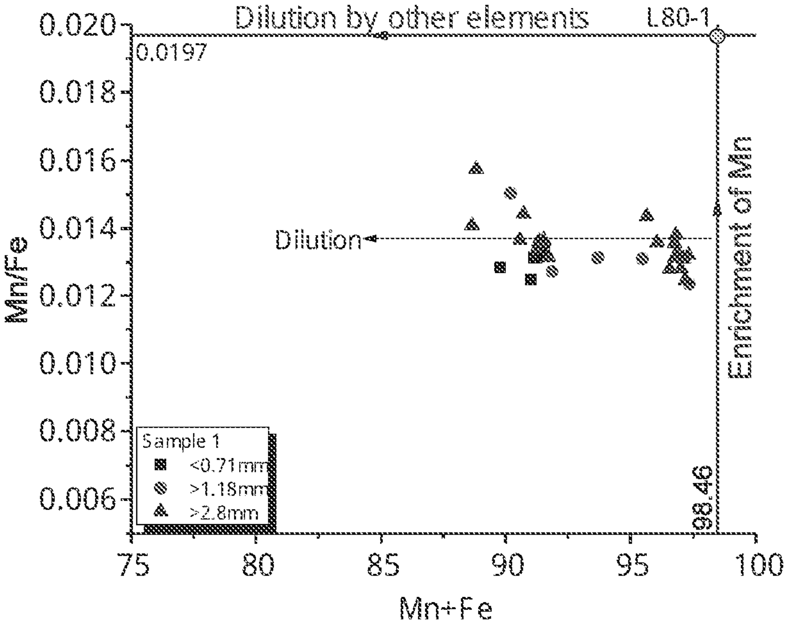

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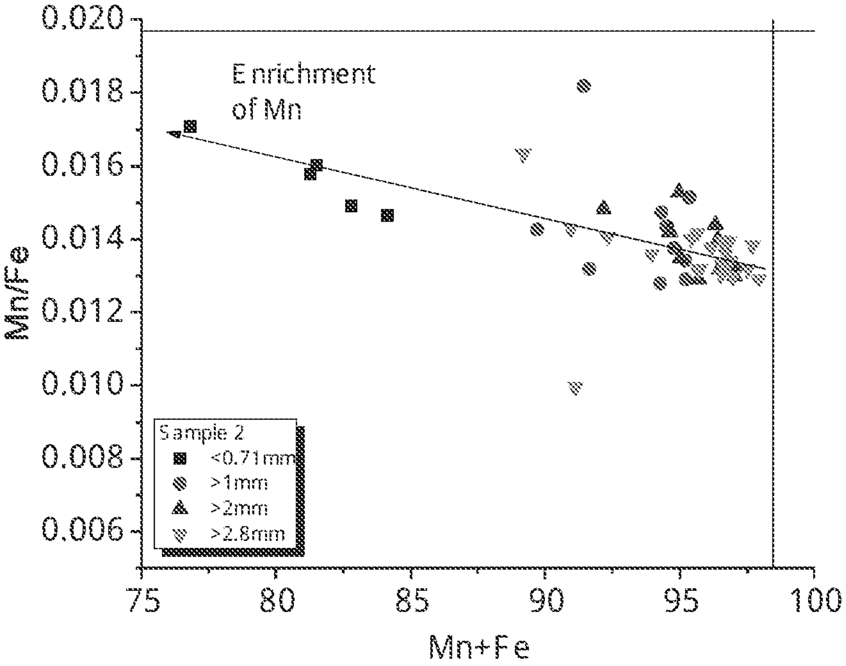

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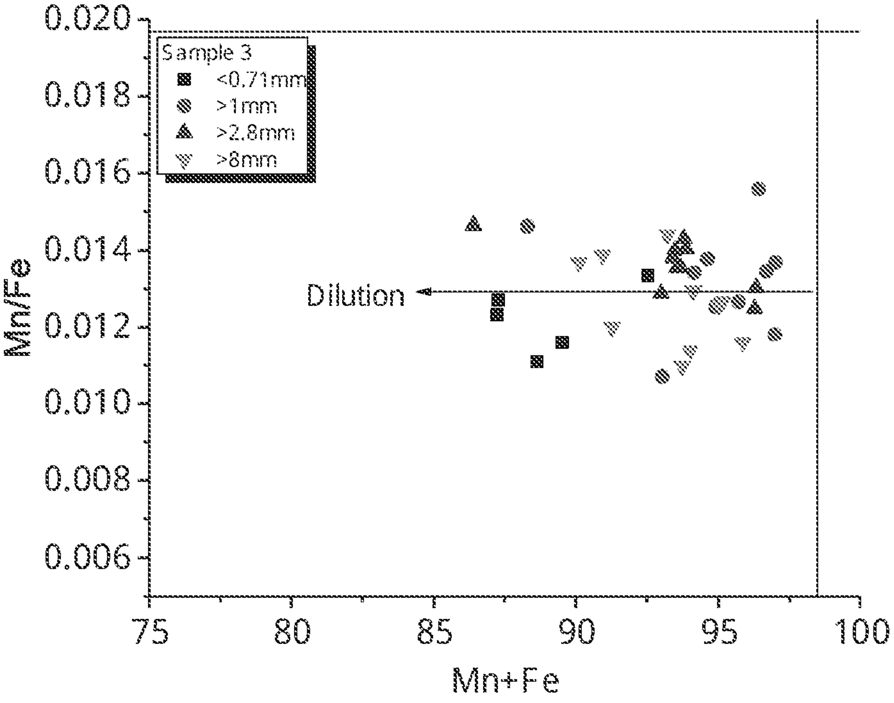

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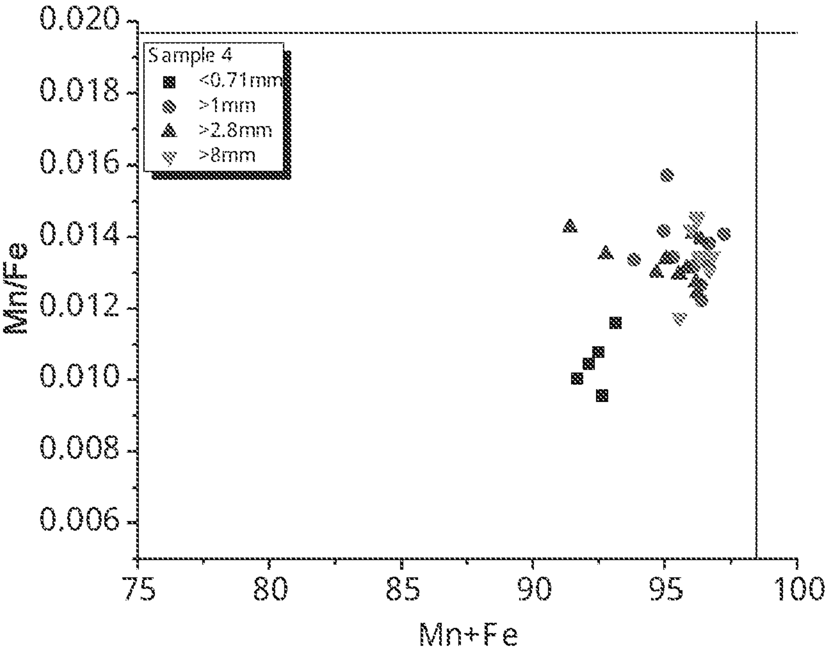

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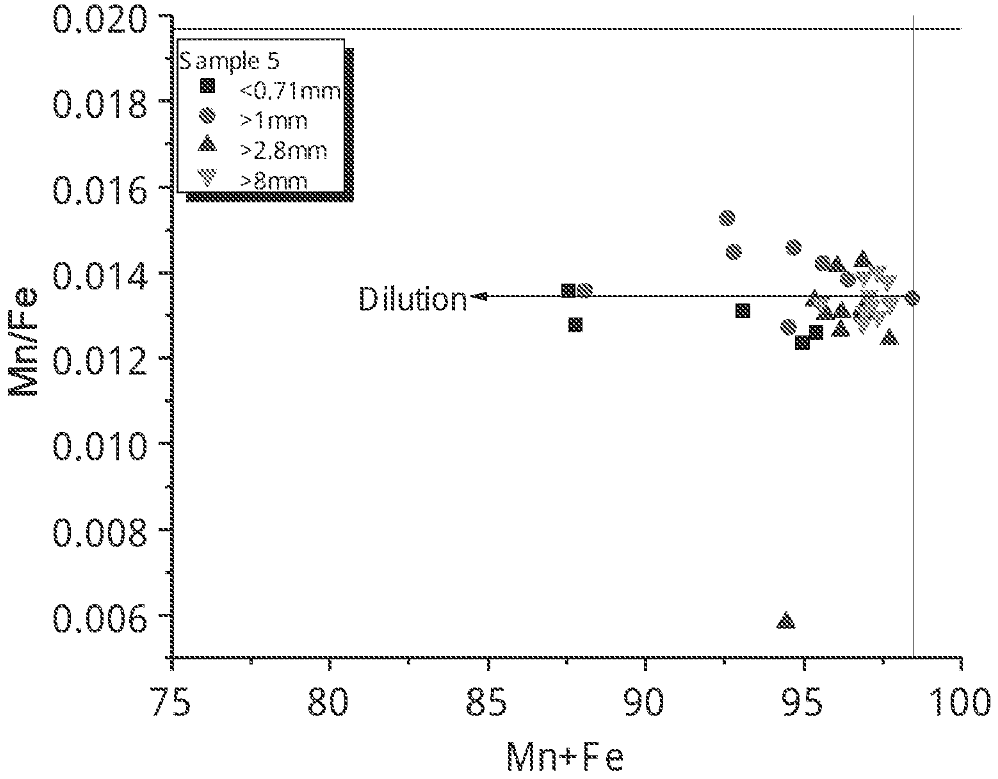

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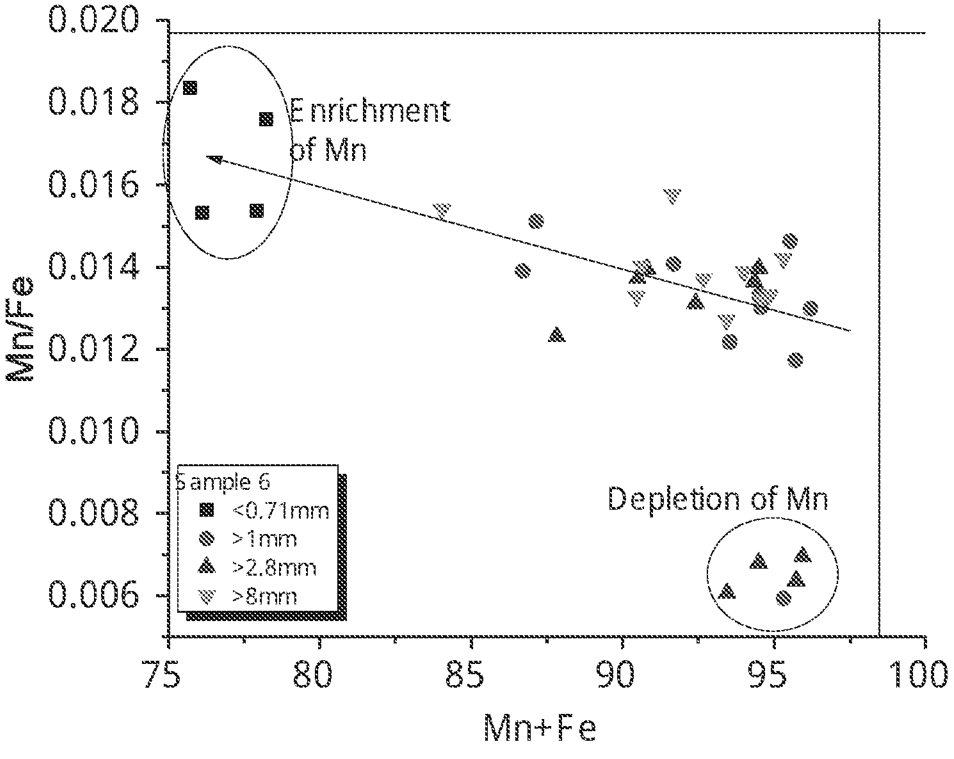

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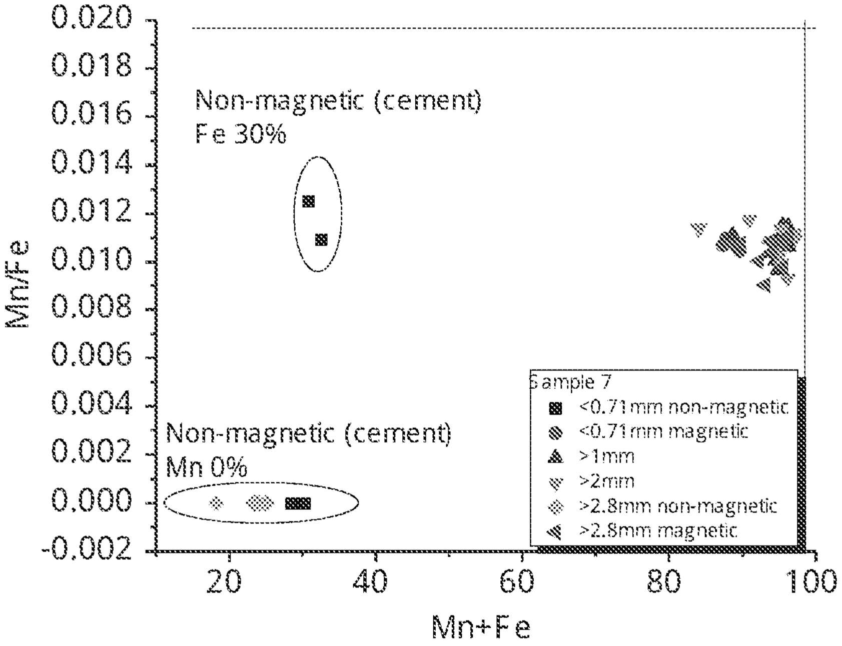

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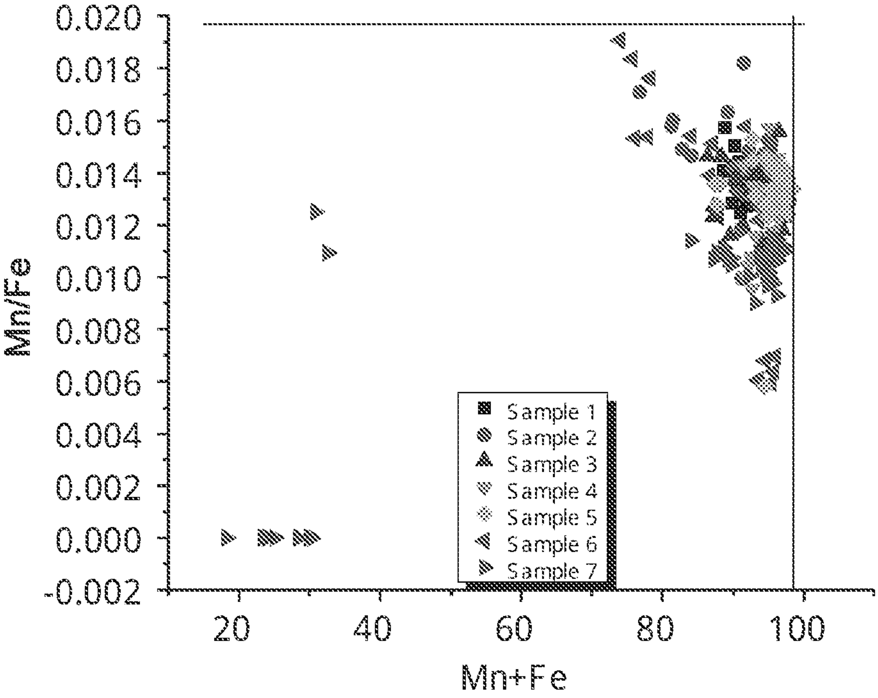

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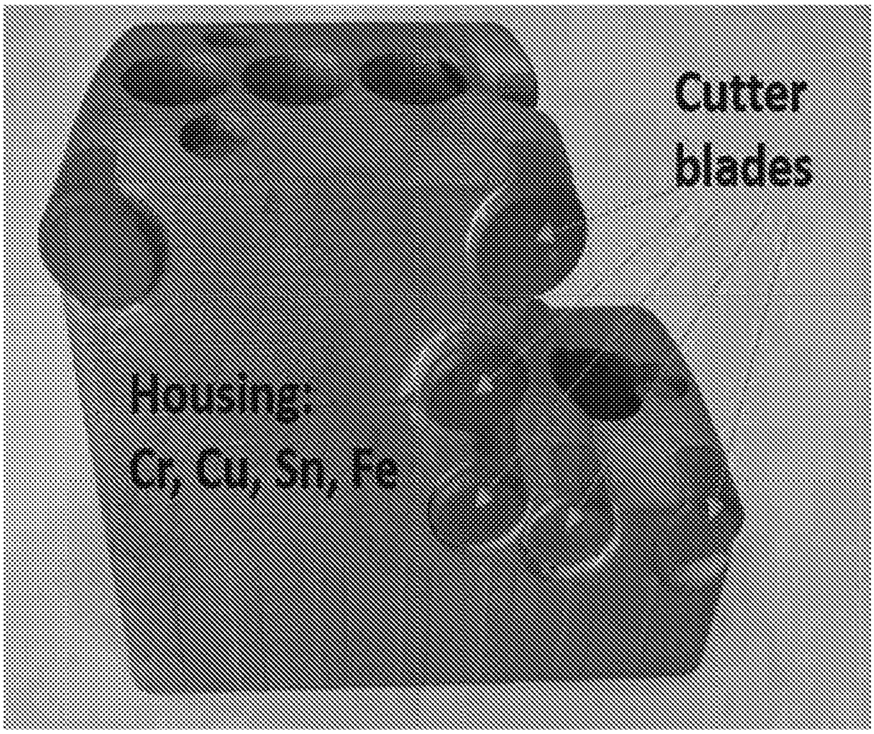

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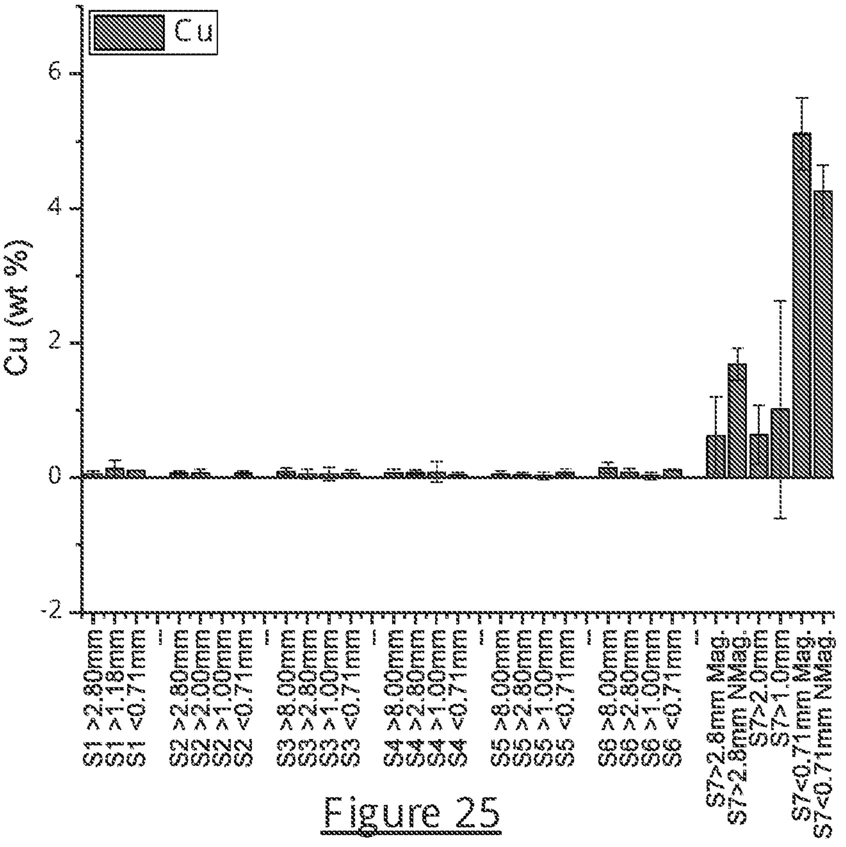

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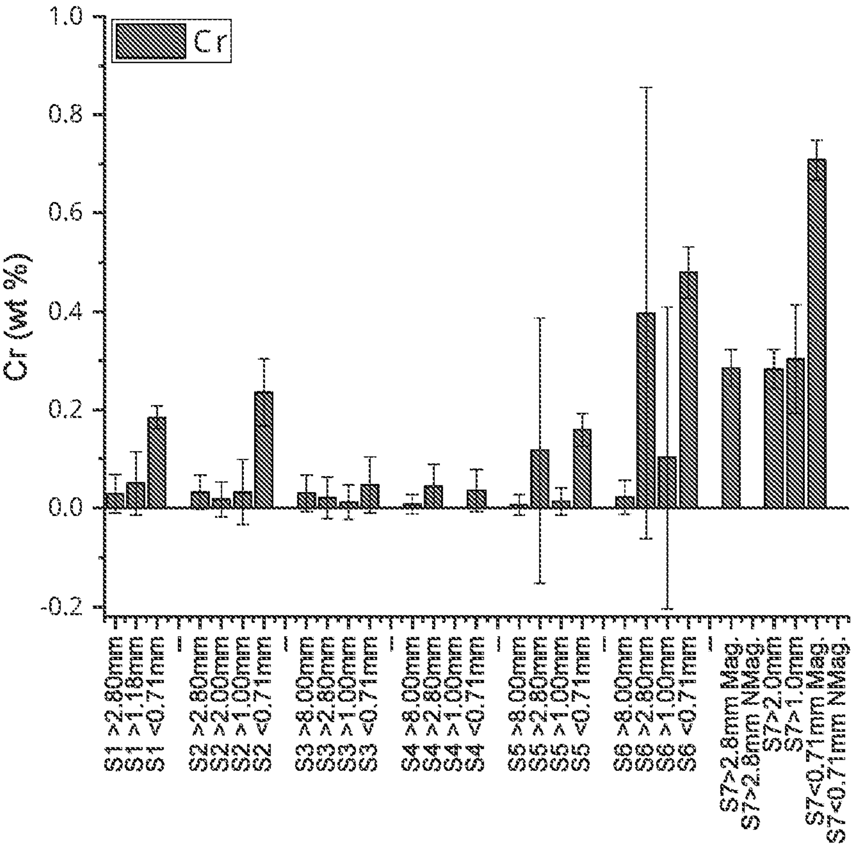

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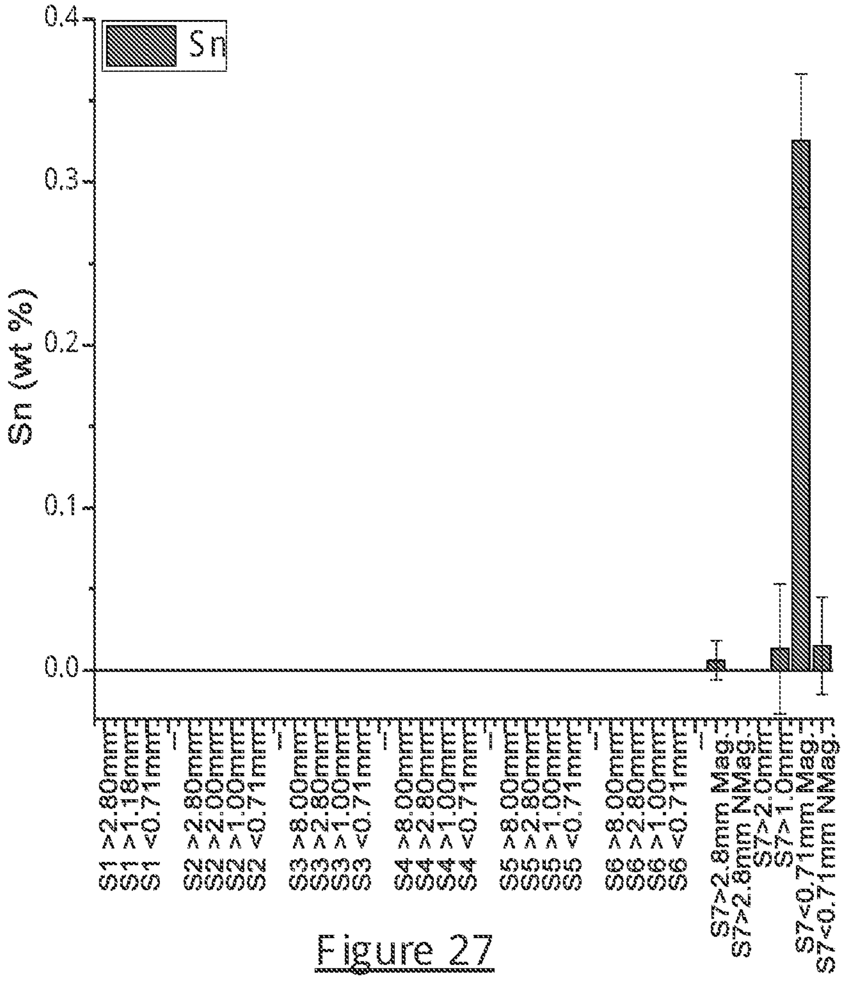

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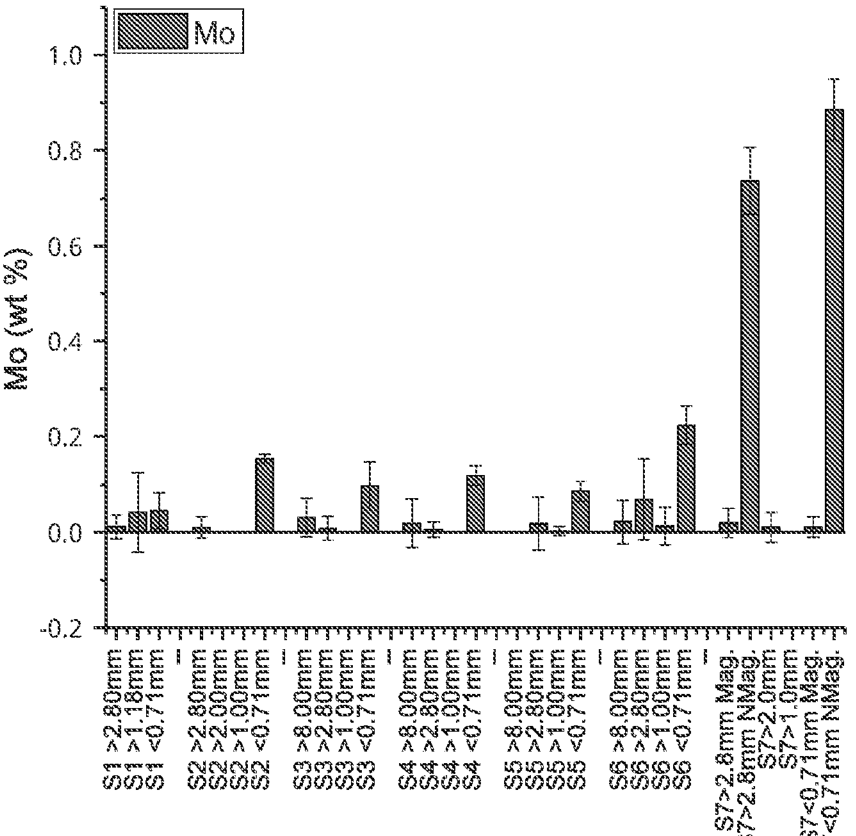

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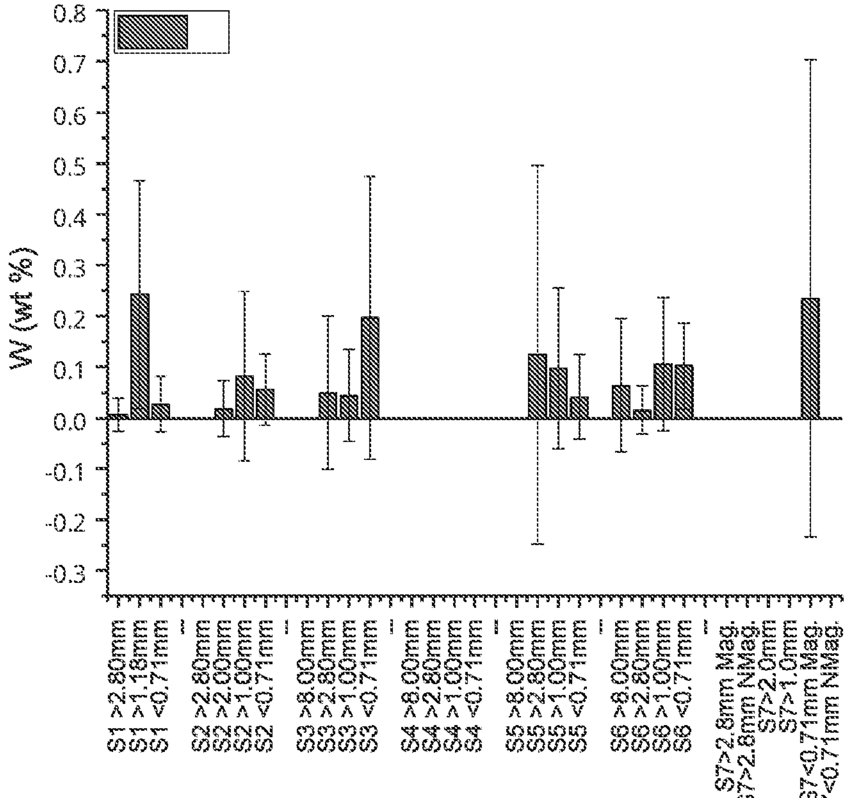

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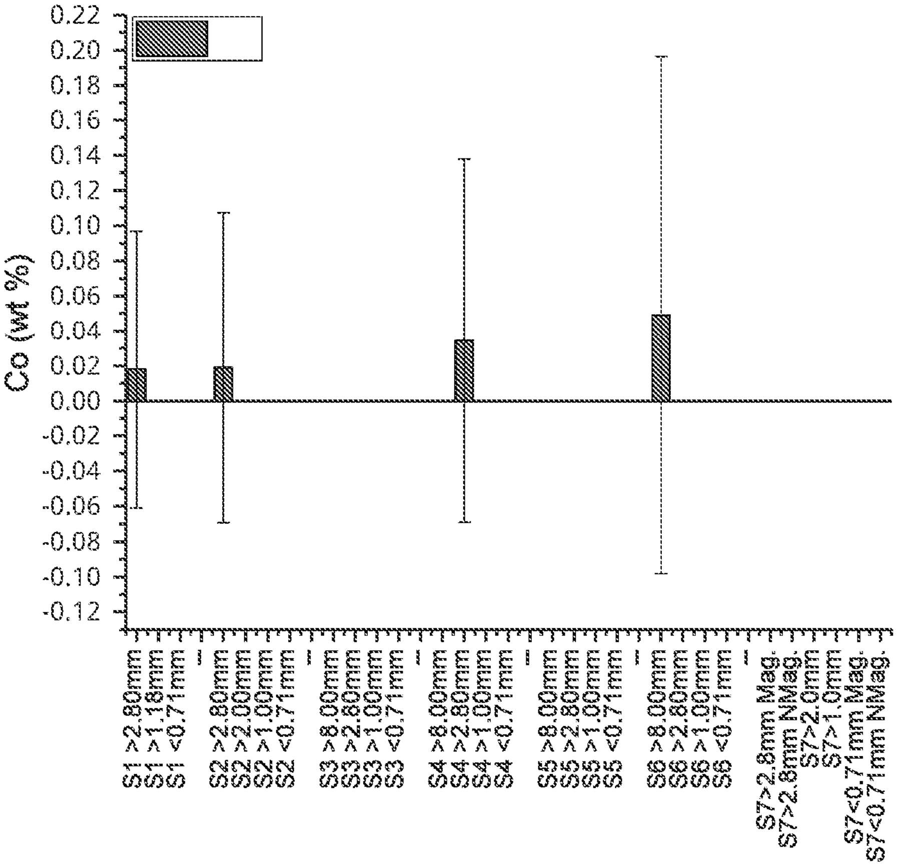

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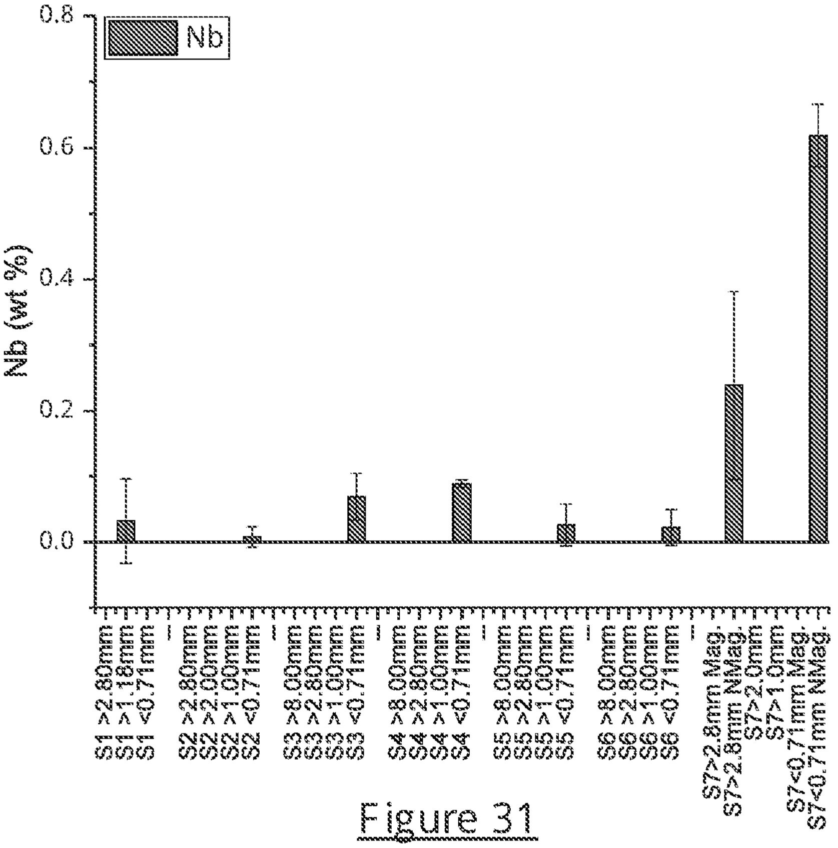

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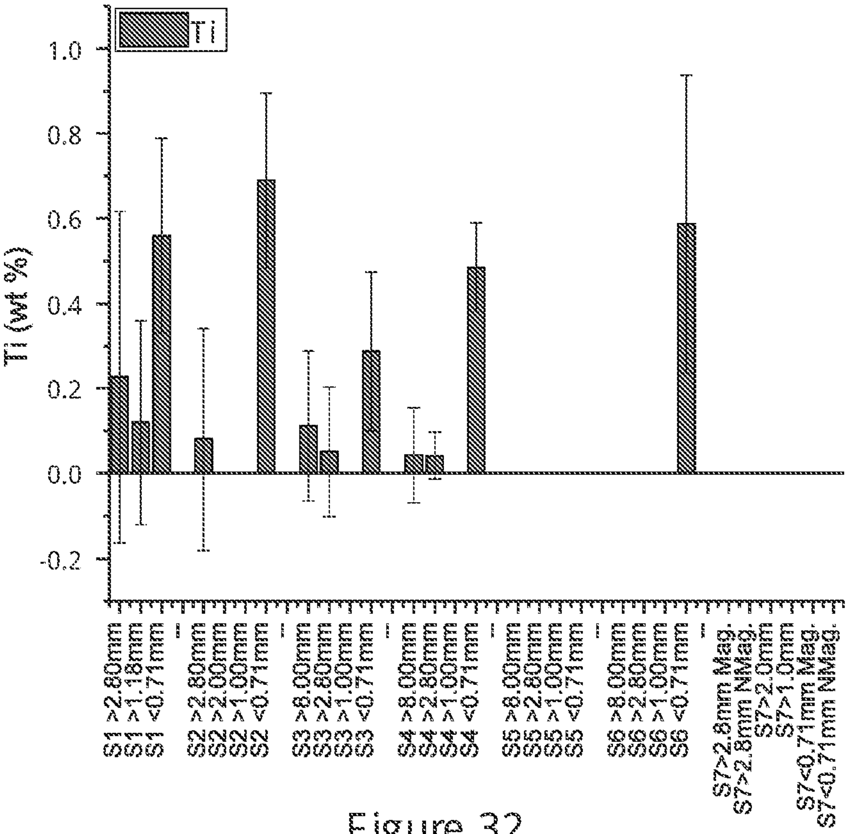

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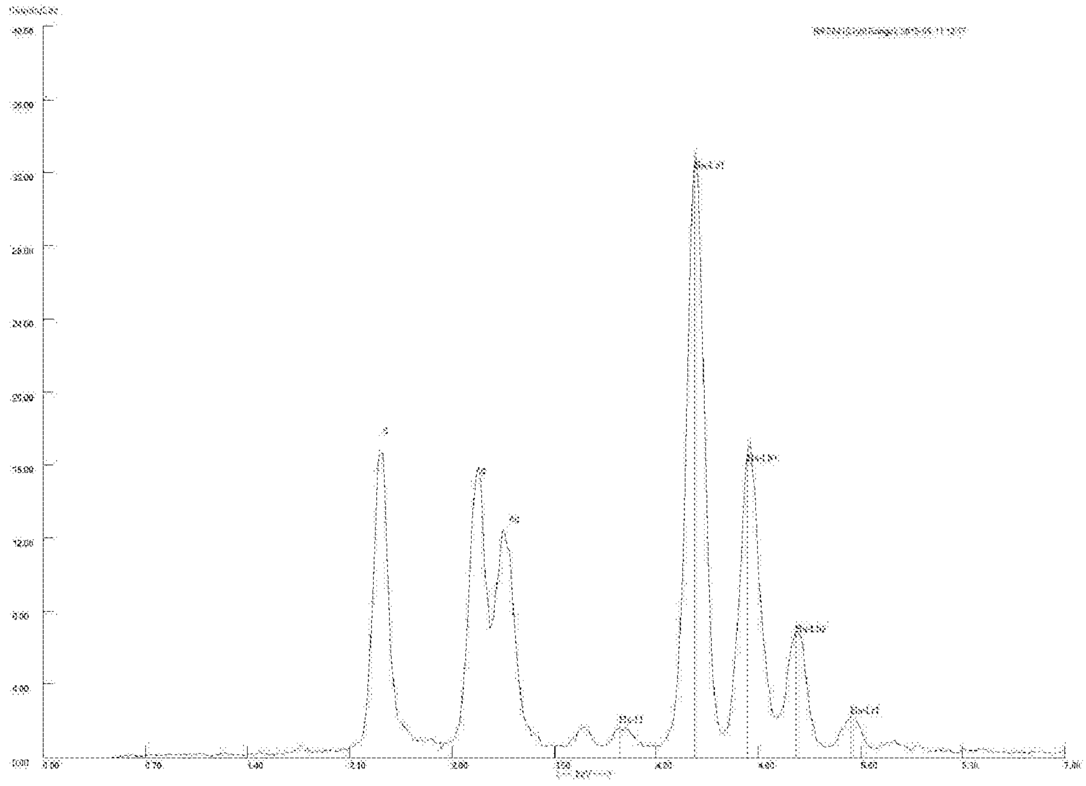

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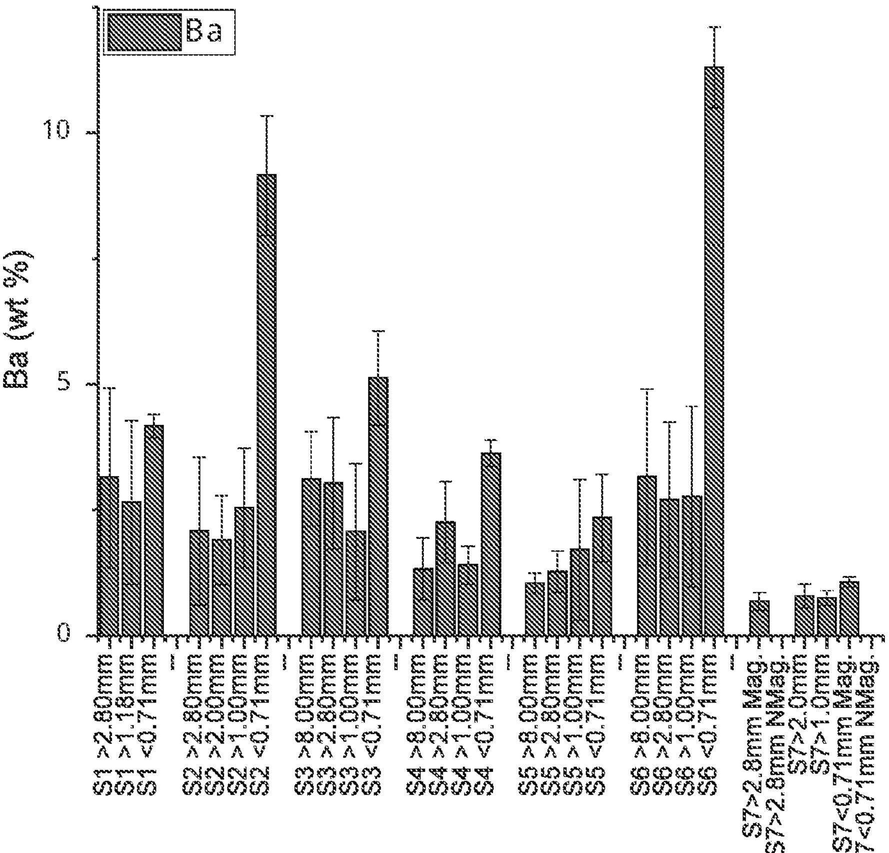

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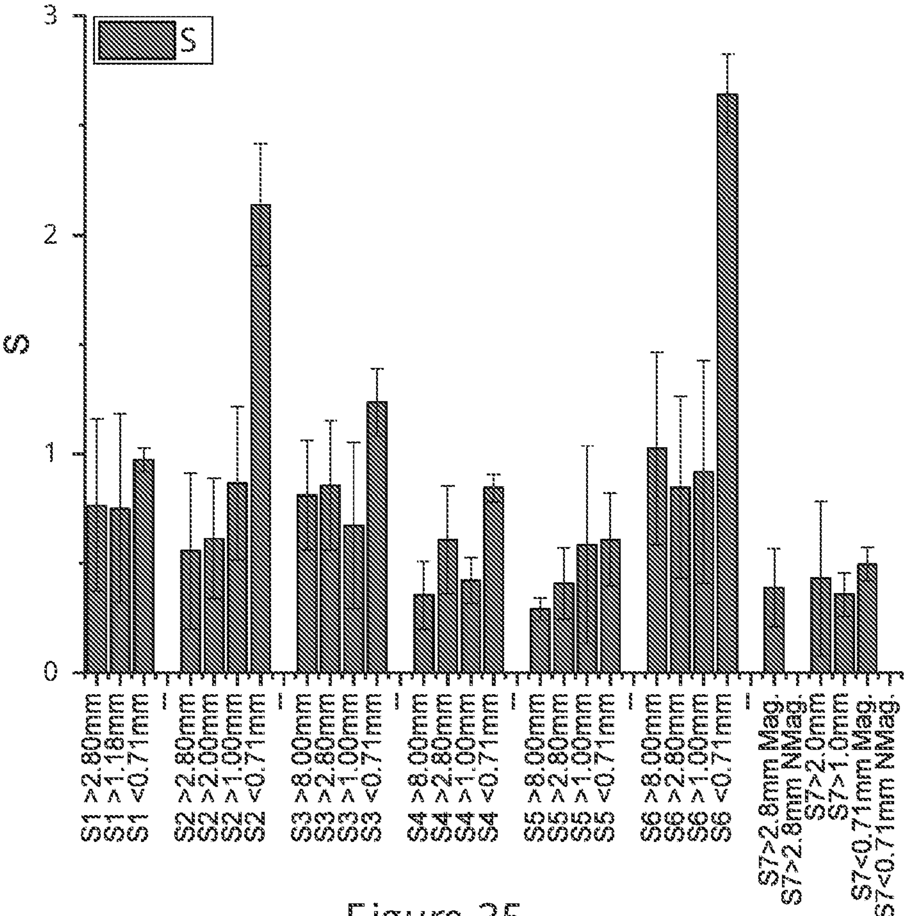

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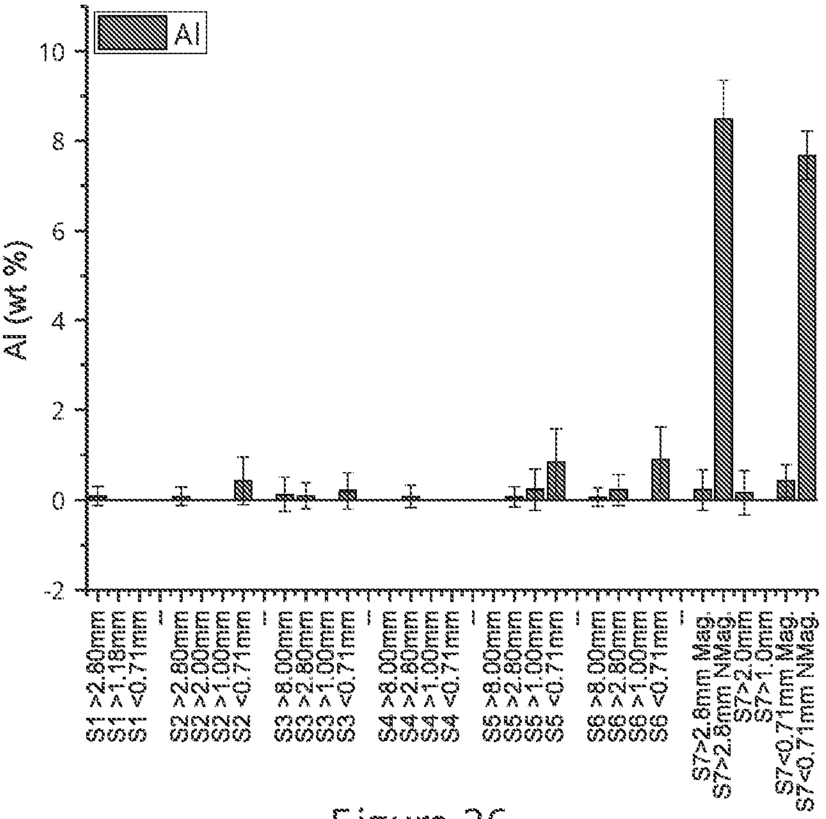

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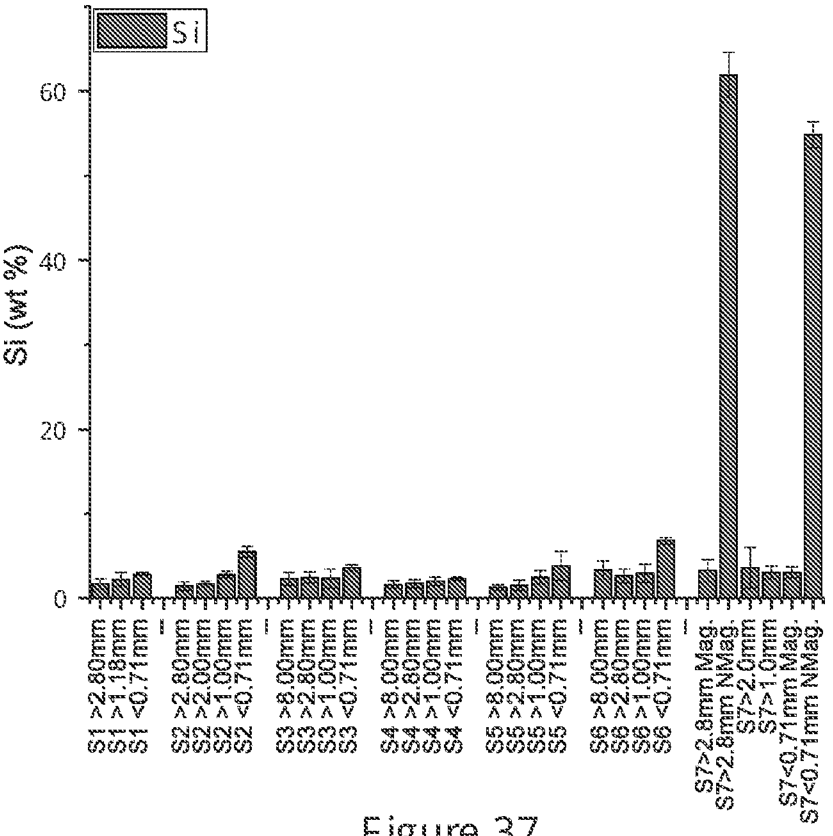

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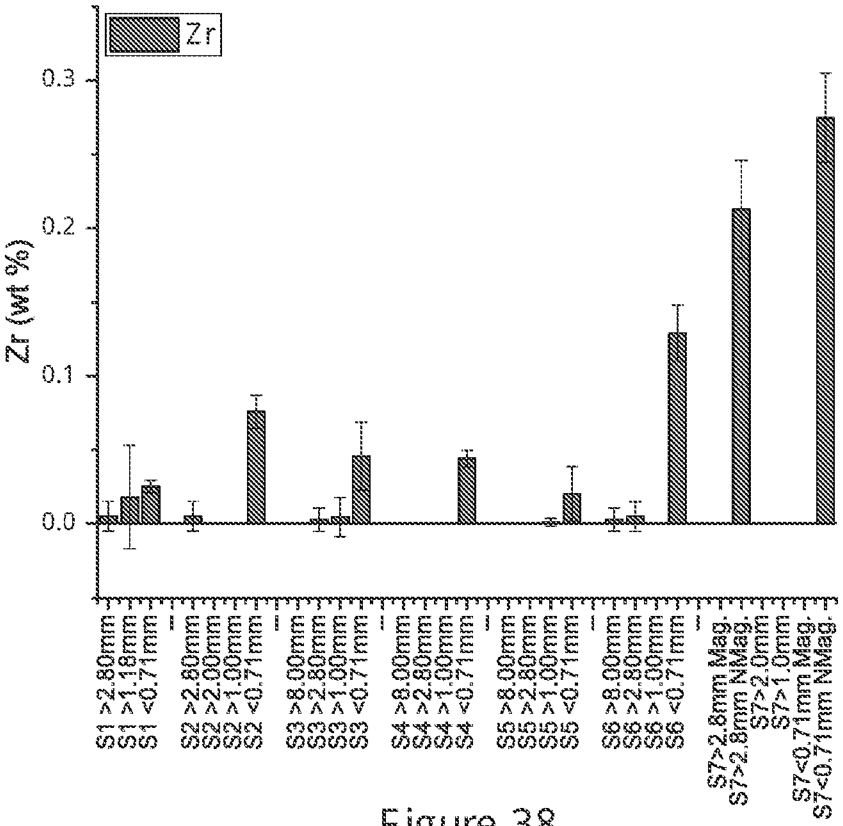

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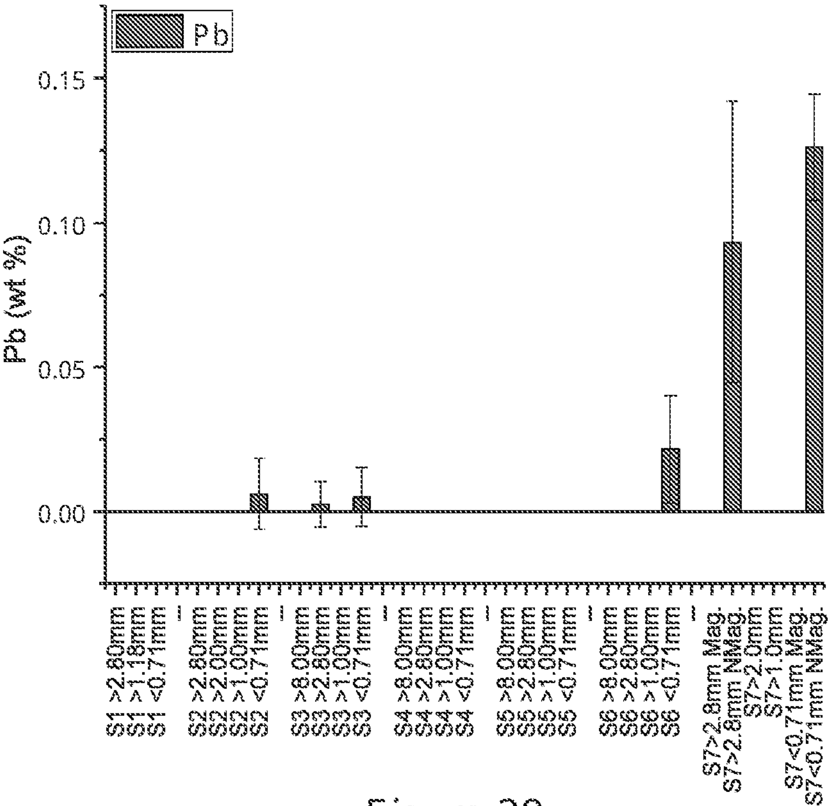

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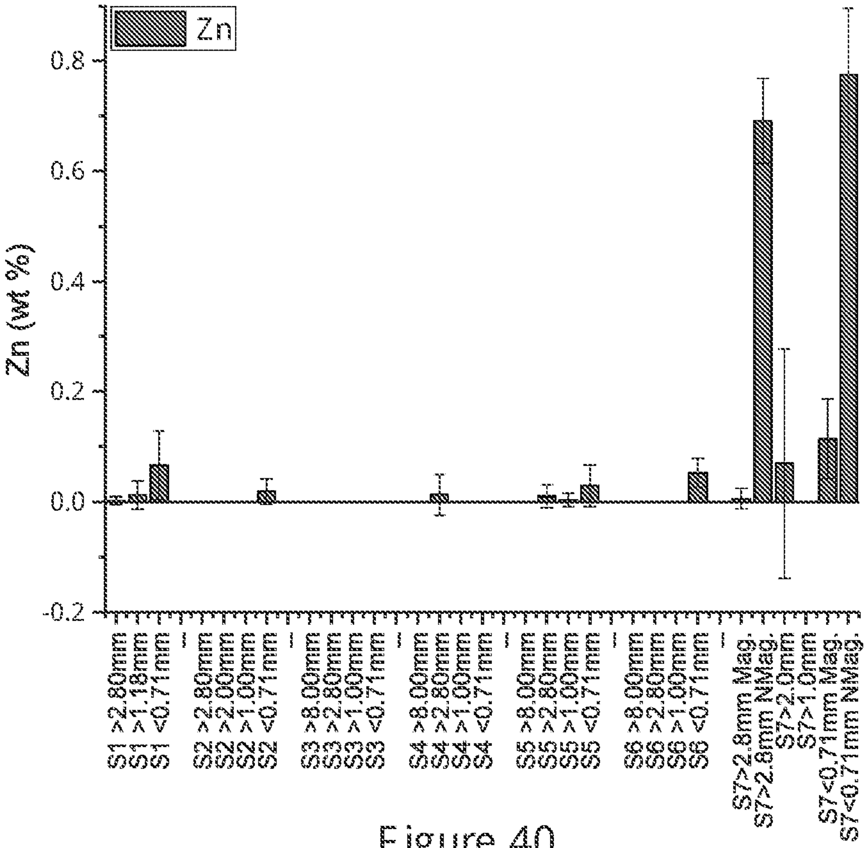

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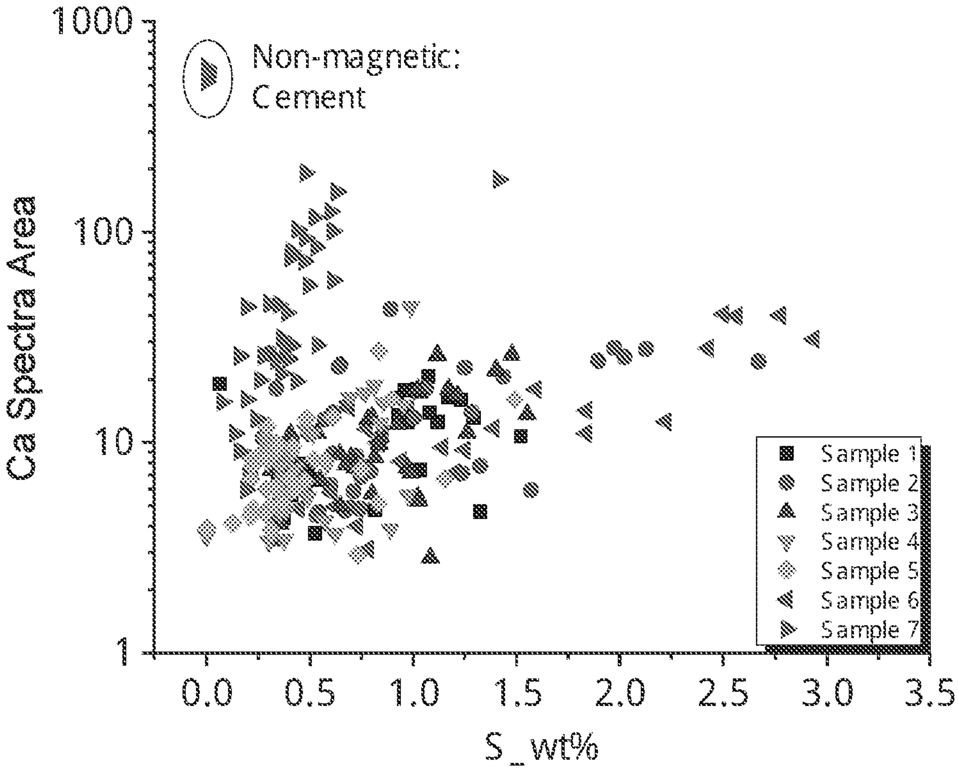

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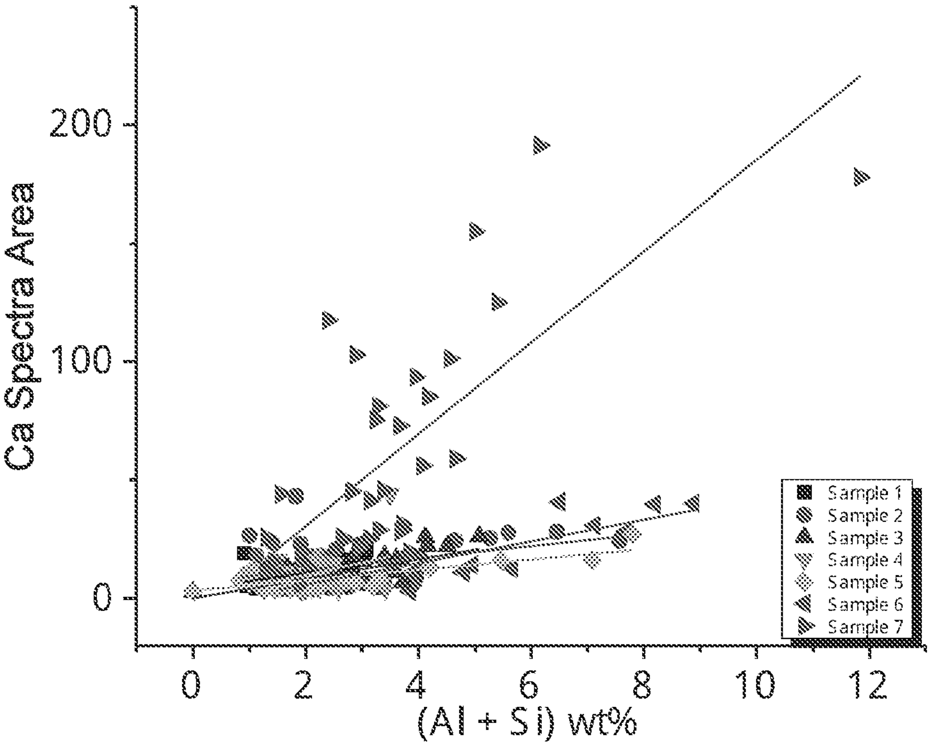

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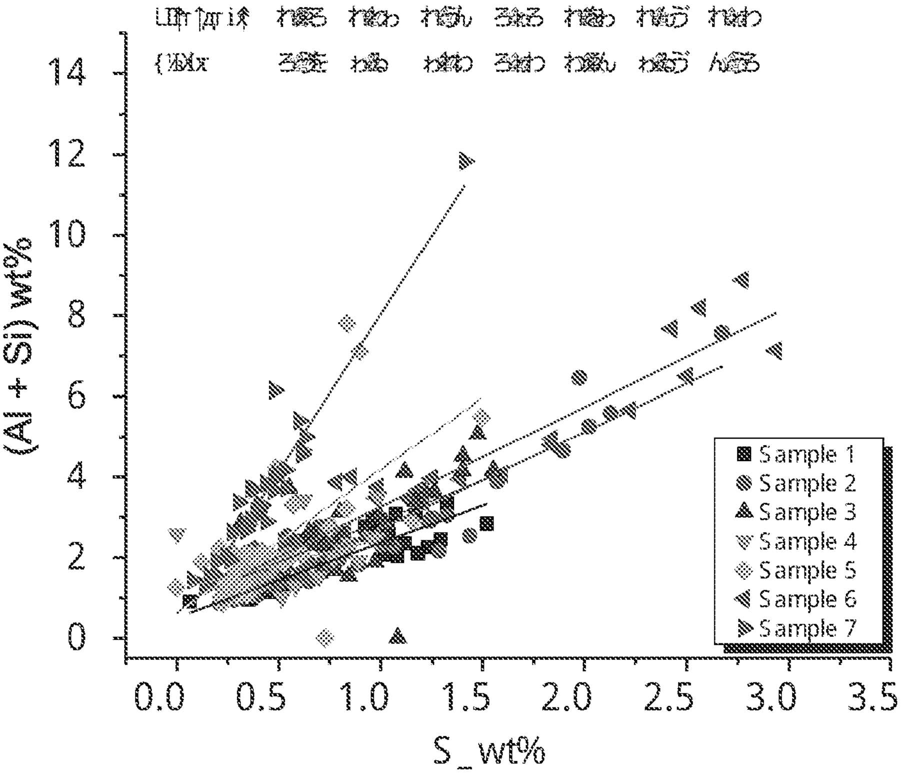

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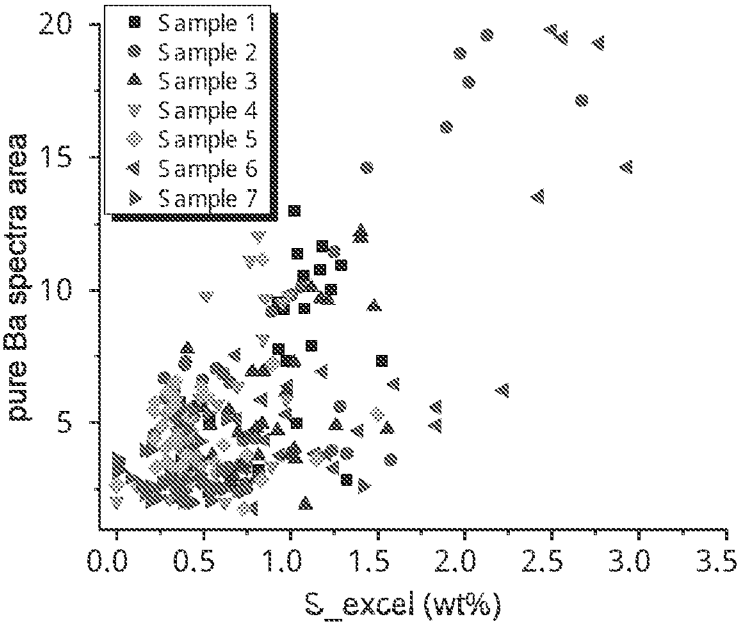

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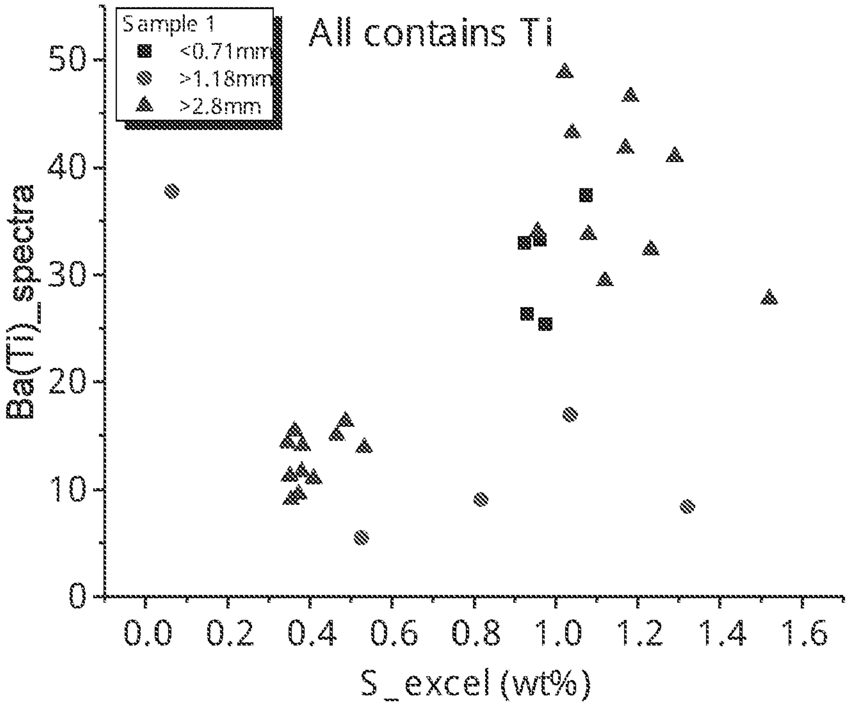

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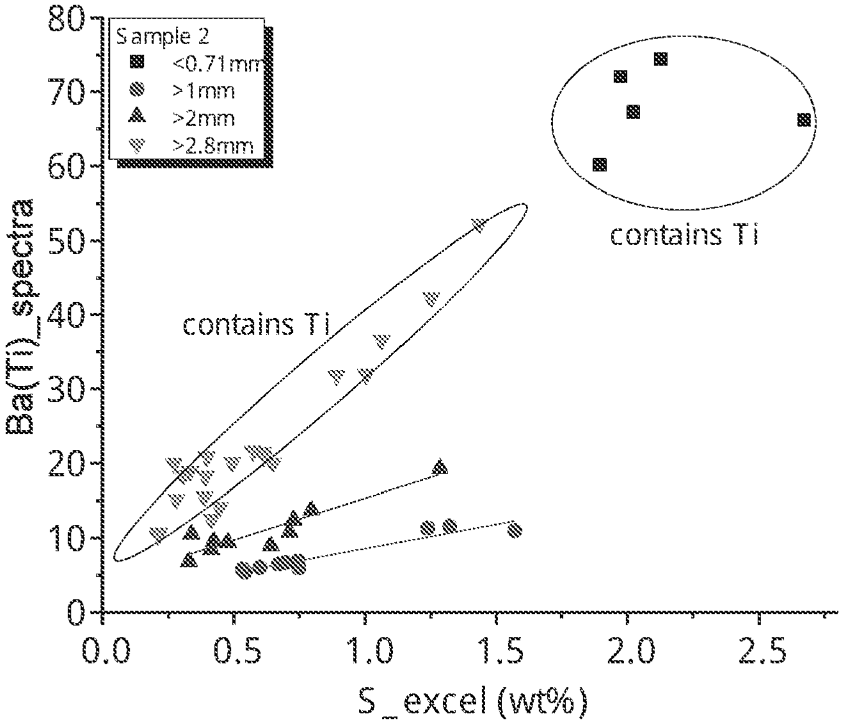

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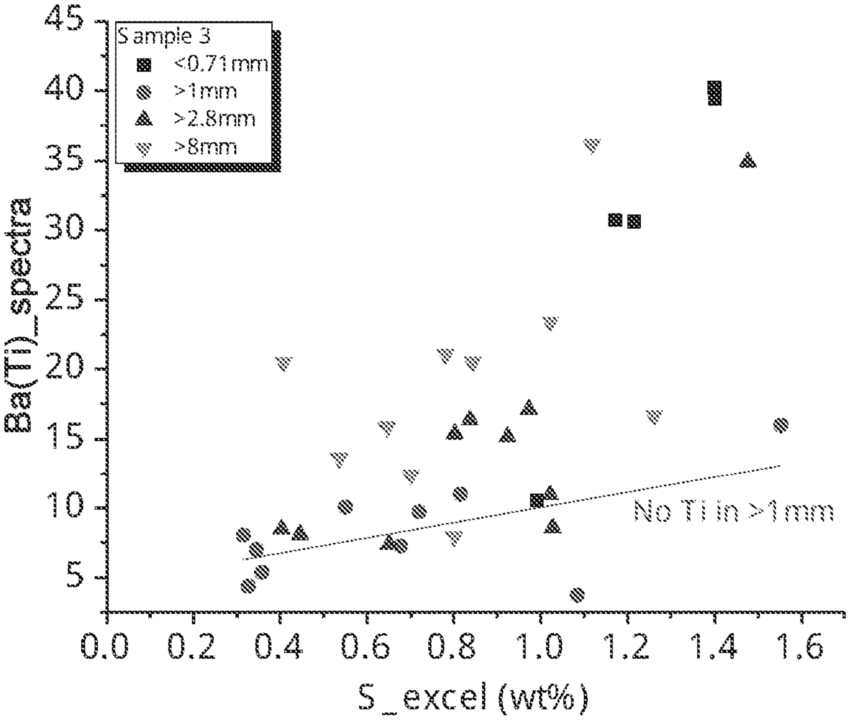

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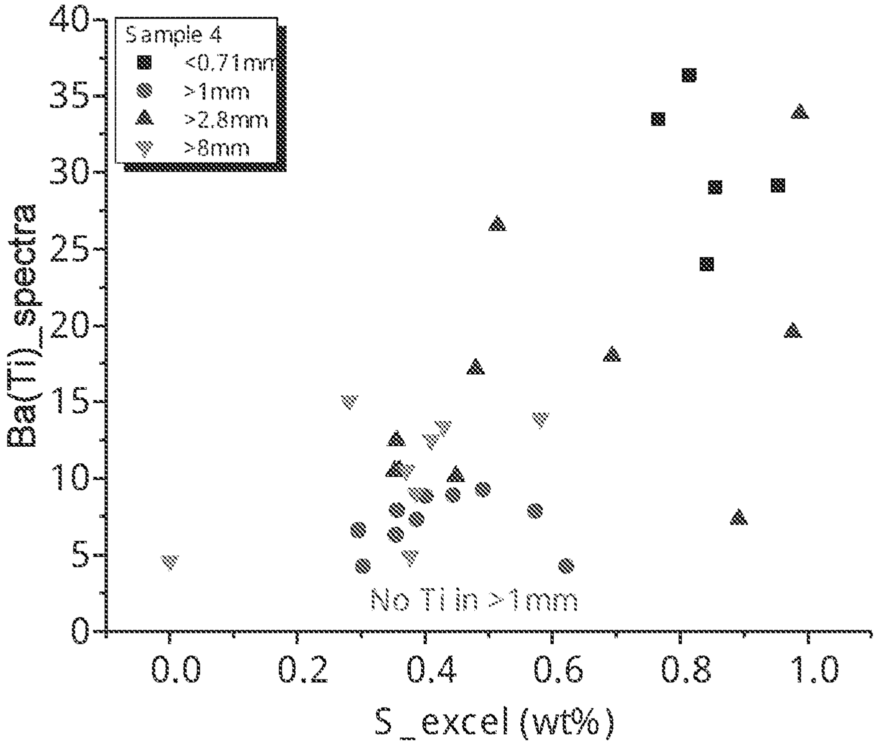

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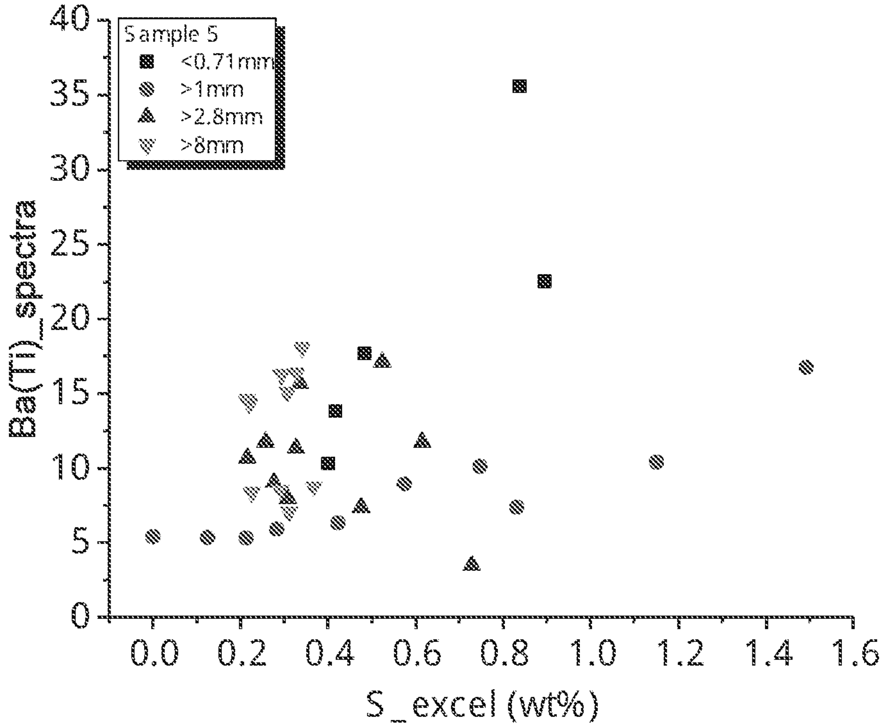

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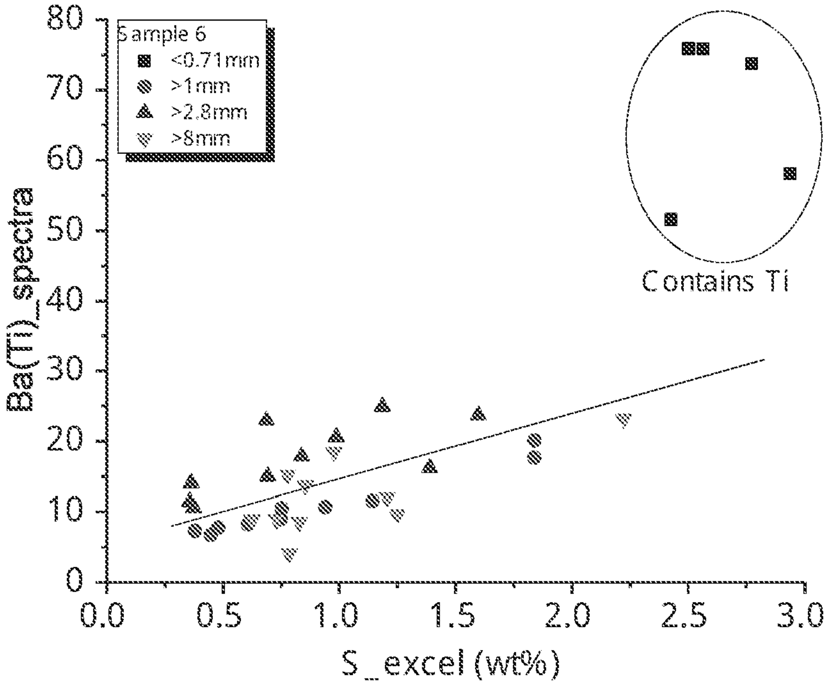

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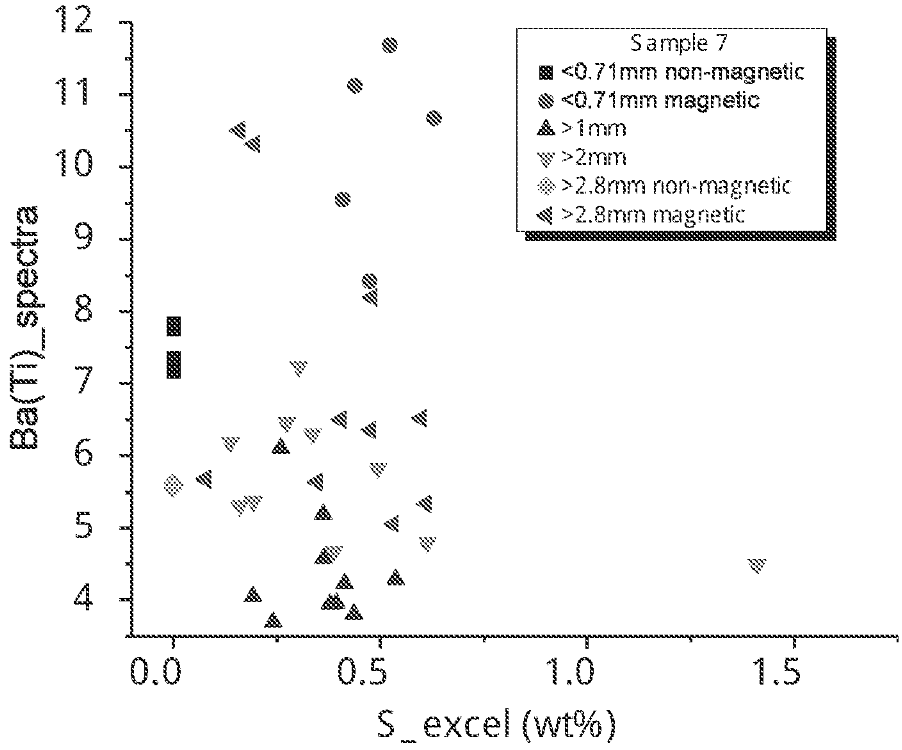

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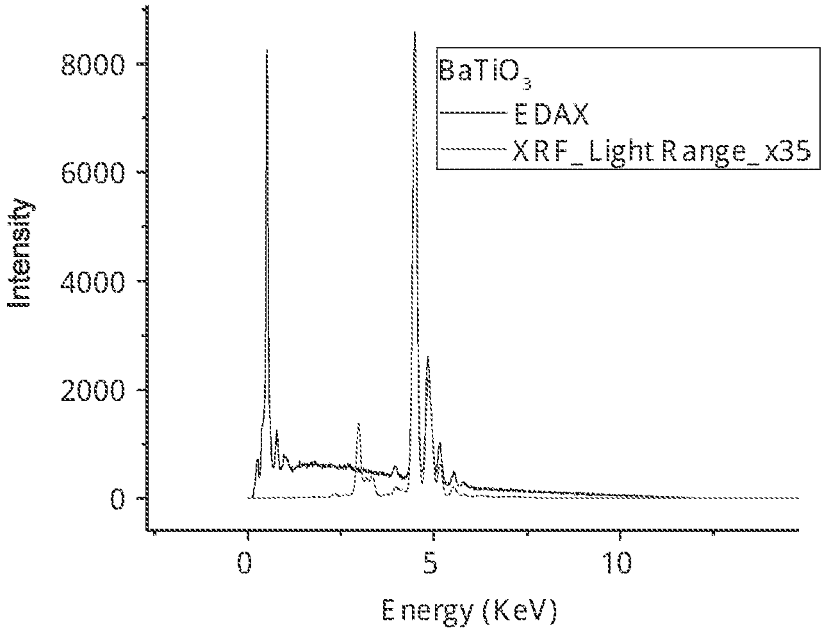
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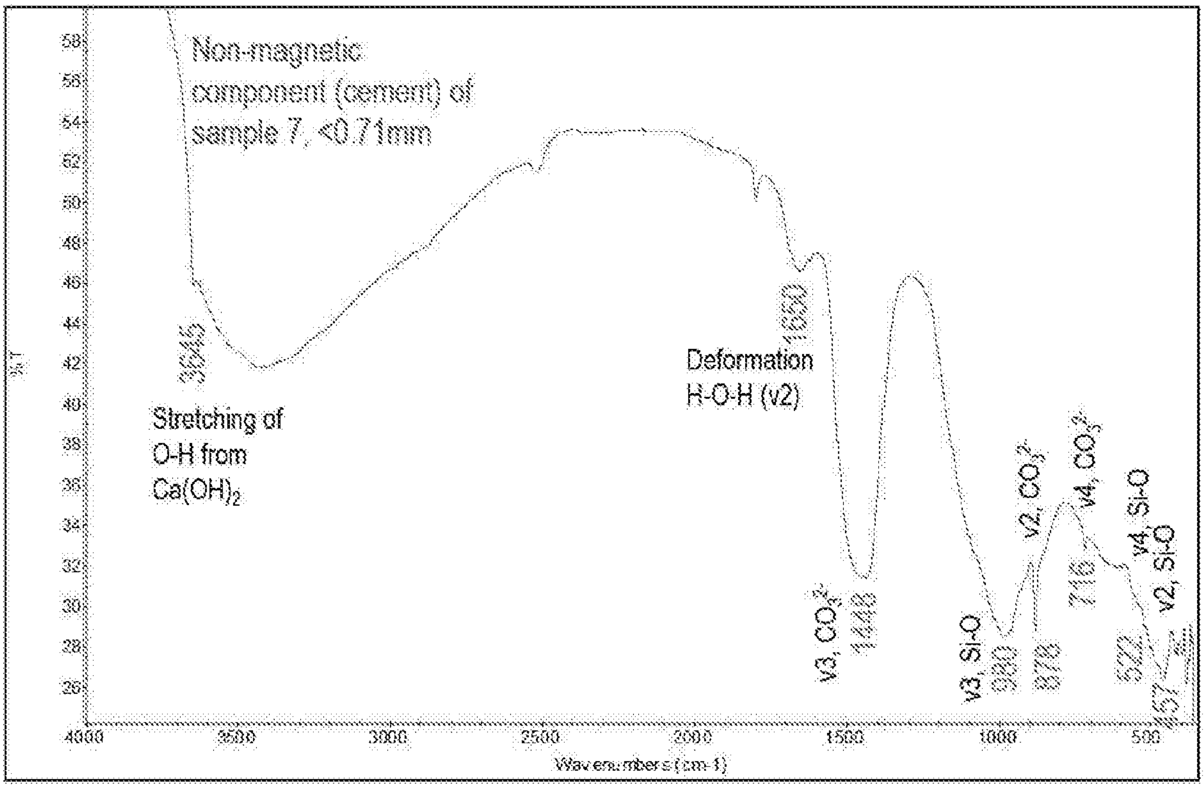
6000
4000
2000
0
0
5
10
Energy (KeV)
$BaTiO_3$
EDAX
XRF_Light Range_x35

Figure 52



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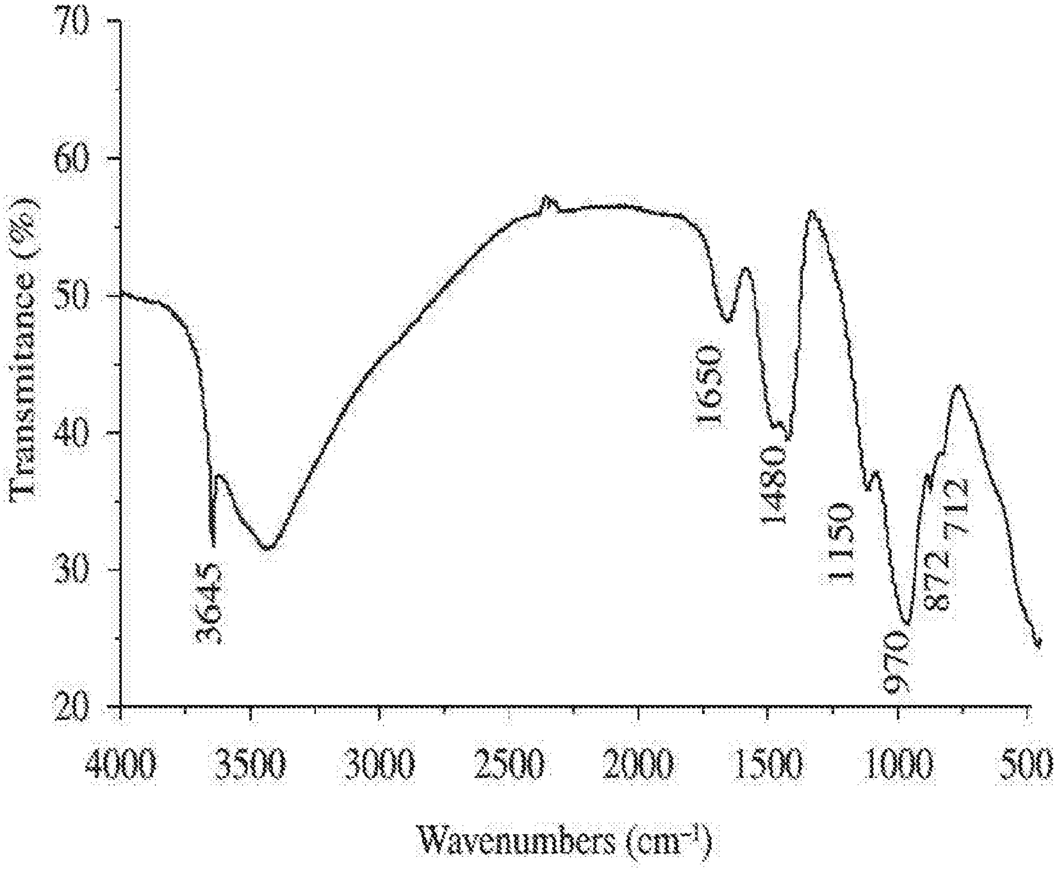

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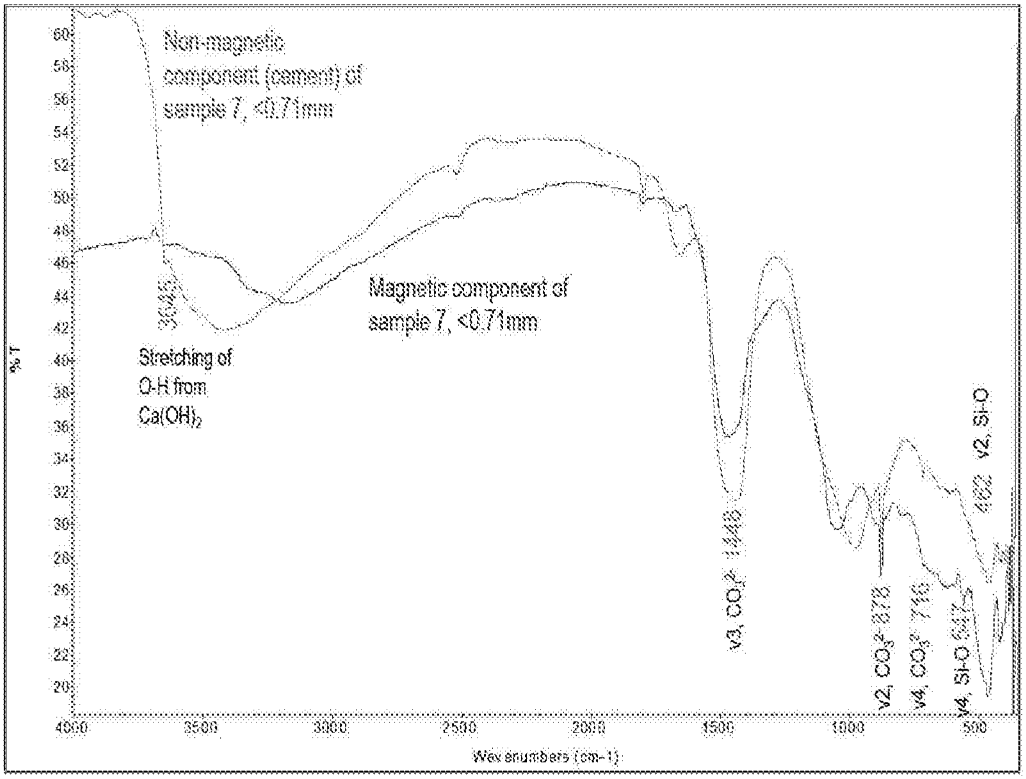

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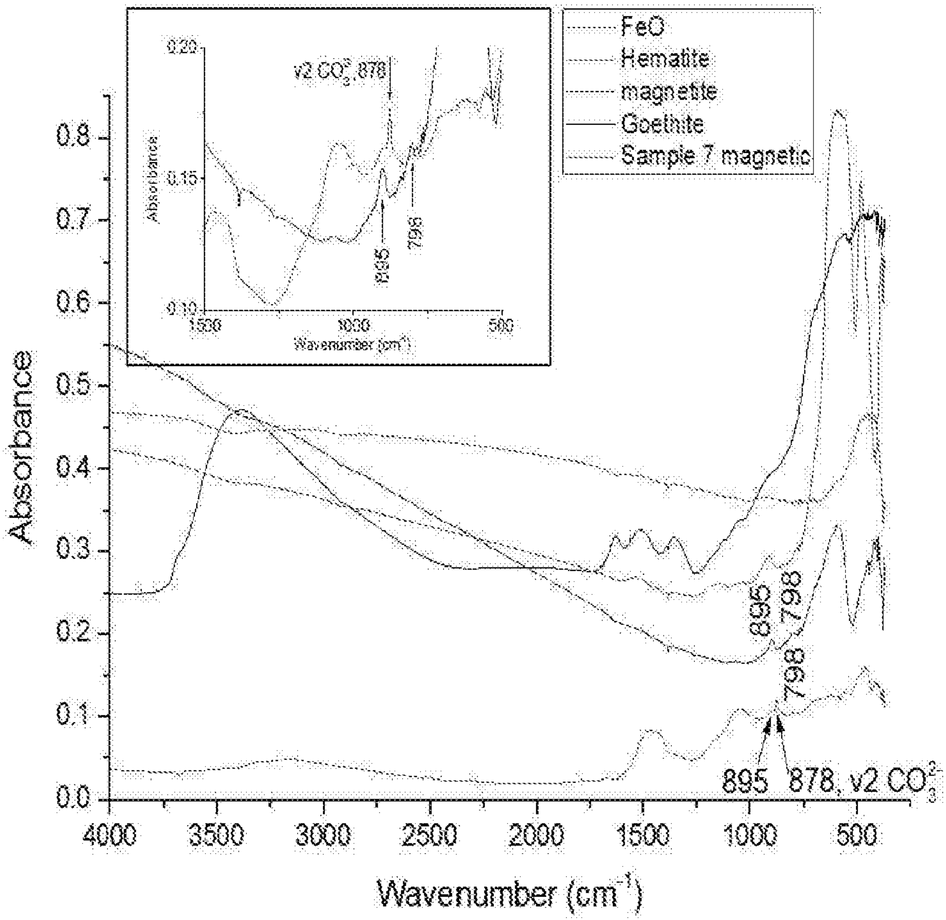

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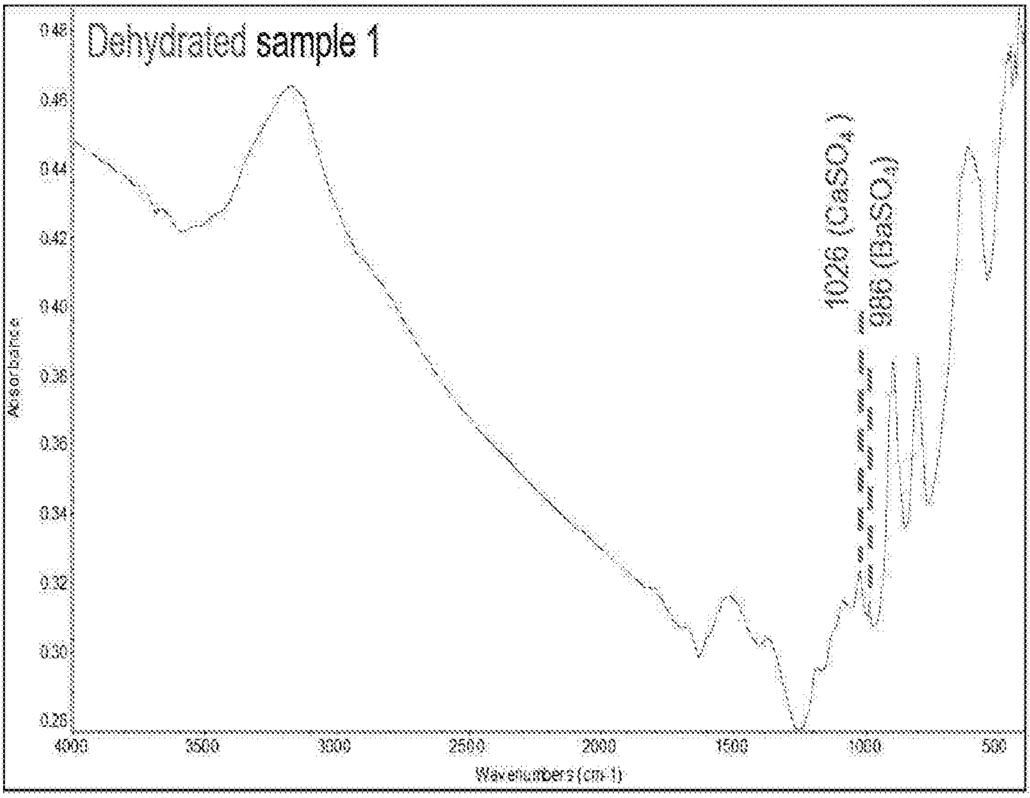

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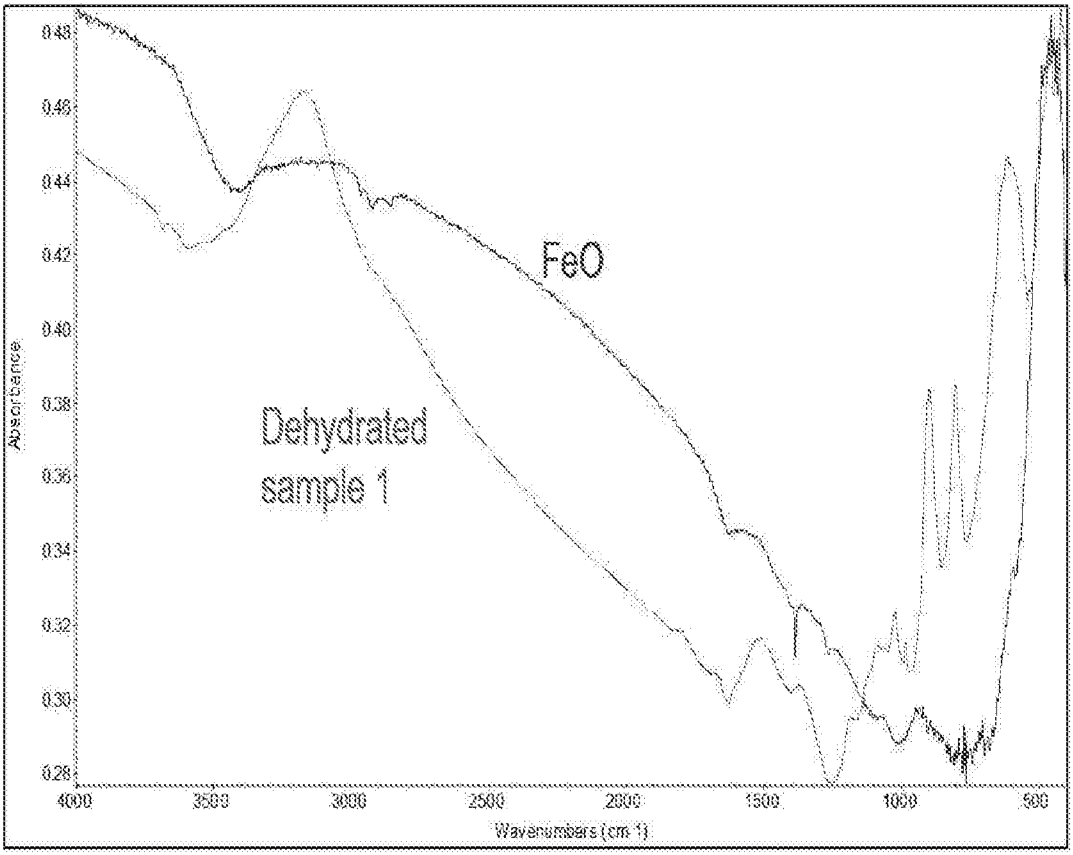

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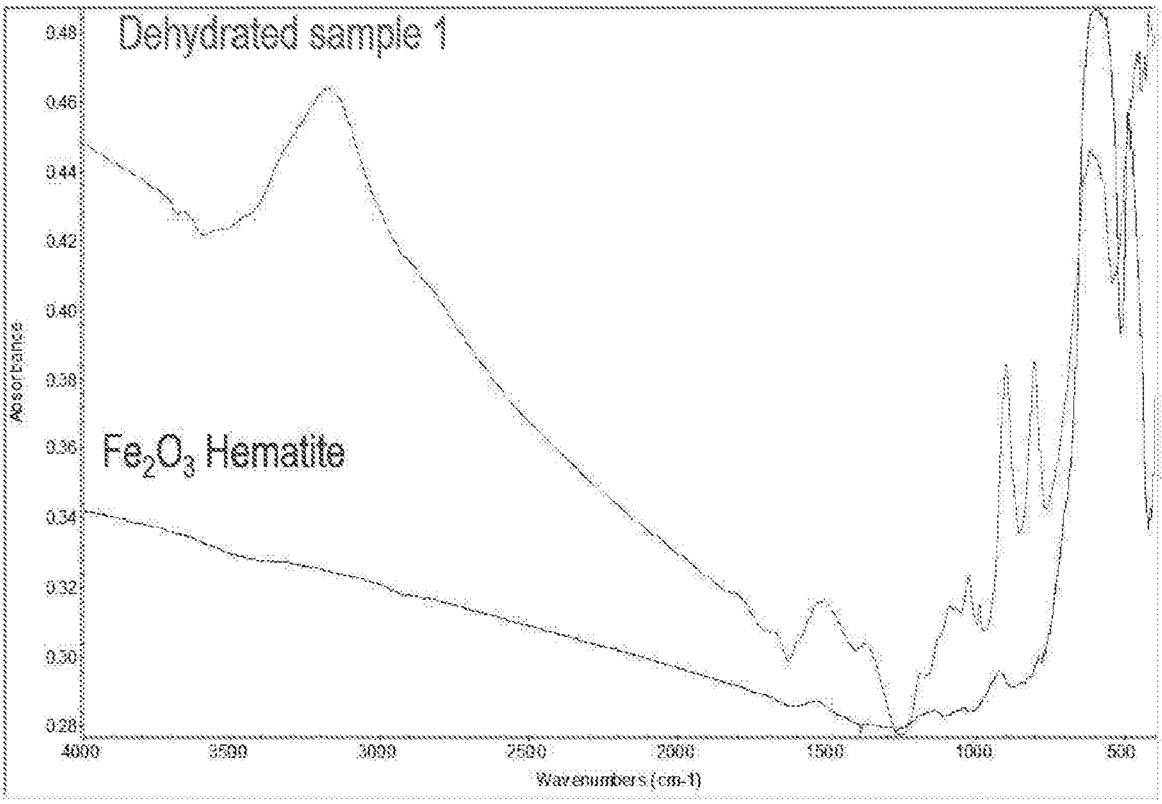

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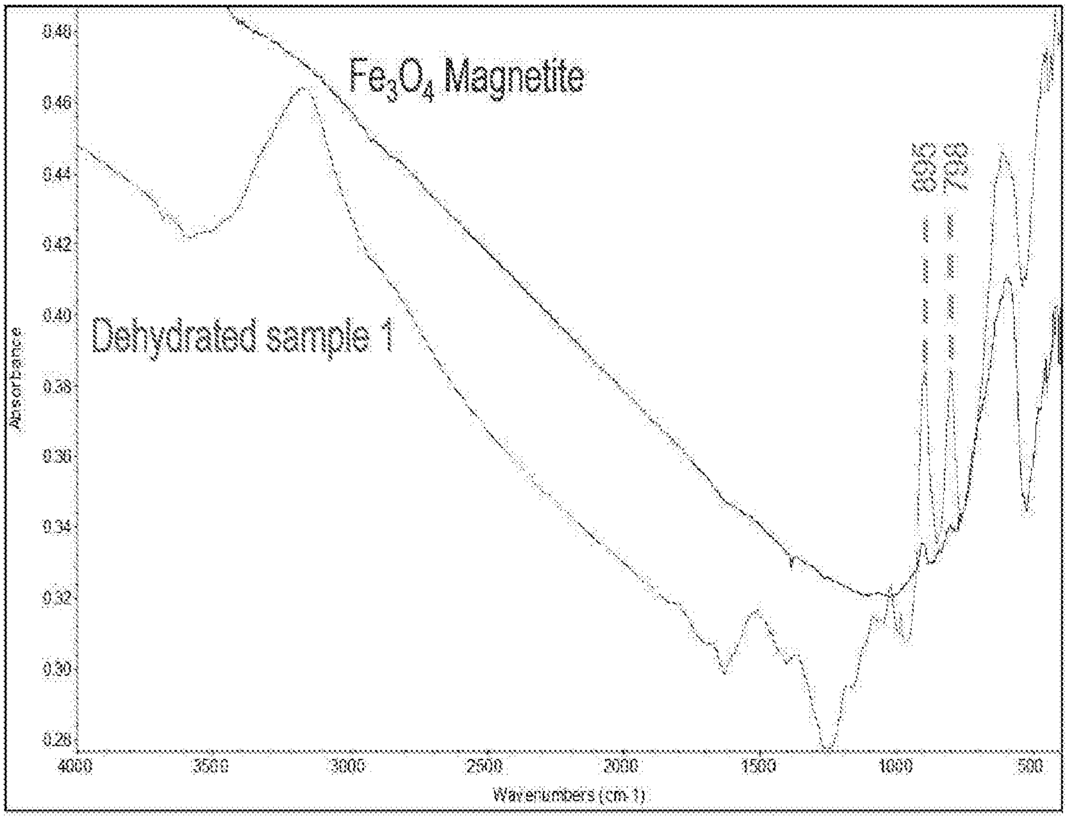

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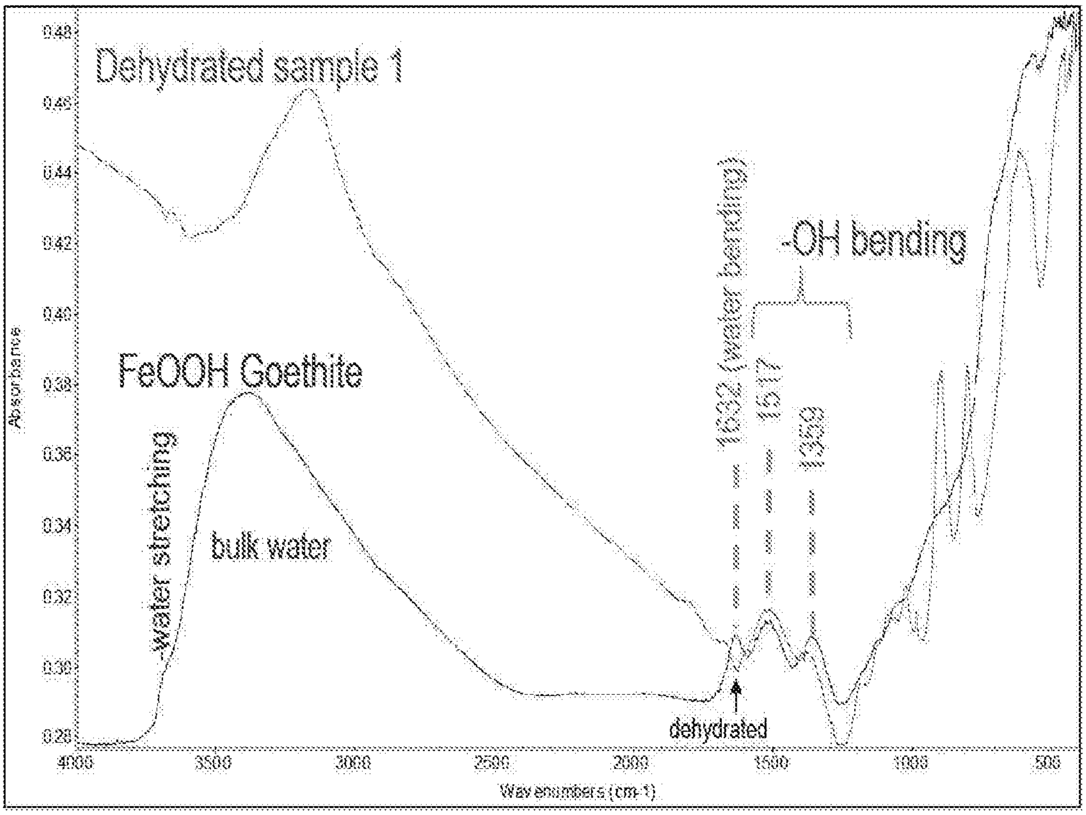

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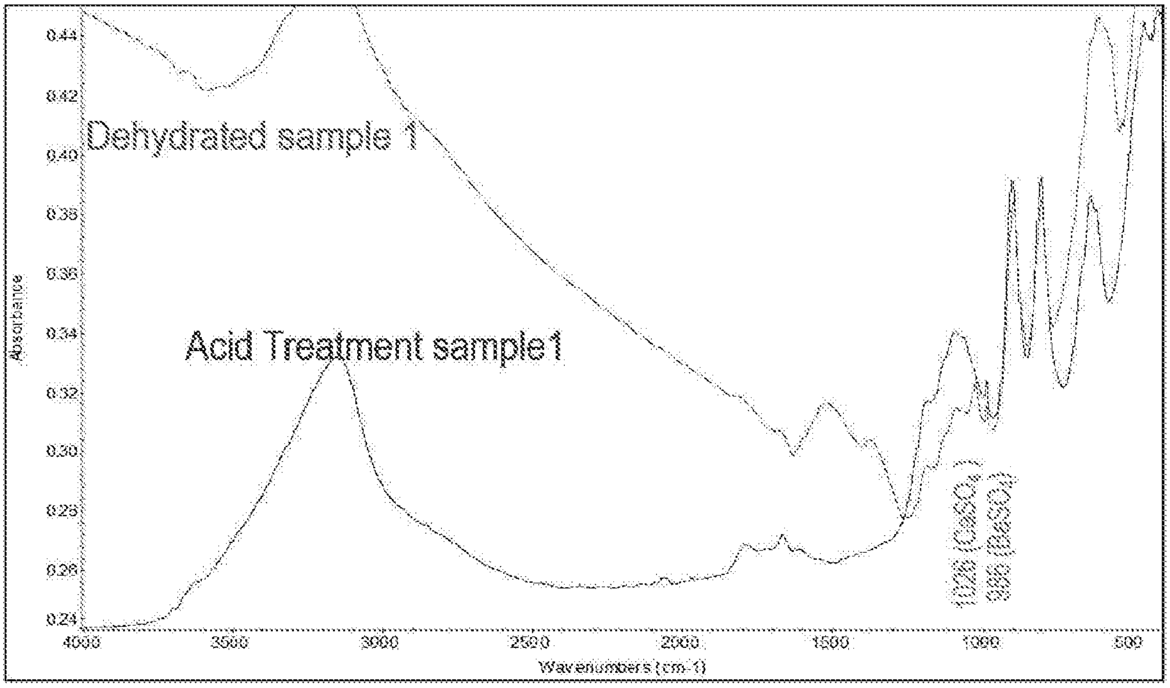

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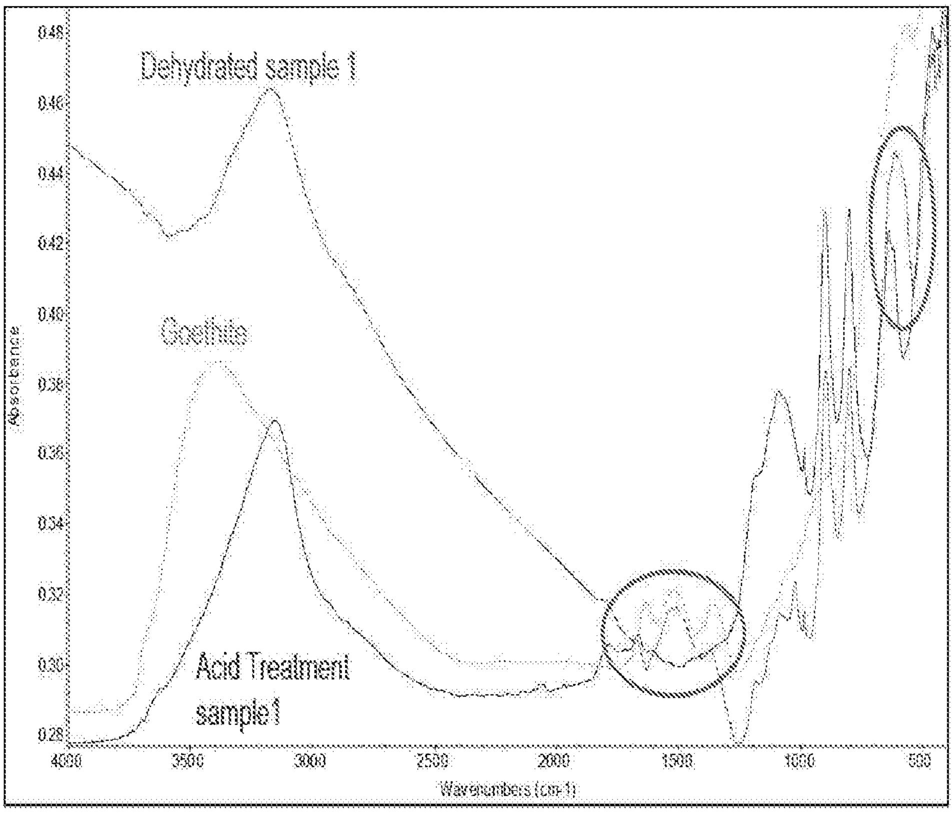

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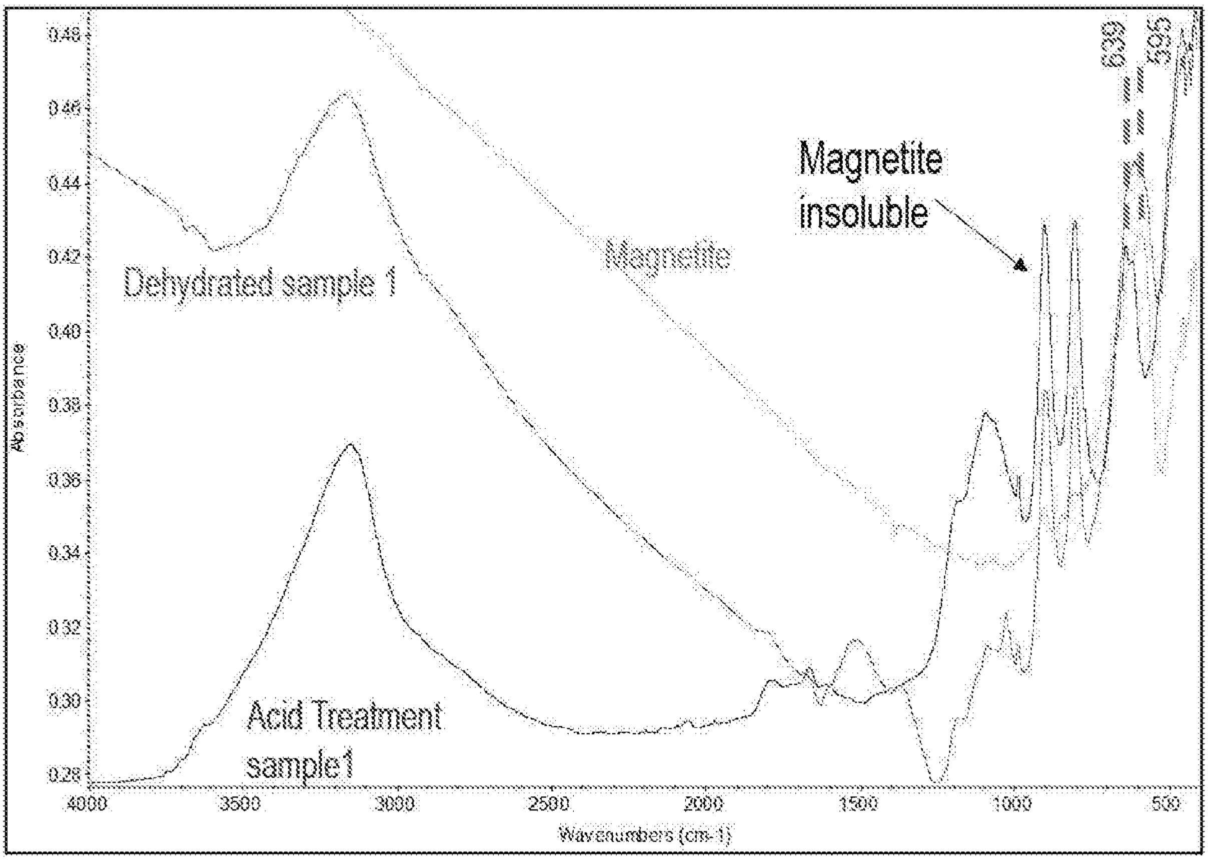

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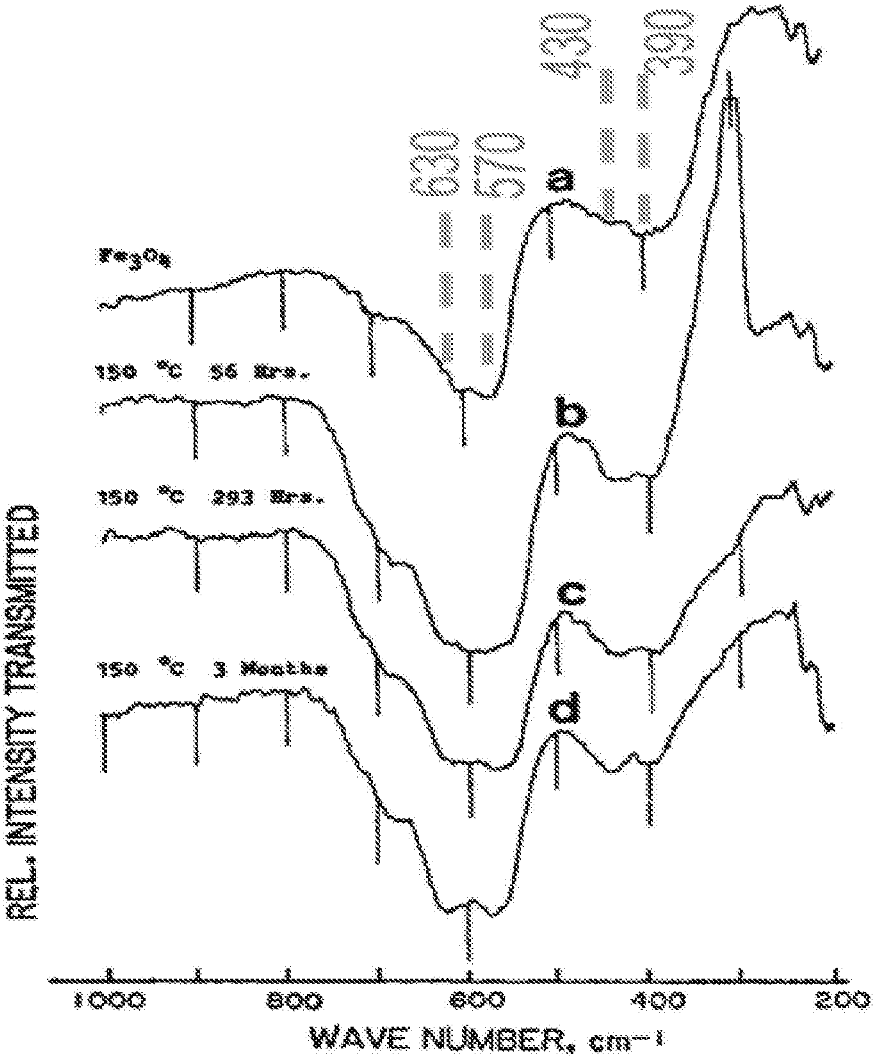


Figure 65

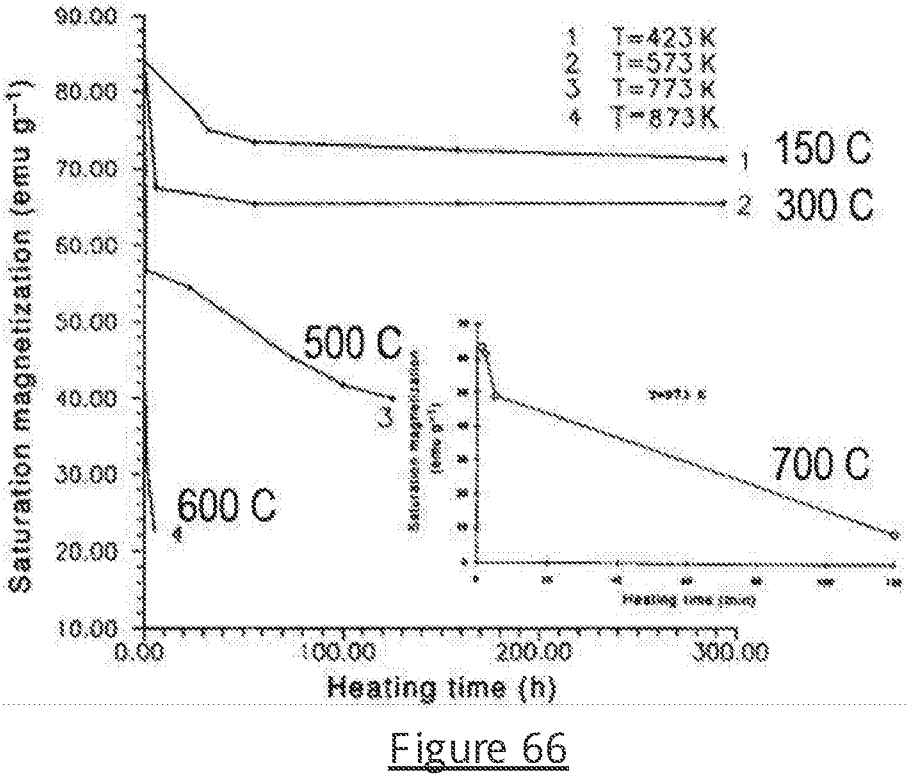


Figure 66

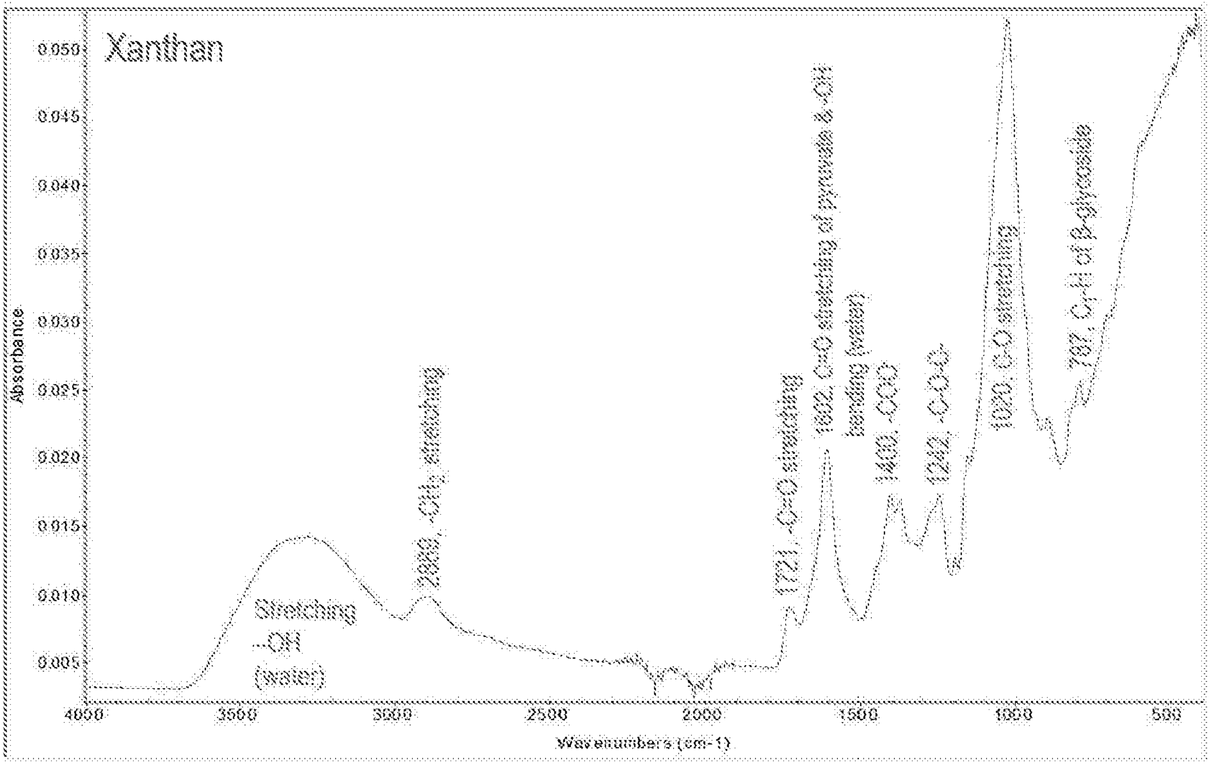


Figure 67

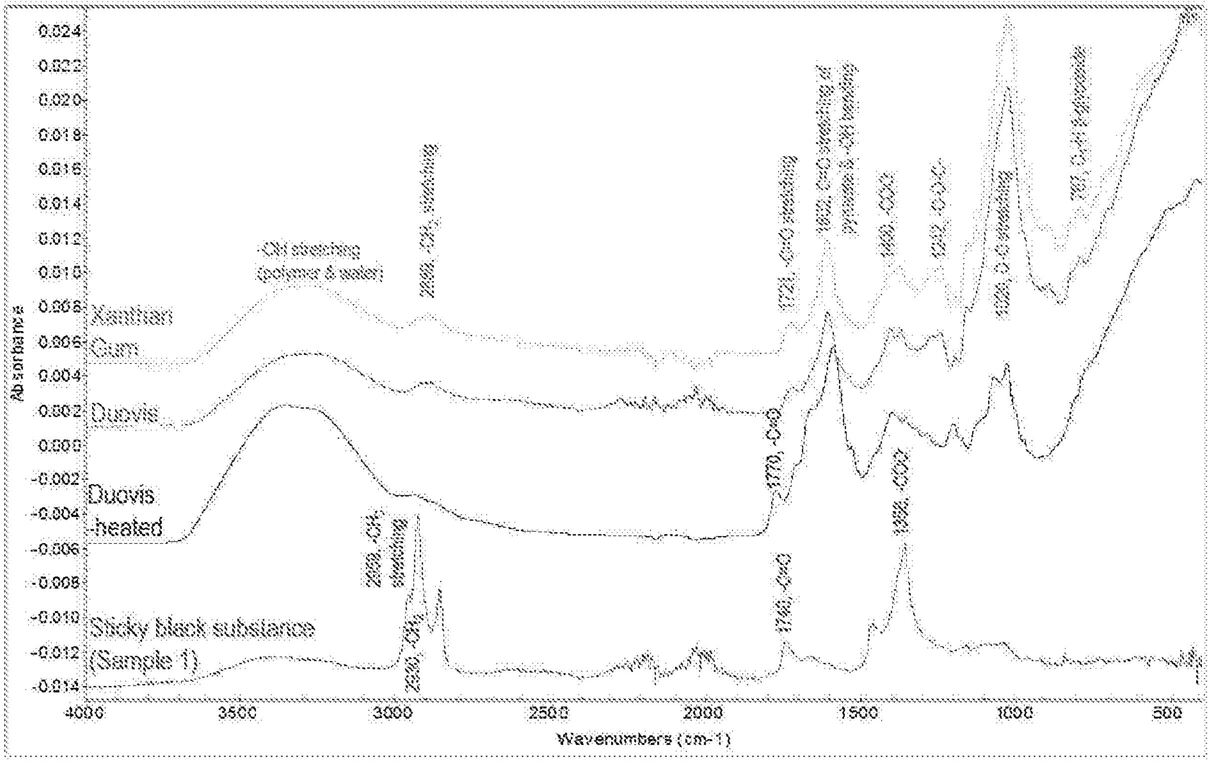


Figure 68

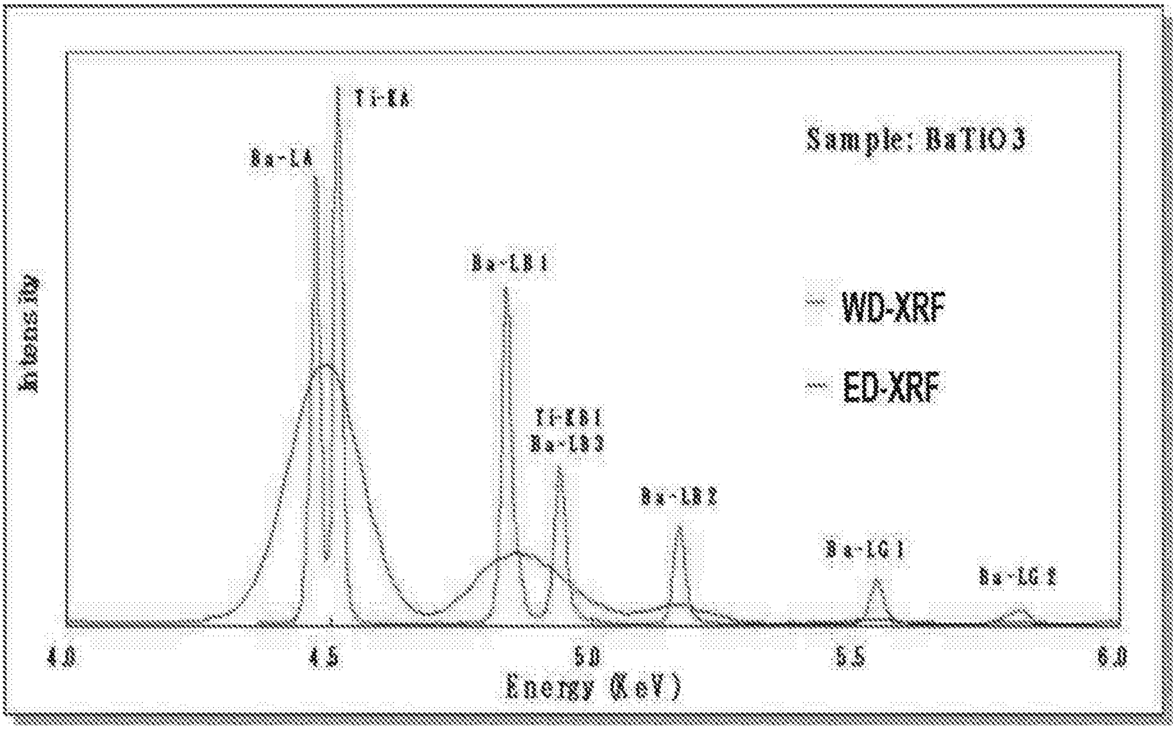


Figure 69

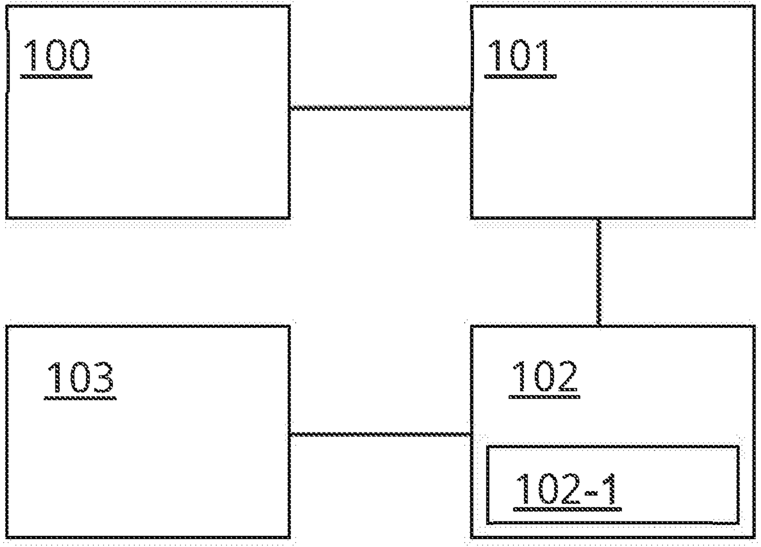


Figure 72

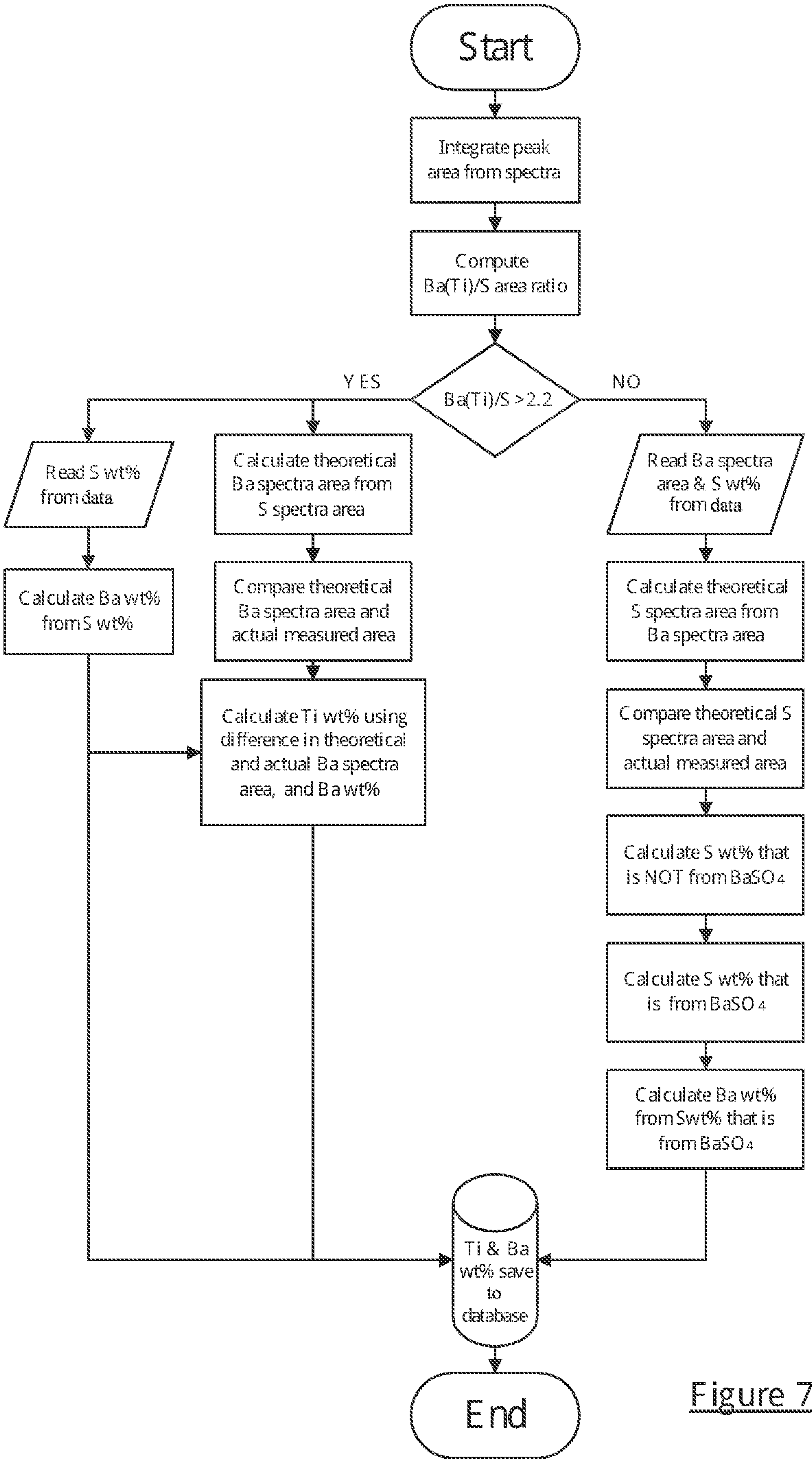

Start
Integrate peak area from spectra
Compute Ba(Ti)/S area ratio
Ba(Ti)/S >2.2
YES
NO
Read S wt% from data
Calculate Ba wt% from S wt%
Calculate theoretical Ba spectra area from S spectra area
Compare theoretical Ba spectra area and actual measured area
Calculate Ti wt% using difference in theoretical and actual Ba spectra area, and Ba wt%
Read Ba spectra area & S wt% from data
Calculate theoretical S spectra area from Ba spectra area
Compare theoretical S spectra area and actual measured area
Calculate S wt% that is NOT from BaSO4
Calculate S wt% that is from BaSO4
Calculate Ba wt% from Swt% that is from BaSO4
Ti & Ba wt% save to database
End

Figure 70

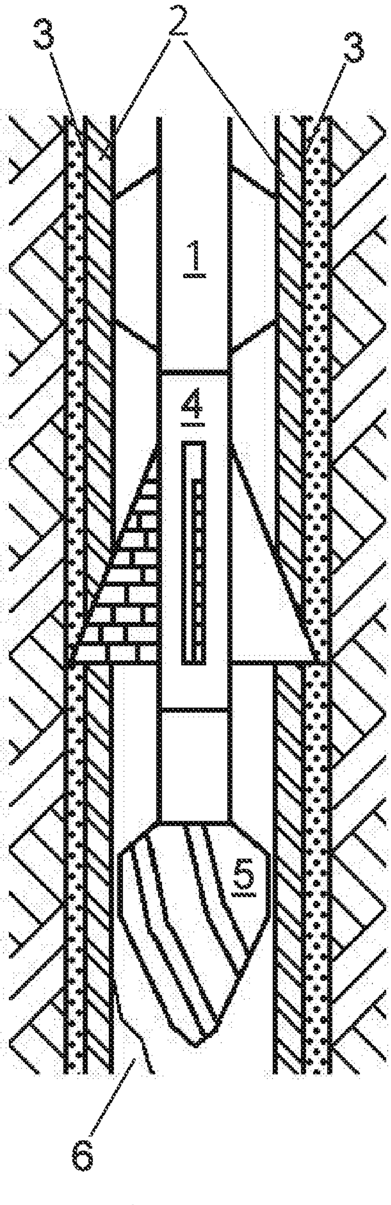


Figure 71

METHODS TO MONITOR THE EFFICIENCY OF CASING MILLING OPERATIONS

[0001]

BACKGROUND

[0002] Metal pipe, for example steel pipe, is used as casing in a wellbore (e.g. used in hydrocarbon production). The casing supports the wellbore against collapse due to pressure from the surrounding formation, and may prevent fluid (e.g., process fluid or natural fluids from the formation) from leaking into or out of the wellbore. Once placed in the wellbore, the casing is set in place using cement.

[0003] The thickness of the casing or cement may vary along the depth of the wellbore. Casing closer to the surface support the weight of lower casing, and is often a larger size than lower casing that may be hung as a liner. Casing is often formed from connected lengths of metal pipe, forming casing string, and the higher sections of the string may be thicker. Cement may be thicker deeper in the wellbore due to increased pressure from the formation.

[0004] There are operations in which there is a desire to remove some or all of a portion of the casing or cement. For example, in order to plug a well during a well abandonment process, it can be desired or even governmentally mandated that old cement around a removed section of casing be removed so that a new cement plug can be in contact with the surrounding rock to plug the well.

[0005] There may, of course, be other operations in which removal of some or all of casing or cement may be required or desired. This may include modification, repair, or reinforcement of the well, slot recovery, wellbore stimulation, or other downhole activities.

[0006] Removal of the casing is sometimes done through a cut-and-pull operation, although removal of both casing and cement is typically achieved using a casing milling operation. Milling operations in which metal is milled generate cutting debris known as swarf. This debris includes the material being removed; however, the tools used in the milling operation also wear down and the resulting debris intermingles with the cutting debris. Some of the debris may be transported to the surface in the drilling/milling fluid used in the milling process for cooling and, indeed, for the purpose of removing debris. At the surface, this debris may be removed from the fluid by filtration, for example. Debris may also gather at the bottom of a wellbore, stick to surfaces or to tools, or even wrap around tools or downhole components. Sufficient build-up of debris may cause a blockage, and debris may hinder fishing operations or further milling, such as when the debris builds up to block an intended direction of milling.

[0007] Removal of debris can be performed by adding scrapers to a downhole tool, which tool scrapes debris from a wellbore as the tool is lowered or raised. Such tools may gather and move debris upwards within a wellbore, or break debris apart. The fewer times that a milling tool is lowered into and retrieved from a wellbore during milling operations, the less time the tool is inactive overall and so the more efficient the milling process can be.

SUMMARY

[0008] Embodiments of the present disclosure provide a method of controlling wellbore casing milling. The illustrative method includes providing a first milling tool configured to mill a wellbore component and delivering a milling fluid to the milling tool. A first milling operation is performed with the first milling tool in relation to the wellbore component. Debris is collected from the wellbore and includes debris generated during the milling operation. At least one physico-chemical property of the collected debris is measured using a first measurement apparatus and a first condition associated with the first milling operation is determined based on the at least one physico-chemical property. A second stage of the milling process is devised based on the first condition, and a second milling operation in relation to the wellbore component is performed according to the second stage of the milling process.

[0009] The wellbore component can include wellbore casing, junk, or other tools. For instance, the wellbore component can include a whipstock or the milling operation can be a sidetracking operation. The stages of the milling process may include stages of a sidetracking process, and the first milling tool may be a sidetracking tool such as a lead mill.

[0010] In some embodiments, a physico-chemical property includes the size distribution of the debris.

[0011] Collecting debris from the wellbore may include collecting a mixture of the debris and a milling fluid from the wellbore. Further embodiments include separating the debris from the milling fluid and removing residual milling fluid from the debris. Example methods can include providing or using a filter, and separating the debris from the milling fluid may include using the filter to separate the debris from the milling fluid.

[0012] In the same or other embodiments, an absorption material may be used or provide. The absorption material can absorb milling fluid and thereby remove residual milling fluid from the debris. Example milling fluids include at least one inorganic additive, and in some embodiments each additive to the milling fluid is an inorganic additive. The milling fluid may include one or more of: a water-based bentonite suspension; a bentonite and mixed metal hydroxide suspension; a bentonite and mixed metal hydroxide suspension without any water-soluble polymer additives; one or more water-soluble polymer additives; one or more water-soluble polymer additives and one or more stabilizers configured to reduce thermo-oxidative degradation of the or each polymer additive; one or more water-soluble polymer additives and one or more stabilizers configured to reduce hydrolytic degradation of the or each polymer additive; an anti-oxidant; an oxygen scavenger; one or more sacrificial compounds which are prone to oxidation; a pH buffer, or combinations of the foregoing.

[0013] In some embodiments, a casing milling method includes mixing debris with a solvent to remove one or more contaminant components of the debris from a remainder of the debris. A solvent may be an organic solvent or mixture of organic solvents, and optionally includes a chlorinated hydrocarbon, a non-chlorinated solvent, a mutual solvent, or any combination thereof.

[0014] Additional example embodiments of casing milling methods include agitating the debris and solvent mixture and/or extracting one or more contaminants from a solvent. Measuring at least one physico-chemical property of collected debris can also include analysing one or more contaminants to determine one or more constituent parts. Analysing the one or more contaminants may include one or more of subjecting the one or more contaminants to infra-red spectroscopy or subjecting the one or more contaminants to x-ray fluorescence spectroscopy.

[0015] Determining a first condition associated with the milling operation based on the at least one physico-chemical property may include identifying a level of degradation of the milling fluid occurring in the wellbore in relation to the first milling operation. Devising a second stage of the milling process based on the first condition can include selecting a milling fluid based on the identified level of degradation and delivering the selected milling fluid to the first milling tool.

[0016] In further embodiments, measuring at least one physico-chemical property of the collected debris may include analysing the debris or a portion of the debris to determine one or more constituent parts. Analysing the debris or a portion of the debris may include subjecting the debris or the portion of the debris to at least one of: infra-red spectroscopy and x-ray fluorescence spectroscopy.

[0017] In some embodiments, a casing milling method includes comparing one or more constituent parts of debris to one or more materials used in the wellbore or the first milling tool. A milled material may be identified as the first condition based on the comparison. In some embodiments, the method includes determining a wear characteristic of the first cutting tool as the first condition based on the comparison and/or determining a temperature associated with the first milling operation as the first condition based on the comparison.

[0018] A second stage of a milling process may differ from the first milling process by one or more of a cutting speed, depth, or angle of the first cutting tool or by using a second milling tool that is different from the first milling tool. Example casing milling methods can also include providing a camera as at least part of a first measurement apparatus, and measuring at least one physico-chemical property of collected debris can include capturing one or more images of the debris and analysing one or more (and potentially each) captured image. Analysing captured images may include one or more of determining a debris size from the or each captured image or comparing the captured image with at least one stock image representative of debris associated with the first condition.

[0019] In some embodiments, the first condition may include a ratio of milled casing to cement a blockage, or a likely blockage of the wellbore by debris. Example methods also include categorizing a first milling operation according to at least one predetermined milling operation category, and determining the first condition can include determining the first condition based at least in part on the at least one predetermined milling operation category. Casing milling methods of the present disclosure are optionally performed at a single geographical location or well, and may be remotely or locally controlled.

[0020] Another aspect of the present disclosure includes methods for developing a milling fluid for use in a casing milling method, and includes creating a test facility having a temperature representative of a temperature in a wellbore during a milling operation. The test facility can include a cutting tool and casing or another wellbore material. In the method, a lubricant, coolant, or a combination thereof is introduced into the test facility and degradation of the lubricant, or coolant, or both is monitored. A milling fluid is then created having components based on the degradation of the lubricant or coolant.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Embodiments of the present disclosure are described, by way of example only, with reference to the accompanying drawings, in which:

[0022] FIG. 1 is a schematic diagram of a process according to some embodiments;

[0023] FIGS. 2–9 are photographs of debris samples;

[0024] FIG. 10 is a graph of the size distribution of the samples of debris;

[0025] FIGS. 11–15 are charts of X-ray fluorescence (XRF) results generated according to some embodiments;

[0026] FIGS. 16–23 are graphical representations of Mn/Fe vs (Mn+Fe) proportions generated according to some embodiments;

[0027] FIG. 24 is a photograph of a cutting tool used in some embodiments;

[0028] FIGS. 25–32 are charts showing XRF results generated according to some embodiments;

[0029] FIG. 33 is a chart of the XRF spectrum of a Barite powder;

[0030] FIGS. 34–40 are charts of XRF results generated according to some embodiments;

[0031] FIG. 41 is a graphical representation of a correlation of Ca spectra area with S weight %;

[0032] FIGS. 42 and 43 are graphical representations of a correlation of (Al+Si) with Ca, and (Al+Si) with S;

[0033] FIG. 44 is a graphical representation of a correlation between pure Ba spectra area and S weight %;

[0034] FIGS. 45–51 are graphical representations of a correlation of Ba (Ti) spectra area with S weight %;

[0035] FIG. 52 is a chart showing a comparison of Energy Dispersive X-ray (EDAX) and XRF measurement of $BaTiO_3$;

[0036] FIG. 53 is a chart showing a diffuse reflectance infra-red Fourier transform spectroscopy (DRIFTS) spectrum of non-magnetic components of a sample;

[0037] FIG. 54 is a chart showing an infra-red (IR) spectrum of cement;

[0038] FIG. 55 is a chart showing an IR-spectra comparing magnetic and non-magnetic components of a sample;

[0039] FIG. 56 is a chart showing an IR-spectra comparing the magnetic component of a sample to FeO, Hematite, Magnetite, and Goethite;

[0040] FIG. 57 is a chart showing a DRIFTS spectrum of a dehydrated sample;

[0041] FIGS. 58–61 are charts showing a comparison of DRIFTS spectrums of the sample of FIG. 57 to FeO, Hematite, Magnetite, and Goethite.

[0042] FIGS. 62–64 are charts showing DRIFTS spectra of a treated sample;

[0043] FIG. 65 is a chart showing infra-red spectra of heated magnetite for different periods of time;

[0044] FIG. 66 is a chart showing saturation magnetization data for magnetite heated at different temperatures for different periods of time;

[0045] FIG. 67 is a chart showing an example Attenuated Total Reflection (ATR) spectrum of xanthan gum;

[0046] FIG. 68 is a chart showing an example ATR spectrum of xanthan gum, a dispersible, non-clarified, high-molecular-weight biopolymer xanthan gum, thermally treated dispersible, non-clarified, high-molecular-weight biopolymer xanthan gum, and organic extract obtained from the sample of FIG. 57;

[0047] FIG. 69 is a chart showing interference between a Barium (La) line and a Ti (Ka) line;

[0048] FIG. 70 is a flow diagram of a process to calculate Ba and Ti weight %;

[0049] FIG. 71 is a schematic, cross-sectional view of a portion of a wellbore; and

[0050] FIG. 72 is a schematic system view of some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0051] Some embodiments of the present disclosure relate to methods of controlling wellbore casing milling, and in particular controlling wellbore casing milling by measuring a physico-chemical property of debris generated during a milling operation. An example milling operation includes an operation in which wellbore casing is milled. Milling casing may include a series of milling operations, and the process may be re-evaluated, updated, or modified at different stages during the milling process.

[0052] In some embodiments, milling the casing of a wellbore and controlling the ongoing milling process is based on characteristics of earlier milling. Example casing milling may occur during drilling of the wellbore (e.g., straight drilling, side tracking, directional drilling, etc.) or in the process of abandoning/decommissioning a wellbore.

[0053] In at least some embodiments, a milling operation of the present disclosure is more efficient than prior operations due to knowledge of characteristics of previously generated debris. For example, sizeable pieces of cement may be removed from a wellbore using strong scraping tools, whereas ferrous debris may be removed more efficiently using a magnet. Knowledge of the debris characteristics may also or alternatively improve the efficiency of a milling operation itself. A sample of debris containing cement may indicate that casing has been fully penetrated, for example, or indicate to an operator that a different tool may be better suited for an operation, to mill cement, or to vary one or more other aspects of the milling operation, such as the rotational speed of the milling tool, the angle (e.g., attack angle, rake angle, etc.) of the milling tool, or the like.

[0054] As will be appreciated from the description herein, the thickness of casing material may vary within a wellbore or the thickness of cement may vary within a wellbore. Therefore, the length of time taken to mill through casing or to mill through cement may be variable even within the same wellbore. As such, time and rate of penetration is not a reliable indicator of progress of the milling operation in many cases. Accordingly, information obtained from analysis of the debris generated from the milling operation may provide useful insight into the progress of the milling operation (which may, in turn, be used to control or modify the milling operation).

[0055] Accordingly, in some embodiments (and with reference to FIG. 71, for example), a milling tool 1 may be provided which is configured to mill a wellbore casing 2. The first milling tool 1 may be or include a casing mill. For instance, the illustrated milling tool 1 includes a section mill 4 and a lead mill 5, which can also be referred to as a taper mill. The section mill 4 may expand to cut the casing 2 during a section milling operation, while the lead mill 5 may be directed into the casing 2 by a whipstock 6 or other deflection tool. Of course, other milling tools may also be used. For instance, the first milling tool 1 may include a cement mill, a junk mill, a bridge plug mill, or the like. In some embodiments, the section mill 4 may be used to generate small cuttings.

[0056] Cutting tools, such as milling tools (including the first milling tool 1), may be made from a variety of materials, based upon a task to be performed. For instance, a cement mill may be used to cut steel. The first milling tool 1, including lead mill 5, may include a roller cone bit, including a mill-tooth bit or other cutting elements for cutting steel. The first milling tool 1, including any cutting elements, may have a carbide dressing for improved durability and hardness. References to a tool herein should be understood to apply additionally to tool parts such as drill bits, cutting elements, cutting knives, and the like.

[0057] In embodiments of the present disclosure, the first milling tool 1 is used to perform a first milling operation, which may be cutting away all or part of the casing 2. This may start at the ground surface at the top of the wellbore or start at a location within the wellbore. Cutting may generally occur starting at an internal surface of the wellbore and work radially outwardly; however, in some embodiments such as intercepting a well, milling may start radially outward and work radially inwardly.

[0058] In some embodiments, the first milling operation may be to initiate a sidetracking operation. This can include, for instance, using a section or casing mill to open a window around the diameter of the wellbore. The first milling operation may include removing cuttings created during the first milling operation. In other words, debris may be removed from the wellbore during the first milling operation, or as the final step of the first milling operation, for example.

[0059] The casing 2 can be formed from a material such as steel. As such, when milling casing 2, fragments of steel are cut away. Debris in a wellbore may therefore include steel fragments or swarf.

[0060] Debris in a wellbore may also include cement 3 that may or may not be even around the wellbore (shown as thicker on one side than the other in FIG. 71). In FIG. 71, the cement 3 used to set the casing 2 is at least partially cut way from the formation when cutting the casing 2. Cement 3 cut away from a higher section of a wellbore could gather in a lower section of the wellbore due to tumbling. If the first milling operation may take place in a section of a wellbore which is closer to the surface (i.e., reached earlier when tripping into the wellbore) than another section of a wellbore, debris may settle in that deeper section.

[0061] In some embodiments, the deeper section is shielded from tumbling debris by inserting a block (for example, a temporary packer) into the wellbore and further shielding may be provided by layering sand onto the block. Removal of the block, sand, and other materials at a later stage, having prevented debris tumbling from the higher section, may in itself lead to sand (or other debris) reaching a lower section of the wellbore.

[0062] Common debris found in a wellbore, other than milled cuttings formed from casing material 2 or from cement 3, includes metal cuttings (which may have been worn away from a milling tool 1) and small hardware (which may have been dropped accidentally into the wellbore by a worker or broken free from another downhole tool).

[0063] In some embodiments, therefore, debris is collected from the wellbore, including debris generated during the first milling operation. For instance, milling fluid maty be pumped through the milling tool 1 and may circulate back through the annulus of the wellbore toward the surface and carry debris. Accordingly, a debris collection apparatus 100 (see FIG. 72) may be provided to collect debris retrieved from the wellbore through fluid circulation, fishing operations, and the like. In some embodiments, the debris collection apparatus 100 includes a milling fluid delivery apparatus 101 that optionally includes a pump and/or pipework.

[0064] The milling fluid is circulated to remove cuttings from a wellbore in a so-called ‘hole-cleaning’ operation. A good milling fluid suspends debris for efficient removal. The milling fluid may be thixotropic (i.e. have increased viscosity when stationary), such that debris does not sink into the milling fluid even when the milling fluid is not in motion.

[0065] A particular milling fluid may be chosen for being non-harmful should, for example, the fluid mix with other functional drilling fluids or leak out into formation. Milling fluid may be chosen to limit corrosion. In high temperature embodiments, an optimal milling fluid would not break down at high temperatures found in the active milling region as breaking down may not efficiently transport the cuttings or may create a substance which attaches to milled cuttings and causes agglomeration and aggregation, which may lead to blockages.

[0066] The milling fluid may contain more than one component material. A property of a material in the milling fluid may change due to a chemical imbalance, or another change in conditions in the milling fluid. A material in the milling fluid may have an associated threshold temperature, above (or below) which a property of the material changes. For example, the material may undergo a phase transition above (or below) a threshold temperature. A component of the milling fluid undergoing a phase transition may lead to agglomeration in the milling fluid, generating debris and potentially blocking the wellbore.

[0067] Debris formed from a component of the milling fluid or a degradation product of the milling fluid may have different physico-chemical properties from debris generated from milling casing 2 (or milling though cement 3). The origin of the collected debris may not be known. For instance, debris resulting from casing 2 milling may be mixed-in with other debris which may have been collected from deeper in the wellbore compared with where the debris was originally created, or may have been collected from higher in the wellbore, having been carried upwards by becoming stuck to a tool or being carried by milling fluid, for example. In other words, collecting debris at a given depth would not guarantee that the debris had been generated at that depth, and collecting debris during a milling operation would not guarantee that the debris resulted solely from that milling operation.

[0068] In any event, in some embodiments, debris may be collected at the surface of the wellbore, having been carried by the milling fluid. This debris may be collected by the debris collection apparatus 100 in a debris collection method. The debris may be in the form of a mixture of different debris materials resulting from the milling operation.

[0069] The debris may be brought to the surface by a downhole tool which may be part of the debris collection apparatus 100. The first milling tool 1 or another milling tool may be adapted to carry debris, for example, through the provision of scrapers or electromagnets. A sample of collected debris may be taken during a first milling operation by the debris collection apparatus 100. For example, a sample of debris may be taken at the end of a first milling operation, representing a completed milling operation.

[0070] Debris may be collected in a series of collection operations by the debris collection apparatus 100 taking place during a first milling operation. Debris from two or more collection operations may be combined into a single collected sample, representative of the first milling operation. For example, debris may be collected before and after the first milling operation, and then a combination of debris may form a single sample.

[0071] Once collected, the debris may be processed by a debris processing apparatus 102. The processing may include a plurality of different processing steps which may be performed by the debris processing apparatus 102, for example. In other words, the debris processing apparatus 102 may be configured to perform a processing step as described herein, or even each processing step described herein. Example processing steps can include drying, washing in a solvent, dehydrating in an oven, treating with an acid, fractionating by size, fractionating by magnetic properties, analysis with a spectrometer, other such processes, or combinations of the foregoing.

[0072] In some embodiments, the processing includes the cleaning of a sample of debris. An example preliminary operation may include cleaning the debris using an absorbent towel, sheet, or material to remove unwanted dirt before subsequent analysis. In some embodiments, the preliminary cleaning operation may include removing dirt formed from degradation products, for example, from the debris. The dirt itself may be of interest in some embodiments, as discussed in more detail herein.

[0073] In some embodiments, processing of the debris includes measuring a physico-chemical property of the collected debris using a measurement apparatus 102-1 (of the debris processing apparatus 102). Measuring at least one physico-chemical property of the collected debris may include analysing the sample or a portion of the sample to determine one or more constituent parts. This process may be aided by the preliminary cleaning operation, which may remove contaminants from the debris (e.g. residues) that otherwise may cause the debris (e.g. particles in the debris) to aggregate or agglomerate. In at least some embodiments, the at least one physico-chemical property may be the elemental, chemical, or mineralogical composition of the debris. The at least one physico-chemical property may in the same or other embodiments include a size (e.g., the cross-section, volume, mass, mesh size, etc.) of one or more pieces of the collected debris, or of a sample of the collected debris. The size may be a mean size, a median size, a modal size, or a size range of the sample.

[0074] In some embodiments, the at least one physico-chemical property includes the size distribution of the debris. A size distribution plot or diagram may be used to quantify a sample having a range of sizes of debris. Where results of analysis show that a sample contains a wide range of sizes (e.g., from sand to sizeable chunks of cement), the sample may be size-fractionated. The new samples, created following size-fractionation, may then be analysed. In other words, a sample which is analysed may be a fraction of a collected sample. Accordingly, in some embodiments, processing of the debris includes separating the debris into two or more fractions based on the at least one physico-chemical property. The sample may be size-fractionated by eye, by a user, by using screens of different sizes, by automated machines, or in other suitable manners.

[0075] In some embodiments, the measurement apparatus 102-1 may include a sieve or filter operable to size-fractionate the debris. In some embodiments, the measurement apparatus 102-1 may include a settlement tank or another size-fractionating apparatus may be used. In some embodiments, separating debris includes producing successive oversize fractions. For example, a sample may be passed through a series of sieves of decreasing mesh size. A fraction may be weighed in order to obtain a quantitative size distribution, and the measurement apparatus 102-1 may include scales for this purpose.

[0076] The processing of the debris may include the separation of the sample into a magnetic and a non-magnetic fraction – for example, using a permanent magnet, or an electromagnet of the debris processing apparatus 102 (e.g. of the measurement apparatus 102-1).

[0077] As the casing 2 may be made from steel, casing 2 debris may be separable from cement 3 by using suitable separation techniques. For instance, a magnetic separation process with the magnet or electromagnet is an example of magnetic separation equipment of the measurement apparatus 102-1 of the debris processing apparatus 102. However, a tool 1 (such as the section mill 4 or lead mill 5 of the first milling tool 1) may also be formed at least partially from a ferrous material and so not separable from steel casing 2 debris using the magnetic separation equipment. In some instances, casing 2 material and a material of the tool 1 may have a different magnetic properties, and magnetic separation equipment may be used to separate these materials.

[0078] Magnetic attraction force within a wellbore may increase the likelihood of blockages. Collecting and analysing debris as in the present method may be used to analyse ferromagnetic behaviour in debris.

[0079] In some embodiments, for instance, processing of the sample may include infra-red (IR) spectroscopy and the debris processing apparatus 102 (and, in particular, the measurement apparatus 102-1, for example) may, therefore, include infra-red spectroscopy equipment. The infra-red spectroscopy may use diffuse reflectance infra-red Fourier transform spectroscopy (DRIFTS).

[0080] In some embodiments, a non-magnetic fraction may be analysed using infra-red spectroscopy on debris that previously was subjected to magnetic separation processes. As any ferrous casing material would have been removed when separating magnetic and non-magnetic fractions, the remaining non-magnetic material may be analysed to identify cement 3, sand, formation, elastomers, composite materials, or any other constituent.

[0081] A spectrum resulting from a non-magnetic fraction may be compared with a stock spectrum, for example the spectrum for the cement used to hold the casing 2 in place. The degree of similarity between the spectra from the fraction and standard cement (e.g., Portland cement) would indicate that the sample contains a given percentage cement 3. For example, identical spectra would indicate that the sample is a sample of cement 3. Based on a sample representative of a first milling operation, a percentage cement sample would indicate that the milling tool 1 had milled through cement 3 in the first milling operation. Similarly, the elemental composition of a particular casing 2 material may be given by the casing manufacturer, or may be otherwise known. Therefore, debris which is formed from casing 2 may be identified using spectroscopy and comparisons to known spectrum in some embodiments.

[0082] Accordingly, in some embodiments, infra-red spectroscopy equipment may be used to generate a debris spectrum (which may be a spectrum of a sample or a fraction of a sample of debris). The debris spectrum may be compared to one or more stock spectra to determine one or more components present in the debris subjected to the infra-red spectroscopy. In some embodiments, a magnetic fraction (e.g., containing casing and casing oxidation products), may be analysed using infra-red spectroscopy such as DRIFTS.

[0083] In some embodiments, a fraction of a sample may be separated into one or more further fractions, for instance by repeating the previous separation methods, or by applying a different method to separate the sample based on a different physico-chemical property. Accordingly, in some embodiments, the debris processing apparatus 102 (and, in particular, the measurement apparatus 102-1, for example) may include fractionating equipment to separate the debris into one or more further fractions.

[0084] In some embodiments, a camera may be provided as part of the debris measurement apparatus 102-1 (and so part of the debris processing apparatus 102). Measuring at least one physico-chemical property of the collected debris may include capturing an image of the debris using the camera and analysing the captured image. Analysing the captured image may include determining absolute or relative size (i.e. sizes of individual pieces of debris, or an average size) from the captured image. The captured image may be compared with at least one stock image, for example. In some embodiments, a neural network is trained with multiple stock images to recognize sizes, shapes, appearance, or other visual characteristics of debris to identify the debris. In some embodiments, several images of the debris may be captured. The images of collected debris may be compared with one another, or with the stock image or images. Image analysis techniques may include transformation, such as the Fast Fourier Transform (FFT) to analyse the captured image or images.

[0085] Of course, where the physico-chemical property is not a property that is easily analysed visually (e.g., weight, mineralogical composition, elemental composition, etc.), other analysis methods (for example, DRIFTS as discussed herein) may be more suitable alternative or additional analysis methods.

[0086] The use of infra-red spectroscopy has already been described. Some embodiments may additionally or alternatively include other spectroscopy equipment such as x-ray fluorescence spectroscopy equipment and the methods of some embodiments may likewise include other forms of spectroscopy such as X-ray fluorescence spectroscopy (this equipment may form part of the debris measurement apparatus 102-1 and/or the debris processing apparatus 102). Such spectroscopy operations on the debris, in a combination or individually, allowing distinguishing between constituents of the debris and separation based on elemental composition.

[0087] X-ray fluorescence spectroscopy may be used in some embodiments to measure the elemental composition of a particular size fraction of the debris or of the debris as a whole. X-ray fluorescence (XRF) may be performed using a hand-held XRF device or a bench-top XRF device, for example. One or more XRF devices may be used in performing analysis at the rig-site, laboratory, repair center, or other location. As mentioned herein, a XRF device may form part of the debris processing apparatus 102 and, in particular, part of the measurement apparatus 102-1, for example.

[0088] Infra-red spectroscopy may be used in some embodiments to determine the nature of casing or tool oxidation products. Again, the spectroscopy tool implemented may be appropriate for use at a rig-site, laboratory, repair centre, or may form part of the debris processing apparatus 102 and, in particular, the measurement apparatus 102-1, for example.

[0089] The use of rig-site equipment may be generally referred to as the use of on-site equipment and may facilitate the monitoring of the progress of a milling operation in real-time (or substantially real-time, i.e. before the milling operation is complete). Analysis at the rig-site can lead to real-time improvements to the milling process due to modification of the milling process in view of the analysis results.

[0090] As will be appreciated, in some embodiments, there may be provided feedback for the milling operation from the debris processing operation (and debris processing apparatus 102). This feedback may be used, in embodiments, to determine one or more characteristics of the milling operation and this may, in turn, allow the milling operation to be modified in light of the one or more characteristics.

[0091] For instance, if the debris is dominated by elements originating from the casing 2 material, this may be indicative of successful milling of the casing 2. In an example of steps of the method, following the first milling operation, the removed debris is analysed and it is found to contain steel cuttings and an overall absence of cement materials. This indicates that the first milling operation milled casing 2, and did not break through to mill cement 3 or barely broke into the cement 3. For instance, this may be useful in an initial cut-out stage to cut radially through the casing 2 before face milling the casing 2 (and optionally also face milling some cement 3). For instance, a next stage of the milling process (for example, a second milling operation) may be performed based on the cement 3 not yet having been broken or having not been significantly broken. For example, a different tool 1 may be chosen which is suitable for milling through cement 3, different milling parameters may be used (e.g., adding weight or moving the milling tool uphole or downhole to perform face milling), milling may continue for a longer period of time, or milling may be undertaken in a different location, at a different rotational speed, at a different weight-on-mill, at a different cutting angle (e.g., using cutting elements of a different attack or rake angle), or the like. Thus, some embodiments of the present disclosure may be used to identify when a casing milling operation transitions into milling-out cement 3 (and in a similar manner determine when a milling operation transitions into milling out formation, or transitions from milling a bridge-plug to milling casing).

[0092] In some cases, it may be undesirable to mill cement 3. As such, the first milling operation may be performed (or may be repeated) until cement 3 is identified in the sample, and then may be completed. Collecting a sample including more cement 3 than casing could indicate that the casing has been milled through, and that the milling tool has reached the cement 3, for example. In some operations, however, there is also a desire to remove old cement 3 and milling would be continued (perhaps in a second milling operation) to remove old cement 3. In some embodiments, a ratio of milled casing 2 to cement

3 may be used to determine when to end the first milling operation. In such an embodiment, a first condition associated with the first milling operation (e.g., status of casing milling) is determined, based on the physico-chemical property of the returned debris.

[0093] In embodiments in which debris analysis is performed using image processing (e.g. using one or more images captured by the camera), the first condition may be represented in a first image (for example a stock image), for comparison with an image generated for collected debris in order to determine whether the first condition is satisfied, or not. Additional first conditions can include a temperature (e.g. a milling site temperature), which may be calculated based on the degradation products identified in the collected debris, as described herein. The first condition may be the size of a collected sample or the absence of a sample (e.g., collection operations may not retrieve any debris from a given region of the wellbore, implying that the wellbore is cleaned in that region or debris is blocking the wellbore in that region, for example).

[0094] In some embodiments, a milling method further includes comparing the one or more constituent parts of the debris to one or more materials used in the wellbore or first milling tool 1. The method may further include identifying the presence of a particular material, or an amount of a particular material, as the first condition based on the comparison. For instance, the first condition may be that a sample contains more than a given percentage of a material found in tool 1.

[0095] A method of the present disclosure may further or alternatively include determining a wear characteristic of the first cutting tool 1 as the first condition based on the comparison. For instance, the presence of a material forming the first cutting tool 1 in the collected debris may indicate how much wear or damage the first cutting tool 1 has undergone at the time of collecting the debris. This may indicate the need to replace the cutting elements of the tool, replace a cutting knife or blade, change to a different cutting tool 1, and the like.

[0096] A cutting tool 1 may be formed to define a housing/body and one or more cutter blades/knives/blocks (collectively blades). The body and the blades may be formed from different materials, and so may have different elemental compositions. Observing the difference in content of elements associated with the body and the cutter blades in a sample may allow tracking of wear and damage of a tool 1, in as much detail as whether the body or the cutter blades are wearing more quickly, and the like. This may be used in developing improved cutting tools 1, for example. Accordingly, analysis as described herein may be used in milling tool 1 or other cutting tool testing.

[0097] Embodiments of the present disclosure may further include determining a temperature associated with the first milling operation as the first condition based on the comparison. For example, knowing that the temperature in the region of an operational cutting tool 1 (the cutting zone or milling site) exceeds a given temperature may indicate that a different tool 1 should be used, such as a tool 1 which has a higher resistance to high temperatures. The temperature, or a range of temperatures, of the wellbore during the first milling operation may also be determined. In some embodiments, temperatures are above 200 °C in the cutting zone.

[0098] The temperature history of a wellbore (i.e. whether the temperature has changed, or how the temperature has changed) may be determined. The temperature during each collection operation, for example, may be calculated and multiple temperatures may be collated. Temperature history from the wellbore may be used to predict the lifetime of a cutting tool 1, based on the properties of the cutting tool 1 material. The cutting zone temperature may be determined in any suitable way, such as based on the elemental composition of the sample, by identifying that phase transitions and the like have occurred.

[0099] Debris may include casing corrosion products (i.e., materials formed through corrosion of the casing) and analysis may include chemical analysis of casing corrosion products. In some embodiments, casing 2 materials experiencing high temperatures of 200 °C during milling may experience metal oxidation or phase transitions. DRIFTS or other spectroscopy methods and equipment may be used to investigate a sample containing casing material (i.e. milled cuttings from the casing 2) in this respect (e.g. in terms of predominant iron oxides in the debris).

[0100] By way of example, a spectrum showing the elemental composition of the debris may be obtained. This spectrum can be compared with a spectrum having elemental peaks matching elements which the debris is predicted to contain, or elements which a previous sample of the debris has contained. The debris may be known to contain casing material, following magnetic fractioning. In some embodiments, a DRIFTS spectrum may be created for the magnetic sample, and compared with a spectrum of pure magnetite (or one or more other elements or substances). Common absorbance peaks would indicate that the magnetic sample contains magnetite (or the one or more other elements or substances).

[0101] As discussed herein, a magnetic sample may be used to calculate the temperature of a wellbore. It is known that magnetite undergoes a phase transition to maghemite at around 200 °C, and to hematite at around 400 °C. Therefore, identifying the presence of maghemite in a spectrum obtained from a magnetic sample shows that the sample was obtained at a temperature exceeding around 200 °C, while the presence of hematite would indicate a temperature exceeding around 400 °C.

[0102] As discussed herein, ferromagnetic behaviour may be evident in a debris sample. Analysing a magnetic fraction may allow casing 2 or tools 1 or the like to be developed such that magnetic properties are minimised, avoiding blockages due to magnetism. Moreover, magnetization may change with phase transitions. For instance, a magnetic fraction may contain elements having a higher magnetization at a lower temperature. Therefore, the extent that a debris sample or fraction is attracted to a magnet may indicate the temperature of the section of the wellbore from whence the debris sample or fraction originated or was obtained. Provided that the phase transition conditions of the elemental components of the debris are known, cutting zone temperature can be calculated using spectroscopy as set out herein.

[0103] In some embodiments, the debris processing method may include dehydrating the debris. Dehydration may be done in an oven, for example, and so the debris processing apparatus 102 (and, in particular, the measurement apparatus 102-1, for example) may include an oven or other dehydrating equipment. Spectroscopy, as described herein (such as DRIFTS) may be performed on a dehydrated debris in some embodiments.

[0104] In some embodiments, a milling method includes categorizing the first milling operation according to at least one predetermined milling operation category, for example 'normal milling,' 'casing cut-out', 'milling first coupling', or the like. A milling operation category may be defined based on a physico-chemical property or another condition. Categories may be used to define debris samples (e.g., 'normal milling, first sample' and 'normal milling, second sample' and the like), so that debris samples are easily associated with the first operation, ensuring efficient analysis at the rig-site or elsewhere.

[0105] During a milling operation, the rate of generation of milled cuttings may be calculated in some embodiments, which may be based on the quantity and appearance of debris or a fraction of the debris as a function of time. The generation rate of milled cuttings may be based on the drilling speed of a tool 1, or based on the volume of debris (or a fraction of the debris) generated in a given time, or the like. The generation rate of milled cuttings may be used in analysis of collected debris. An estimate of the generation rate of milled cuttings may be sufficient to categorize a first milling operation.

[0106] In some embodiments, the mass of the collected debris or fraction is used as the volume of the milling cuttings in this analysis (scales may be provided for this purpose as part of the debris processing apparatus 102 and, in particular, the measurement apparatus 102-1, for example).

[0107] In some embodiments, the generation rate of milled cuttings may be calculated using a series of images of a part of the wellbore, captured at known intervals (e.g. by one or more cameras). The generation rate of milled cuttings may be calculated using video. The video may be a livestream or another continuous video. The camera (which may be a video camera) may be attached to a downhole tool, for example, in some embodiments. In some embodiments, the camera is positioned to image debris which has left the wellbore and images captured by the camera may also or alternatively be used to determine the generation rate of milled cuttings (e.g. by virtue of the rate of generation of debris).

[0108] According to some embodiments, method include determining or otherwise categorizing a stage of a milling process using the generation rate of milled cuttings and one or more other properties. The other property or properties may be a physico-chemical property, such as chemical composition or size or any other physico-chemical property mentioned herein. For example, by knowing the generation rate of milled cuttings and percentage content of milled cuttings in the debris, this information may be used in some embodiments to identify a specific stage of a milling process as 'normal milling', 'casing cut-out', etc. where normal milling, casing cut-out, and the like have a particular known characteristic or range of characteristics to differentiate the stage from another stage of a milling process.

[0109] Collecting debris from the wellbore may include collecting a mixture of the debris and a milling fluid. Milling fluid may degrade or undergo a phase transition due to conditions within the wellbore. Accordingly, the debris and the milling fluid constituents may become indistinguishable or difficult to distinguish in some embodiments, and parts of the milling fluid may solidify, or a milling fluid constituent may bind to debris. Thus, milling fluid or a milling fluid constituent may undergo a phase transition to form a sticky or residue, due to processes occurring in the wellbore (for example, a raised temperature) and may stick to debris.

[0110] The mixture of debris and milling fluid may persist even after washing, drying, or other processing of the debris, and may persist after one or more of the other measurement processes described herein. As such, measuring a physico-chemical property of the collected debris may include measuring a physico-chemical property of the collected milling fluid (or components thereof).

[0111] Residual milling fluid may cause pieces of debris to agglomerate, or may coat debris, and the presence of milling fluid may affect size or size distribution measurements. Analysis of debris may be performed in accordance with some embodiments in order to determine whether or not milling fluid is present. Milling fluid degradation products may be analysed while the milling fluid degradation products are mixed with other debris, or following separation, as described herein.

[0112] In some embodiments, the milling fluid includes at least one inorganic additive. In some embodiments, the milling fluid may not contain anything other than inorganic additives (i.e., the milling fluid may only have inorganic material aside from insubstantial impurities, and thus consists essentially of inorganic material). The inorganic additives may be chosen based on rheological properties (e.g., for control of fluid flow), may stabilize the milling fluid in the cutting zone, may be harmful to surrounding formation should there be a leak (and so additives may be selected which are unlikely to be harmful in the event of a leak), and so forth. In some embodiments, the milling fluid includes one or more of a water-based bentonite suspension, a bentonite and mixed metal hydroxide suspension, a bentonite and mixed metal hydroxide suspension without any water-soluble polymer additives, one or more water-soluble polymer additives, one or more water-soluble polymer additives and one or more stabilizers configured to reduce thermo-oxidative degradation of the or each polymer additive, one or more water-soluble polymer additives and one or more stabilizers configured to reduce hydrolytic degradation of the or each polymer additive, an anti-oxidant, an oxygen scavenger, one or more sacrificial compounds which are prone to oxidation, a pH buffer, other additives, or combinations of the foregoing.

[0113] As described in U.S. Patent Application No. 62/944,267 titled, “Efficient Casing Milling Operations”, research has been conducted to describe the benefits of employing specific stabilizing additives or a package of different stabilizing additives to increase the thermal stability of water-soluble polymers used in drilling and milling fluids.

[0114] In the present disclosure, the content of stabilizers in the milling fluid may be selected based on the conditions within the wellbore, and the conditions may be established using analysis of collected debris as set out herein. The milling fluid may be adapted following a first milling operation, for example, for use in a second milling operation. In some embodiments, therefore, there is provided a method of modifying or otherwise adapting the milling fluid based on the results of the debris analysis process (as described herein). Embodiments may include milling fluid adaptation equipment 103 which is configured to perform the adaptation. For instance, the adaptation equipment 103 may introduce one or more additives to the milling fluid, cease the addition of one or more additives, change to a different milling fluid, and so on. When additives are added or ceased, the additives may include stabilizers which may minimize the effects of particular conditions which otherwise cause degradation of water-soluble polymers in the milling fluid, for example. Degradation may be thermo-oxidative or hydrolytic. The casing milling fluid composition may be optimized to achieve efficient hole-cleaning during milling as well as stability at high temperatures.

[0115] As discussed herein, in some embodiments, debris is separated from milling fluid and residual milling fluid is removed from the debris (for example, from the surface of pieces of debris). The residual milling fluid may be a sticky residue, resulting from a phase transition in the milling fluid (as described above). The sticky residue may coat part of or the entire surface of a piece of debris. It is desirable to remove that residue for some embodiments of the present disclosure.

[0116] Where the physico-chemical property being measured is size distribution, a coating of residue having any significant thickness would skew the results, for example. The sticky residue may cause agglomeration of debris, so that the debris appears to comprise larger pieces of material, affecting size measurements.

[0117] In some embodiments, a filter is used for separating the debris from the milling fluid.

[0118] In some embodiments an absorption material is provided to absorb milling fluid, in order to remove milling fluid from a sample.

[0119] In some embodiments, a solvent is used to remove one or more contaminant components of the debris from a remainder of the debris. The method may include mixing the debris with the solvent and agitating the debris and solvent mixture.

[0120] The solvent may be an organic solvent or a mixture of organic solvents. The organic solvent or mixture may include a chlorinated hydrocarbon such as chloroform or dichloromethane. The organic solvent or mixture may include a non-chlorinated solvent such as an alcohol such as iso-propanol or a ketone such as acetone. The solvent or mixture may include a mutual solvent so that the mixture includes water.

[0121] One or more contaminants may then be extracted from the solvent. Extracting the contaminants may be done using a sieve or filter, as described above – i.e. extracting contaminants is a method of separating debris.

[0122] Measuring at least one physico-chemical property of the collected debris may include analysing the one or more contaminants to determine one or more constituent parts. A contaminant may be residue.

[0123] Analysing the one or more contaminants may include subjecting the one or more contaminants to spectroscopy (such as infra-red spectroscopy as described herein), x-ray fluorescence spectroscopy or a combination of both of these analysis methods.

[0124] In some embodiments, the solvent may be an organic solvent such as dichloromethane or acetone or the like.

[0125] In some embodiments, a second stage of the milling process is devised based on the first condition, adapting the milling process based on the success or progress of the first milling operation. This adaptability means that the milling process may be more efficient, compared with processes which perform the same milling operation repeatedly, beyond a necessary number of times.

[0126] Determining a first condition associated with the milling operation based on the at least one physico-chemical property may include identifying a level of degradation of the milling fluid occurring in the wellbore in relation to the first milling operation. Devising a second stage of the milling process based on the first condition may include selecting a milling fluid (or milling fluid adaptation) based on the identified level of degradation and delivering the selected milling fluid to the first milling tool (or the adapted milling fluid to the first milling tool).

[0127] In some embodiments, a second milling operation may be performed in relation to the wellbore casing 2, according to a second stage of the milling process (having been devised based on the first condition).

[0128] In other words, the methodology some embodiments may include first and second milling operations, where the second milling operation is performed in the knowledge that debris resulting from the first milling operation had one or more characteristics.

[0129] The second stage of the milling process may differ from the first milling process – for example, the cutting speed of the milling tool may be increased, or decreased. The depth and angle of the milling tool 1 may differ – i.e. a different tool 1 may be chosen, or a different tool attachment. In other words, the second stage of the milling process may use a second milling tool 1 which is different from the first milling tool 1.

[0130] Overall, the second milling operation is an update to the milling process based on the first milling operation, to improve the efficiency of milling.

[0131] Performing the step of determining a second stage of the milling process, based on the first condition, at the same geographical location as the milling process itself (i.e. at the rig-site) may improve the efficiency of the method, reducing overall downtime, in which one or more milling tools 1 are not being used.

[0132] The analysis methods discussed may be performed using mobile analysis equipment (i.e. the measurement apparatus 102-1 may be mobile). An analyser who is analysing debris, for example, may wish to perform analysis on a sample of debris as soon as practicable once the debris has been removed from the wellbore – the analyser may therefore wish to set up the analysis equipment near to the opening of the wellbore. Mobile analysis equipment (such as a desk-top XRF device) would be suitable.

[0133] In embodiments, the present method is carried out in a region including a wellbore opening. The method may be carried out with at least a part of analysis equipment (i.e. some of the measurement apparatus 102-1) inside the wellbore. In other words, the analysis may be a real-time analysis of debris (or milling fluid) inside the wellbore.

[0134] Collecting debris and measuring at least one physico-chemical property may be performed automatically. Debris may be collected and analysed remotely (i.e. without human interference).

[0135] It may be that initial analysis is required inside a wellbore or at a wellbore opening, but that further analysis takes place elsewhere on a rig-site – or elsewhere, entirely, such as at a remote laboratory.

[0136] The present method may be used to predict the likelihood of well blockage. As the method may be undertaken during a milling operation – i.e. in real-time – the milling operation may be updated accordingly, should analysis of debris indicate that there is a build-up of, for example, sizeable debris fragments which may lead to a blockage.

[0137] Wellbores having a complicated trajectory may benefit from the present method, and in particular from predicting and preventing a blockage. Removal of a blockage may be problematic where a wellbore is not straight, as there are more surfaces on which debris may sit, and build-up.

[0138] It may be more difficult to feed a milling tool through a bent wellbore, without the tool catching on a surface and displacing casing (which may have been loosened during a previous milling operation) or wearing itself down – i.e. contributing to debris build-up. Such a wellbore may be the result of sidetracking.

[0139] In some embodiments, the wellbore casing 2 is whipstock, and the milling operation is a sidetracking operation. The stages of the milling process discussed herein are, in such embodiments, stages of a sidetracking process, and the first milling tool 1 is a sidetracking tool.

Whipstock is casing 2 which is inclined, to direct drilling. Sidetracking is drilling to create a secondary wellbore branching from an original wellbore. Often, the secondary wellbore runs parallel to the original. Sidetracking is performed via a window, created in the casing of the original wellbore. Sidetracking may be used to bypass an unusable section of the original wellbore, which may have been rendered inaccessible.

[0140] Analysis of debris discussed herein may be used in an abandoned wellbore, or in a wellbore in the process of abandonment. Lessons can be learned about how blockages formed (which may have led to the wellbore being abandoned) and this knowledge may be applied to future wellbores.

[0141] Identifying debris which resulted from tool wear-and-tear may be useful in developing new, stronger tools 1. Analysis methods set out herein may be used in testing a new tool 1 or tool head, for example.

[0142] The present method may include developing a milling fluid which is more resilient at high temperatures (such as those in a cutting zone), reducing the amount of degradation residue produced. For example, residue sticking to debris may be due to degradation of polymers such as xanthan gum, a common milling fluid component, where xanthan degradation results in a sticky product having an affinity for milled cuttings (i.e. sticking to debris).

[0143] Therefore, in embodiments, removal of residue may not be necessary, where residue is not present.

[0144] A method of testing potential milling fluids may be performed by re-creating or simulating a cutting zone having a realistic cutting zone temperature. For example, before starting work in a new wellbore, the wellbore could be used for testing milling fluids. Equally, before abandoning a wellbore, the wellbore could provide a testing area.

[0145] The simulation may include using a cutting tool 1 and casing material 2. The simulation may include performing cutting at a geometry and rate realistic for a milling operation.

[0146] A variety of known lubricants and/or coolants may be used in the simulation, and compared, in order to determine suitable components for a milling fluid having desired properties. The components may include those listed above.

[0147] Temperatures generated in the simulation cutting zone may be estimated using analysis described herein. For example, casing 2 corrosion products or milling fluid degradation products may be analysed using spectroscopy.

[0148] Accordingly, in some embodiments and with reference to FIG. 1, debris from a milling operation in the form of swarf, milling fluid, and other debris material is obtained from a wellbore. This debris may be transported by the milling fluid to the surface.

[0149] The debris may then be processed to remove the milling fluid — which may then be re-circulated to be reused in the milling operation.

[0150] The separation of the debris from the re-useable portion of the milling fluid (i.e. that milling fluid which has not contaminated the swarf) may be performed by the use of filtration and/or settling tanks for example.

[0151] The resulting debris may be transported (e.g. by conveyor) for disposal. However, a sample of the debris may be taken prior to disposal to enable the or each measurement process (using the debris measurement apparatus 102-1) to be undertaken.

[0152] The purpose of the or each measurement process may be to obtain information about the progress of the milling operation and/or the characteristics of the milling fluid and/or conditions in the wellbore.

[0153] The measurement process may begin with fractionating of the debris (i.e. the sample of the debris) by size (e.g. using a sieve or filter) and/or by magnetic properties (using a magnet or electromagnet).

[0154] The debris (or one or more fractions thereof if it has been fractionated) may be treated to remove contaminants from the milling fluid. This may include, for example, exposing the debris to a solvent, and/or agitating a debris-and-solvent mixture, and then removing the debris from the solvent (e.g. by the use of a filter and/or sieve).

[0155] The debris, so treated, may then be subjected to one or more debris measurement processes as described herein.

[0156] For example, one or more fractions of the debris (if it has been fractionated) may be measured to determine the size distribution, for example, of the debris in that fraction. A similar process may be applied if the debris has not been fractionated.

[0157] For example, one or more fractions of the debris (if it has been fractionated) may be subjected to spectroscopy to determine composition of the debris in that fraction. A similar process may be applied if the debris has not been fractionated.

[0158] The resulting of the debris measurement process may be, for example, a size distribution for the sample of debris, and/or a composition distribution for the sample of debris (which may, of course, be divided by size and/or another characteristic of the debris — such as its magnetic properties).

[0159] The output from the debris measurement process may then be compared to one or more known characteristics with a view to determining:

- the original of the debris (e.g. casing 2, cement 3, the surrounding formation, etc);
- the extent of milling tool 1 degradation (e.g. by identifying debris from a housing of the milling tool 1 or the proportion of debris from the milling tool 1 housing compared to the debris from one or more cutting elements of the milling tool 1);
- a temperature at the milling site (e.g. based on the decomposition of the debris and/or contaminants such as the milling fluid); and/or
- one or more corrosion products associated with the milling tool 1 and/or the casing 2.

[0160] The method of some embodiments may include using the output from the debris measurement processes to determine:

- progress of the milling operation;
- milling operation efficiency;
- the rate of cutting during the milling operation;
- whether to replace, change, or otherwise alter the operation of the milling tool 1;
- when the milling operation has penetrated a casing 2 and reach underlying cement 3; and/or

- whether the milling fluid is functioning correctly and whether it requires any adaptation (e.g. the addition or non-addition of one or more additives or a change to a different milling fluid entirely).

[0161] The analysis and resulting changes to the operation of the milling process and/or the milling fluid may be undertaken by a suitably programmed computer, for example.

[0162] In order to aid understanding reference is now made to the example images in FIGS. 2-8. These figures show images of debris collected from wellbores as detailed below.

[0163] FIGS. 2-5, and 8 each show an original sample of debris (at the top of the figure) and two size fractions of that sample as indicated (at the bottom of the figure). FIG. 2 shows sample 1 from a first wellbore at Berkel (BRK), FIG. 3 shows sample 2 from the first wellbore, FIG. 4 shows sample 3 from the first wellbore, FIG. 5 shows sample 4 from the first wellbore, and FIG. 8 shows sample 7 (the first sample from a second wellbore (located in Houston)). FIGS. 6 and 7 each show an original sample of debris (at the top of the figure) and one size fraction of that sample (at the bottom of the figure). FIG. 6 shows sample 5 from the first wellbore and FIG. 7 shows sample 6 from the first wellbore.

[0164] The size distribution of the debris is indicated below in Table 1 for each sample (with the percentages being percentages by weight):

Percentage of Fraction	**> 2.8 mm**	**> 8 mm**
Sample 1, Berkel BRK	13%	-
Sample 2, BRK sample after cut, initial milling	42%	-
Sample 3, BRK normal milling	50%	9%
Sample 4, BRK milling out centralizer	44%	2%
Sample 5, BRK 1st coupling	82%	65%
Sample 6, BRK 2nd coupling	32%	4%
Sample 7, Houston 45 degree cut	43%	-

Table 1

[0165] The same information is also depicted graphically in FIG. 10 for ease of reference).

[0166] As can be seen, some samples (see samples 3 and 5, for example) exhibited relatively long and curly cuttings in the debris. This form of debris has an increased tendency to cause blockages by forming a “bird’s nest” structure. Discontinuous chips of a smaller size are desirable for efficient operation during the milling process.

[0167] The identification of samples with such characteristics as samples 3 and 5, may result in embodiments causing adaptation of the milling fluid to reduce the risk of aggregation of the debris, and/or increasing or decreasing the cutting speed, and/or increasing the depths of cut and/or reducing the rake angles for the milling operation.

[0168] The characteristics such as shown in relation to samples 3 and 5 may be determined by using the size distribution and/or the camera as described herein, for example.

[0169] FIG. 9 shows sample 7 exposed to a permanent magnet from which it can be seen that some of the sample is attracted to the magnet and some is not. Therefore, a magnet may be used to fractionate the sample. From this magnetic fractionation it could be assumed that a portion of the sample is cement or part of the surrounding formation and a part is casing 2 or tool 1 material. However, spectroscopy may be used – as described in relation to some embodiments – to confirm the constituents of the two fractions evident in FIG. 9.

[0170] The samples 1 to 7 above (S1-S7) were, in an example embodiment, subjected to XRF. The results are shown in the graphs of FIGS. 11-15 (with each graph showing the percentage weight of the indicated element in the indicated fractions of the samples). It will be noted that sample 7 includes magnetically separated fractions as well as size separated fractions with "Mag" indicating the fraction which was attracted to the magnet used in the process.

[0171] The elements identified in the XRF process and shown in FIGS. 1 to 7 were selected based on the elements indicated by the manufacturer of the casing 2 as being present in the casing 2. These, along with their proportions in weight percentage are shown in Table 2 below:

Grade	**Type**	**C**		**Mn**		**Mo**		**Cr**		**Ni**	**Cu**	**P**	**S**	**Si**	**Fe**
		min	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**max**	**max**	**max**	**max**	**max**	**balance**
L80	1	--	0.43	--	1.9	--	--	--	--	0.25	0.35	0.03	0.03	0.45	96.56

Table 2

[0172] FIGS. 16-21 show plots, for each sample, of Mn/Fe vs (Mn+Fe), as indicated in the figures.

[0173] From the elemental analysis the results of which are shown in FIGS. 11-15, it can be observed that the debris is made up of 70% to 95% of Fe. The Mn content ranges from 0.96% to 1.32%.

[0174] With regard to FIGS. 16-21, the theoretical value of Mn/Fe calculated from the manufacturer specification is 0.0197. The ratio Mn/Fe should be constant since it is controlled during the manufacturer process. All samples have Mn/Fe ratio around 0.013, which is below the theoretical value of 0.0197. Samples 1, 3 and 5 have a relatively constant Mn/Fe ratio of around 0.013. On the other hand, for samples 2 and 6, the Mn/Fe ratios are not constant. The lowest ratios are 0.013 which are observed in the larger size-fractions, they are then gradually increased to 0.018 in the fine fraction (<0.71mm). This increase in the Mn/Fe ratio suggests that there is an enrichment of Mn in the fine fraction.

[0175] The theoretical value of (Mn+Fe) calculated from the manufacturer specification is 98.46. All samples show a dilution of the (Mn+Fe) due to the presence of other elements in cement (Si, Al) and milling fluid (Ba, S). The majority of the data points for all samples lie within (Mn+Fe) > 90%. However the fine fraction (<0.71mm) of sample 2 and sample 6 has only (Mn+Fe) range from only 75% to 85%.

[0176] Ni is only observed in the fine fraction (<0.71mm) of all samples. Sample 6 has the highest Ni content in its fine fraction. Furthermore Sample 6 also has Ni at size >2.8mm. The high Si content observed (> 1%) is due to the fact that Si is also present in cement 3.

[0177] Thus, from this analysis, according to some embodiments, elemental composition is dominated by the casing 2 material. This would confirm the successful milling out of casing 2 material from the well. Other elements from cement 3 and milling fluid can cause a dilution in the XRF reading of the casing 2 elements. The fine fractions (<0.71mm) contain more alloying elements than the larger fractions.

[0178] Sample 7 may be compared to samples 1-6 (see FIGS. 22 and 23). From this information, the magnetic component of sample 7 in general has a lower Mn/Fe ratio of 0.011 (FIG. 23), a lower Mn and a remarkably higher Cu weight percentages. This high Cu content may be determined to be due to the wear of the milling tool 1.

[0179] As discussed herein, the content of the debris may be used to determine wear on the milling tool 1.

[0180] With this in mind, the cutter blade assembly used in the operation which provided sample 7 is shown in FIG. 24.

[0181] The main alloy elements of the housing of the cutter blade assembly used in the operation resulting in sample 7 include Cu (25.50 wt%), Cr (10.50 wt%), Sn (2.53 wt%), Al (3.40 wt%), Si (3.34 wt%) and Mo (0.033 wt%).

[0182] From the XRF analysis of the cuttings samples (see FIGS. 25-28), there are higher concentrations of Cu, Cr, Sn and Mo in sample 7 compared to samples 1-6. In particular, the Cu weight percentage is higher and Sn is only observed in sample 7 due to the wear of the housing. This information can, therefore, be used to track the wear of the cutter blade assembly.

[0183] Tables 3 and 4 below compares the elemental composition (in % weight) of cutter blades according to the supplier and XRF measurements taken in accordance with embodiments. The two main elements in the cutter blades are tungsten carbide (WC) and Co. W from the XRF measurements is lower by at most 7.6% than the manufacturer specification while that of Co is more than doubled. Other alloying elements, such as Ta, Nb and Ti are observed. However the distribution of Ti is inhomogeneous on the surface.

Manufacturer's Spec. Grade	**HS6 (P40)**
W	76.9
Co	11.7
Ta(Nb)	8.0
Ti	3.4

Table 3

XRF measurement of cutter blade, cylinder sample											
Bottom side											
tests #	Cr	Mo	Ni	Fe	Co	Ti	Zr	Nb	Ru	Ta	W
5044	/	0.118	0.443	0.4	23.03	0.457	0.024	0.647	0.043	2.09	72.61
5045	0.198	0.082	0.282	0.375	22.62	/	0.027	0.636	0.044	1.8	73.58
5046	0.178	0.126	0.381	0.38	22.81	/	0.039	0.607	0.068	1.76	73.24
average	/	0.109	0.369	0.385	22.82	/	0.03	0.63	0.052	1.88	73.15
Top side											
tests #	Cr	Mo	Ni	Fe	Co	Ti	Zr	Nb	Ru	Ta	W
5048	/	/	0.353	0.435	24.49	0.581	/	0.655	0.062	2.16	71.09

5049	0.178	0.087	0.467	0.397	24.13	0.535	/	0.656	0.048	1.83	71.66	
5050	0.173	0.086	0.404	0.354	24.45	/	/	0.661	0.054	2.15	71.31	
average	/	0.08	0.408	0.395	24.36	0.49	/	0.658	0.054	2.05	71.35	
XRF measurement of cutter blade, "Sine wave" samples: grade HS6												
tests number	Cr	Mo	Ni	Fe	Co	Ti	Zr	Nb	Ru	Ta	W	
5096	0.35	0.107	0.345	0.512	23.14	/	/	0.345	0.038	0.978	74.18	
5097	/	0.137	0.483	0.439	23.31	/	/	0.403	0.057	/	74.56	
5098	0.271	0.1	0.494	0.477	23.63	0.418	/	0.35	0.045	0.504	73.44	
XRF measurement of cutter blade, "Peak wave" samples: grade HS6												
tests number	Cr	Mo	Ni	Fe	Co	Ti	Zr	Nb	Ru	Ta	W	Re
5099	0.327	0.153	0.296	0.427	21.8	/	/	0.354	0.051	0.73	75.01	0.513
5100	/	0.129	0.373	0.419	22.33	/	/	0.399	/	/	75.72	/
5101	0.196	0.12	0.407	0.382	22.64	/	/	0.35	0.056	/	75.29	/

Table 4

[0184] The addition of Co to cutter blades increases toughness but the hardness is reduced. Additions of NbC, TaC and TiC result in increases in hardness and wear resistance. The alloying elements coming out of the blades due to wear can be detected by XRF. FIGS. 29-32 show XRF measurements of the cutter blade-related alloying elements in various milled casing 2 cuttings samples.

[0185] For samples 1-6, W is observed in most samples except from sample 4 when the centraliser was milling out. Co is detected in large fractions. The large error is due to some samples having no Co reading while some have (at least 5 measurements from each size fraction were taken in these examples). Nb and Ti are observed in the fine fraction (<0.71mm). No Ti is observed in sample 5 (1st coupling). By tracking the evolution of these elements and their ratios, different mechanism/stages of the tool 1 wear can be identified in accordance with embodiments. For example, a decrease in the ratio of Ti/W might indicate the gradual wear of the TiC coating.

[0186] For sample 7, W is only present in the magnetic fine fraction (<0.71mm) and Nb is only measured in the non-magnetic components. No Co or Ti was observed. Ni is only observed in the fine fraction (<0.71mm) of all samples.

[0187] In some embodiments, and/or for the purposes of investigation, an extra analysis of one or more samples of debris may be performed. For the purposes of this example this extra analysis was performed on the >1.18mm size fraction of sample 1 using Scanning Electron Microscopy coupled with Energy Dispersive X-ray (SEM/EDAX) spectroscopy – see FIG. 52. The Ti – La line around 0.452 KeV does not have any interference with Ba. This peak gives a good indication of the presence of Ti. In this test example, the energy range of the XRF instrument is from 1.5 to 60 KeV. On the other hand, EDAX has a lower energy, range from 0 to 40 KeV. Compared to XRF, EDAX analysis was able to distinguish Ba and Ti more accurately, as shown in FIG. 52 for the measurement of Barium titanate ($BaTiO_3$). The theoretical weight percentages of Ba, Ti and O are 58.9, 20.5 and 20.58, respectively while EDAX gives 54.8%, 19.29% and 22.46% which are in good agreements with the theoretical weight percentages.

[0188] Table 5 below shows the EDAX measurement of sample 1 with fraction size >1.18mm:

Measurement No.	**Weight %**			
	S	**Ca**	**Ba**	**Ti**
1	1.13	1.17	4.93	0.27
2	0.96	-	5.26	0.09
3	-	-	2.31	0.05
4	0.33	1.94	4.45	0.11
5	-	1.56	3.66	0.16
6	0.77	-	7.03	0.23
7	-	1.56	7.68	-
8	-	0.94	3.96	-
9	-	-	4.47	-

Table 5

[0189] Nine measurements on different spots were performed in this example (although other numbers of measurements could be performed). Ti is detected within 6 spots. The Ti average value among this 6 spots is 0.15 wt%. This is comparable with the weight % obtained from XRF in FIG. 32 which is 0.12 wt%.

[0190] Other elements of interests from EDAX are Ba from the milling fluid which is detected in all spots, some spots also contain S. Calcium from the cement is also observed in 5 spots. Unfortunately the weight percentage data from the XRF output does not report Ca, but its spectrum does show Calcium peaks. This again indicates limitations in the current XRF algorithm.

[0191] From the table above, it can also be seen that several spots reveal Ba but no S indicating that some of the sample contained Ba in a non-sulphate form. This may suggest the presence of barium carbonate, for example.

[0192] As will be appreciated, the samples may include elements from the milling fluid.

[0193] Milling fluid used in relation to the milling operations resulting in samples 1-6 comprise KCl, Polyanionic cellulose and Barite. All samples contain Ba and S (see FIGS. 34 and 35 which show XRF elemental composition of the debris samples related to the milling fluid elements), and the highest weight percentages are measured for the fine fractions (<0.71mm). The operation resulting in sample 7 employed only water as the milling fluid; however, traces of Ba were detected. Therefore, in-well contamination is a possibility. No Ba or S is observed in the non-magnetic component (cement 3) of sample 7. Barite is only present in the magnetic components of sample 7. Potassium peak due to KCl is also detected from the XRF spectra (see FIG. 33 which shows an XRF spectrum of a reference Barite powder).

[0194] The samples also include components relating to the cement if cement is cut by the milling tool 1, for example. Cement 3 is typically composed of different clinker phases, such as Alite (C_3S), Belite (C_2S), Ferrite (C_4AF) and Aluminate (C_3A) where C, S, F and A refer to CaO, SiO_2, Fe_2O_3 and Al_2O_3, respectively. FIGS. 36-40 show the XRF measurements of elements which are likely to be associated with cement (Al, Si and the trace elements, Zr, Pb and Zn). The main cement elements Ca, Si, Fe and Al are detected in all samples. For sample 7, the highest Al and Si are observed in the non-magnetic component. Fe in non-magnetic component is 30% compared to 90% in the magnetic component. For the Ca component of the cement, the Ca spectra area is shown in FIG. 41. Sample 7 has the highest Ca spectra area, especially in the non-magnetic components. All the major cement elements are observed in the non-magnetic components. It suggests that the non-magnetic component in sample 7 is cement 3.

[0195] As can be seen, the cement component in sample 7 is also rich in Zr, Pb and Zn. It is known that Zn interacts with cement clinker grains during hydration and to retard setting. The main phases involved in the fixation reaction of Zn is $Ca(OH)_2$. Zn in cement 3 can react to form $Zn(OH)_2$ which can form insoluble calcium salt: calcium hydroxyl-zincate $CaZn(OH)_6 .2H_2O$. The hydration will be retarded until these reactions are completed. Other literature has shown the immobilisation of Cr^{6+}, Cd^{2+}, Zn^{2+} and Pb^{2+} in alkali-activated slag binders.

[0196] Cement 3 normally contains 97% of clinker phases and 3% of gypsum ($CaSO_4.2H_2O$). Three correlations might be expected: i) (Al + Si) correlates with Ca; ii) (Al + Si) correlates with S; iii) Ca correlates with S.

[0197] As shown in FIGS. 42 and 43, (Al+Si) weight % correlates with both Ca Spectra Area and S weight %. The slope for sample 7 is different from samples 1 to 6. Sample 7 contains higher Ca, Al and Si. This suggests that the sample 7 contains clays (Bentonite (Na, Ca, K)Al2O3.4(SiO2).H2O). Furthermore, the amount of (Al + Si) and S also depends fraction sizes. The fine fractions <0.71mm in sample 2 and sample 6 have the highest (Al + Si) and S weight % within samples 1-6. The non-magnetic component (cement 3) of sample 7 has an order of magnitude higher (Al+Si) wt% than the magnetic component.

[0198] Ca spectra area also correlates with S weight % as shown in FIG. 41. Again, sample 7 from sample 7 has higher Ca content than samples 1-6. The non-magnetic fragment of sample 7 has the highest Ca content. From the fraction size analysis, the fine fraction <0.71mm of sample 6 has a higher than expected Ca content when predicted from the larger fraction sizes. It suggests that the source of Ca might come from something else other than CaSO4, for example CaCO3.

[0199] Milling mud KCl/Polyanionic cellulose/Barite was used in relation to the well from which samples 1-6 were obtained. Correlation between Ba and S is expected due to the barite (BaSO4) used. Ba peak with no Ti interference can be found at 5.16 KeV. FIG. 44 shows the spectra area of this pure Ba peak versus the S weight%. Samples 1-6 exhibited a linear Ba-S correlation whereas sample 7 showed no correlation. This could be due to the Ba as in-well contamination. In most samples, the finer fraction (<0.71mm) has higher Ca and Ba as compared to the other larger fractions.

[0200] Strontium (Sr) is a common impurity in Ba. Although Sr is not reported in the excel spreadsheet output of XRF, its peak is observed in the spectra. Linear correlations between pure Ba and Sr spectra peak area were observed in samples 1, 3, 4 and 5.

[0201] Another peak area of interest is the Ba peak with Ti interference at 4.5KeV. The spectral area of this peak is plotted against S wt%, as shown in FIGS. 32, 45-51. The Ti weight percentage bar chart is also included in FIG. 32. According to the bar chart, Ti is present in all size fractions of sample 1. A linear correlation is observed between the Ba(Ti) spectral area and S weight %. In sample 2, it is observed that two size fractions (> 2.8mm and <0.71mm) have a steeper slope than the other fractions. This steeper slope is due to the Ti interference, as indicated by the higher Ti wt% content in the bar chart. In both sample 3 and 4, the size fraction >1mm has no Ti content shown in the bar chart, and as a result, a shallower slope is observed in the Ba(Ti) spectra area vs S plot. There is no Ti present in sample 5. For sample 6, only the finer fraction (<0.71mm) has Ti in the bar chart, this is reflected in the Ba(Ti) spectra area vs S plot where the finer fraction has Ba(Ti) area much higher than the expected value extrapolated from other size fractions. Sample 7 has no Ti and no correlation between Ba(Ti) spectra area and S wt%.

[0202] As discussed, in accordance with some embodiments, Diffuse Reflectance Infra-red Fourier Transform (DRIFT) analysis is performed. In an example involving the samples discussed above, DRIFT was performed on samples 1-7. In this instance, and in some embodiments, an objective of this process is to analyse further the non-metal components (e.g. barite, cement 3) and to identify the casing 2 oxidation projects (iron oxides).

[0203] The DRIFT spectra of the magnetic and non-magnetic components of sample 7 with size <0.71mm were analysed. FIGS. 53 and 54 compare the DRIFT spectrum of the non-magnetic component of sample 7 with the infra-red spectrum of ordinary cement (the latter being shown in FIG. 54). The spectra in FIGS. 53 and 54 resemble each other.

[0204] Table 6 below compares peak positions and the assignment of peaks:

Assignment	**Frequencies cm^{-1} (Sample 7 non-magnetic)**	**Frequencies cm^{-1} (literature)**
Stretching of O-H from $Ca(OH)_2$	3645	3645
Deformation v2 H-O-H	1650	1650
v3, CO_3^{2-}	1448	1480
v2, CO_3^{2-}	878	872
v4, CO_3^{2-}	716	712
Stretching Si-O v3	980	970
v4, Si-O	522	522
v2, Si-O	457	452
v3, SiO_4^{2-}	-	1150

Table 6

[0205] The peak at 3645 cm^{-1} is assigned to the O-H stretching of $Ca(OH)_2$ formed. The band at approximately 1650 cm^{-1} is the bending vibrational mode H-O-H (v2) of water.

[0206] The bands at 1448, 878 and 716 cm^{-1} are due to the v3, v2 and v4 vibrational modes of CO_3^{2-}, respectively. The carbonate is likely to be in the form of $CaCO_3$, resulting from CO_2 absorption and reaction with $Ca(OH)_2$ during hydration.

[0207] The bands at 980, 522 and 457 cm^{-1} correspond to the v3, v4 and v2 vibrational modes of Si-O, respectively.

[0208] The DRIFT measurements corroborate the findings from XRF that the non-magnetic component of Sample 7 is cement.

[0209] When the DRIFT IR spectrum of the cement 3 and the magnetic components of sample 7 are compared (see FIG. 55), it can be concluded that there is some cement 3 contamination of the magnetic component. When the absorption IR spectra of the magnetic component of sample 7 is compared with FeO, Hematite, Magnetite and Goethite (see FIG. 56), it can be determined that both magnetite and the sample have peaks at 895 and 798 cm^{-1}. The peak at 895 cm^{-1} for the magnetic sample is a shoulder due to the sharp peak of v2 CO_3^{-2} close by at 878 cm^{-1}. The magnetic component of sample 7 contains magnetite.

[0210] With regard to samples 1-6, as described herein the measurement process may include dehydration of the debris – e.g. in an oven. In this example, the debris of sample 1 was dehydrated by putting the debris sample into an oven at 60 °C for 2 hours. The DRIFT spectrum of the dehydrated is shown in FIG. 56. With table 7 below in mind, the peak at 986 cm^{-1} is due to $BaSO_4$, supporting the elemental analysis of Ba and S from XRF; the peak at 1026 cm^{-1} may be due to $CaSO_4$ (anhydrite), $CaSO_4,0.5H_2O$ (bassanite) and $CaSO_4,2H_2O$ (gypsum). Again, this supports the presence of cement 3 as indicated by the elemental analysis from XRF.

	v_1 cm^{-1}
$CaSO_4$ (anhydrite)	1013
$CaSO_4$, $0.5H_2O$ (bassanite)	1012
$CaSO_4$, $2H_2O$ (gypsum)	1000
$BaSO_4$	980

Table 7

[0211] The casing material experienced high temperature during the milling process. At such high temperature, metal oxidation and phase transformations may have occurred.

[0212] The DRIFT measurement may be employed to investigate the chemical composition of the casing 2 material cuttings in terms of the predominant iron oxides present.

[0213] Four reference DRIFT spectra of FeO, Fe_2O_3 (Hematite), Fe_3O_4 (Magnetite) and FeOOH (Goethite) were also measured and/or otherwise obtained.

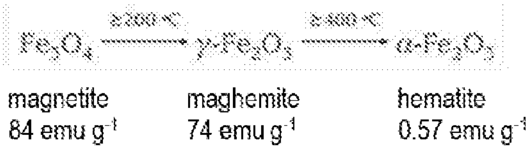
[0214] As shown in FIGS. 58-62, the spectral peaks of sample 1 do not match FeO or Hematite, but match those of magnetite at 895 cm^{-1} and 798 cm^{-1}. So sample 1 contains magnetite and this explains why the cuttings are attracted to a permanent magnet. Sample 1 also matches with Goethite as shown by the –OH bending of goethite at 1517 cm^{-1} and 1359 cm^{-1}. Thus sample 1 also contains Goethite.

[0215] In some embodiments, a sample of debris may be treated with an acid (e.g. after dehydration) prior to a DRIFT spectrum being obtained.

[0216] For example, 0.44g of Sample 1 was incubated in 10ml 4M HCl at room temperature for 24 hours. FIG. 62 compares the DRIFT spectrum before (dehydrated sample 1) and after the acid treatment (acid treatment sample 1).

[0217] The CaSO4 peak at 1026 cm^{-1} disappeared after acid treatment due to the dissolution of $CaSO_4$ in 4M HCl. On the contrary, the 986 cm^{-1} peak of $BaSO_4$ which is insoluble in 4M HCl remains. FIG. 63 shows the dissolution of Goethite in sample 1 after acid treatment. Peaks at 1517 cm^{-1} and 1359 cm^{-1} which corresponds to the –OH bending in Goethite (FeOOH) disappear. Split peaks are revealed instead of one broad peak around 610 cm^{-1} after the dissolution of Goethite. FIG. 64 shows the characteristic peaks of magnetite at 895 cm^{-1} and 798 cm^{-1} remain after acid treatment. Magnetite is insoluble in 4M HCl. One of the split peaks at 639 cm^{-1} is due to the presence of maghemite (γ-Fe_2O_3).

[0218] Magnetic nanoparticles have been used in a large range of biomedical applications such as medical diagnosis and therapy. Magnetite nanocrystals with magnetite-maghemite core shell structures may be used for such purposes. The oxidation product of magnetite (Fe_3O_4) is maghemite (γ-Fe_2O_3) and/or hematite (α-Fe_2O_3) depending on the oxidation temperature and the crystal size of the starting magnetite. Below are shown the temperature requirements for the phase transformation from magnetite to maghemite and to hematite, for example:



[0219] Around 200 °C is needed to cause a phase transformation from magnetite to maghemite and greater than 400 °C is required to form hematite.

[0220] FIG. 65 shows the infra-red spectra of magnetite heated in air at 150 °C for different periods of time. Two strong bands at 570 cm^{-1} and 390 cm^{-1} (due to the Fe-O stretching of magnetite) are observed. The strong band of magnetite at 570 cm^{-1}, if sharp, indicates the purity level. Continuous heating of the sample at 150 °C results in broadening and eventually splitting of both bands (570 and 390 cm^{-1}). This split creates two new peaks at around 430 and 630 cm^{-1}. These new peaks are due to the formation of maghemite (γ-Fe_2O_3). When magnetite is further heated at and above 300 °C, the intensity of the bands at 570 and 390 cm^{-1} is reduced and eventually the bands disappear after 293 hours whilst the bands at 430 and 630 cm^{-1} are enhanced. This indicates the phase transformation from magnetite to maghemite.

[0221] The debris may show ferromagnetic behaviour. Therefore, it may be beneficial to understand and analyse the effect of phase transformation on the magnetic properties of the material, to evaluate if the magnetic attraction force can cause the formation of blockages and bird's nest.

[0222] As shown in above, magnetite has the highest saturation magnetization value, 84 emu/g, followed by maghemite, 74 emu/g. The lowest is hematite, only 0.57 emg/g. FIG. 66 shows the changes in saturation magnetization data for magnetite heated at 150, 300, 500, 600 and 700 °C for different periods of time.

[0223] For 150 and 300 °C, magnetite has been transformed in to maghemite. The saturation magnetization plateau to 72 and 64 emu/g after 50 hours for 150 and 300 °C, respectively. No further decrease in saturation magnetization is observed. This indicates that the temperature is not high enough for further phase transformation into hematite. However when the temperature is high enough, e.g. > 400 °C, saturation magnetization decreases rapidly with heating time, indicating the further phase transformation to hematite. Activation energy of phase transformation, Q, can be calculated according to the equation:

$$Q = 1.987 \frac{T_1 T_2}{T_2 - T_1} 2.303 log \frac{t_1}{t_2}$$

where Q is in cal/mol, T_1 and T_2 are temperature in kelvin, t_1 and t_2 are the time taken for magnetite powder to develop a certain value of magnetization.

[0224] The range of temperature in the cutting of material is in practice around 360 to 600 °C. From the debris sample, it is know that magnetite is transformed to maghemite, once the time taken for the duration of the milling process is known, it is possible to estimate the temperature during milling. In the present instance, for this sample example it can be estimated that the temperature experienced by the debris during milling is >150 °C. Temperature profile is a major factor in the life-span of the milling tool and this can, therefore, be determined in this manner as part of the measurement process.

[0225] Another observation is the presence of oxygen downhole.

[0226] We now know that the debris sample contains magnetite, maghemite and goethite. The former two have high saturation magnetization, and especially magnetite which is the most magnetic of all the naturally-occurring minerals on earth. On the other hand, goethite is antiferromagnetic. The aggregation of the debris sample can be due to i) magnetic attraction force; and/or ii) sticky black organic substance coated on the cuttings due to the decomposition of Xanthan (polymer used in milling fluid).

[0227] In the present examples, it was found that after washing the debris with acetone, the cuttings no longer aggregate together. It suggests that the magnetic attraction force is secondary and not strong enough to hold the cuttings together since the cuttings also contains goethite. Therefore the primary cause for conglomeration is the sticky black organic substance which is formed by the milling fluid.

[0228] DUO-VIS^{TM} xanthan gum is a dispersible, non-clarified, high-molecular-weight biopolymer of Schlumberger and is the polymer used in the milling fluid for the milling operation resulting in samples 1–6. DUO-VIS^{TM} xanthan gum is mainly composed of standard xanthan gum which is a high molecular weight polymer used for rheology control. Xanthan gum has a polysaccharide β-D-glucose backbone like cellulose, but every second glucose unit is attached to a trisaccharide comprising mannose, glucuronic acid and mannose. The mannose closest to the backbone has an acetic acid ester on carbon 6, and the mannose at the end of the trisaccharide is linked through carbons 6 and 4 to the second carbon of pyruvic acid. The negatively charged carboxyl groups on the side chains render the polymer water-soluble. Xanthan gum forms very viscous fluids when mixed with water.

[0229] FIG. 67 shows the Attenuated Total Reflection (ATR) spectrum of xanthan gum. The band at 3000-3600 cm^{-1} is due to –OH stretching of the OH groups on the polymer and water presented in the polymer. The bands at 2889 cm^{-1} is due to –CH, –CH_2 and –CH_3 stretching; the band at 1721 cm^{-1} is due to C=O stretching of the ester and carboxylic acid groups; the band at 1602 cm^{-1} is due to C=O stretching of the pyruvate and –OH bending vibrational mode of water presented in the polymer; the band at 1400 cm^{-1} is due to carboxylate; the band at 1242 is due to –C-O-C-; the band at 1020 cm^{-1} is due to C-O stretching; the band at 787 cm^{-1} is due to C_1-H of β-glycoside. A summary of these assignments are given in the following Table 8:

Assignment cm^{-1}	**-OH**	**-CH_2**	**-C=O of ester, carboxylate**	**-C=O of pyruvate**	**-COO^-**	**-C-O-C-**	**-CO**	**C_1-H of β-glycoside**
Xanthan	3600-3000	3000-2850	1721	1602	1400	1242	1020	787
Sticky black substance	3600-3000	2959-2857	1740	-	1356	-	-	-

Table 8

[0230] Sugar and ester bond can be cleaved in alkaline fluid at high temperature. The temperature generated during the milling process is high, and as a result, the large Xanthan polymer with molecular weight range from 10 to 20 million can be degraded into fragments with lower molecular weight. The black sticky substance observed in samples 1-6 can be products of such degradation.

[0231] In this embodiment, and potentially in other embodiments, Attenuated Total Reflection (ATR) was performed on one or more parts of the debris. In this instance, on the black sticky substance which was extracted by acetone. ATR was also performed on DUO-VIS^{TM} milling fluid and the thermal treated DUO-VIS^{TM} milling fluid. The corresponding spectra are shown in FIG. 68. The spectra of the xanthan gum and DUO-VIS^{TM} are very similar. This is expected since DUO-VIS^{TM} fluid is mainly composed of xanthan gum. In order to simulate the thermal break down of the polymer, 5g of DUO-VIS^{TM} fluid was first dissolved in 1L of water followed by heat treatment in a hot rolling oven at 177 °C overnight. It was then dried off in an oven at 105 °C. The residue was a black sticky fluid. The thermal treated DUO-VIS^{TM} fluid has similar spectral features as the non-treated DUO-VIS^{TM} fluid except a new carbonyl peak is observed at 1770 cm^{-1}. The peak intensity at 1020 cm^{-1} which is assigned to C-O stretching is much reduced.

[0232] The spectrum of the sticky black substance from sample 1 is also shown in FIG. 68. Low molecular weight hydro-carbon chain is observed around 2959 to 2857 cm^{-1} which is assigned to the stretching of –CH_3 and –CH_2. Comparing to the DUO-VIS^{TM} fluid spectrum, a new carbonyl peak is observed at 1740 cm-1 and the carboxylate peak is shifted from 1400 to 1366 cm^{-1}. The carboxylate peak shift might be due to the different metal ions (e.g. Fe^{2+}) that form complexes with the carboxylate. There is no distinguishable C=O stretching peak due to pyruvate or –OH bending at 1602 cm^{-1}, and no distinguishable C1-H β-glycoside peak at 787 cm^{-1}. The ester band at 1242 cm^{-1} due to –C-O-C- is not observed, since ester bond can be cleaved easily in alkaline fluid at high temperature. Accordingly, the analysis determines that the stickiness of the black substance in sample 1 is due to the carboxylate and carbonyl groups, potentially coming from the Xanthan breakdown fragments.

[0233] All seven samples have been analysed. The following information has been determined using a range of different analytical techniques:

- Composition of milling fluid residues on surface of cuttings – organic extraction followed by infra-red spectroscopy;
- Size-distribution of casing cuttings and other components – sieving and weighing of fractions;
- Elemental composition of size-fractionated sub-samples including casing elements (Fe, Mn, Ni, Cu, Si), non-casing elements (Al, Si, Ca from cement; Ba, S from milling fluid) and cutting tool elements (W, Co, Nb, Ti) – X-ray fluorescence spectrometry; and
- Compositional analysis of casing oxidation products and non-casing components by infra-red spectroscopy and various chemical treatments to reveal acid-soluble and acid-insoluble components.

[0234] Some of the findings of the analysis of the example samples are as follows:

- Samples 1-6 were covered with a black sticky substance which induced self-aggregation or agglomeration of the casing and non-casing cuttings. Only after this substance had been extracted using an organic solvent could the cuttings sample be size-fractioned using sieves. Infra-red spectroscopic analysis of this substance revealed that it is a sticky residue (low molecular weight alkyl carboxylates) formed by the high temperature oxidative degradation of the polymer (xanthan gum) in the milling fluid. By contrast, the sample 7 did not contain such a sticky residue as the milling fluid used to test the milling tool was pure water for this sample.
- The size-fractionation of samples 1-6 revealed a very broad size distribution. Two of the samples (sample 3: normal milling and sample 5: 1st coupling) contained long curly entangled pieces of casing. Sample 5 (1st coupling) has 65 wt% > 8mm as compared to sample 6 (2nd coupling) which has only 4 wt% > 8mm. Clearly, the details of specific operations such as 'normal milling' or 'milling of the couplings' have a profound effect on the size distribution and in turn this will affect cuttings removal efficiency in the well and at surface. All of samples 1-6 were attracted to a permanent magnet. As regards sample 7, none of the sample is > 8mm and the sample comprises magnetic and non-magnetic components.
- The XRF analysis for elemental composition revealed casing elements (Fe, Mn, Ni, Cu and Si), non-casing elements (Al, Si, Ca from cement; Ba, S from barite in milling fluid) and cutting tool elements (W, Co, Nb, Ti). The composition of samples 1-6 is dominated by casing elements. Most of the samples contain >90 wt% of Fe+Mn but sample 2 (initial milling) and sample 6 (2nd coupling) contain only 75-80 wt% Fe+Mn. These samples are 'diluted' by non-casing elements such as Al, Si, Ba and S. In general, the fine fractions (<0.71mm) of each sample contain a higher concentration of alloying elements (Cr, Ni, Mo, Nb) but Co is higher in the larger

>2.8mm fractions. As regards to sample 7, the magnetic fraction is rich in Fe, Mn and W, Nb are also present. The non-magnetic fraction contains a high concentration of cement leading to high concentration of Al, Si, Mo, Zr, Pb and Zn.

- Compositional analysis of the casing oxidation products for samples 1-6 reveals the presence of magnetite, maghemite and goethite. High temperatures generated during cutting lead to oxidation of the casing and magnetization. The oxides composition indicates that the casing has experienced at least 150 °C and probably higher temperatures. Samples 2 and 6 contain appreciable quantities of barite originating from the milling fluid and this is concentrated in the finer fractions < 0.71mm. The higher content of Al and Si in samples 7 appears to originate from clays and cement whereas samples 1-6 are mainly cement. A remarkable and distinctive feature of sample 7 are its high Cu, Cr and Sn contents which are the main alloying elements in the cutter blade housing. It is also observed that the non-magnetic fraction (mainly cement) contains high levels of Zn, Zr and Pb – this may indicate the presence of alkali-activated slag binders.
- During the XRF analysis, it was discovered that the instrument and associated algorithms suffer from a limitation that Ba interferes with the Ti analysis – see the discussion herein.

[0235] In conclusion, the application of chemical analysis to casing milling debris samples is very informative. The analysis can be used to monitor the size distribution and the chemistry of each size fraction during various operations such as initial milling, normal milling, coupling milling, etc. This can be used to warn of a pending blockage in the well. The analysis reveals casing elements and casing oxidation products. The latter indicate that the casing is magnetized by high temperature oxidation during the process. The analysis also reveals the presence of elements which can be traced to the cutting tools 1, the milling fluid and the cement 3 behind the casing 2.

[0236] In samples 1-6, a sticky black substance was generated from the milling fluid by high temperature oxidative degradation of the polymer (Xanthan) used to viscosify the fluid. This substance promotes self-aggregation and agglomeration of the cuttings which could lead to easier blockages. In view of this analysis, the composition of the milling fluid should be redesigned to eliminate any formation of agglomerating agents.

[0237] As mentioned above it was discovered that the instrument and associated algorithms, used for the XRF analysis, suffer from a limitation that Ba interferes with the Ti analysis

[0238] X-ray fluorescence (XRF) spectroscopy was measured on the size fractionated sample to obtain elemental composition. The instrument used was an energy dispersive XRF from Thermo Scientific Niton XL2 GOLD.

[0239] WC, Co, Ta(Nb)C and TiC are present in the alloying elements of the cutter blades. When the cutting tools wear out, the TiC coating and tungsten carbide layer can be de-laminated. Therefore, Ti and W are likely to be observed in the elemental analysis. At the same time, Barium from barite ($BaSO_4$) in the milling fluid is also present.

[0240] In XRF analysis, Ba can cause significant interference with regard to Ti analysis. This interference can be observed in a reference sample of Barium titanate ($BaTiO_3$) from sample 8, as shown in FIG. 68 and from Table 9 shown below:

Energy/KeV	**Kα1**	**Kα2**	**Kβ1**	**Lα1**	**Lα2**	**Lβ1**
Ti	4.511	4.505	4.932	0.452	0.452	0.458
Ba	32.194	31.817	36.378	4.466	4.451	4.828

Table 9

[0241] Wavelength dispersive (WD) XRF is able to resolve the individual peaks related to Ti and Ba, namely Ba-La and Ti-Ka lines around 4.5 KeV. On the other hand, energy dispersive (ED) XRF is not able to properly resolve these elements. This is the case of our XRF instrument which is also an energy dispersive XRF.

[0242] A new methodology and algorithms to obtain more accurate weight percentages for Ti and Ba was devised for implementation in accordance with some embodiments.

[0243] The XRF instrument has two outputs, a spectrum and a spreadsheet containing element weight percentages. The area under the peak from the spectrum is used by the built-in algorithm to calculate individual element weight percentages in the spreadsheet.

[0244] The milling fluid used in the operations generating samples 1-6 is KCI/PAC/Barite mud based on MI-SWACO recommendations. Full properties of the milling fluid can be found above. Thus Barium will be in the sample. Nevertheless, the XRF algorithm reported no Barium and an unrealistic high weight percentage of Ti in the sample.

[0245] To resolve the Ti and Ba interference problem, firstly, the spectra were examined. The spectra of the reference Barite powder ($BaSO_4$) (FIG. 33), two samples (#4461 and #4466) were collected. Table 10 below shows the calculated spectra areas:

Peak No.	**Element**	**Energy /KeV**	**Integrated Peak Area from Spectra**		
			$BaSO_4$	**Sample #4466**	**Sample #4461**
1	S	2.308	2.27	28.2 (2.67wt%)	4.3 (0.6 wt%)
2	Ca (K_{a1})	3.692	0.33	24.4	6.3
3	Ba (L_{a1}), Ti (K_{a1})	4.466	5.00	66.2	6.1
4	Ba (L_{b2})	5.156	1.10	17.1	2.5
Area ratio: peak3 ÷ peak1	-	-	2.2 (Ba only)	2.35 (Ba + Ti)	1.4

Table 10

[0246] For the barite powder, which is free from Ti contamination, area ratio of peak 3 / peak 1 (Ba/S) is 2.2 where as it is 2.35 for the sample #4466 with Ti contamination. The ratio 2.2 is a decision point indicating if there is Ti contamination. Ratio >2.2 suggests the presence of Ti. For sample #4461, ratio <2.2 suggests that there is no Ti contamination and S is not just from $BaSO_4$ but also other compounds, such as $CaSO_4$ from cement.

[0247] Area ratio >2.2 (Ti contamination) #4466:

[0248] For area ratio of peak 3/peak 1 greater than 2.2, assume all S measured is from $BaSO_4$:

- S_area (peak no. 1) = 28.2
- Ba_theoretical_area = S_area x 2.2 = 62.04
- Actual measured area Ba_area (peak no. 3) is 66.2
- S wt% from spreadsheet = 2.67 wt%
- Therefore, Ba wt% = 2.67 x 4.28 = 11.4wt%
- Ti wt% contamination = $\frac{66.2-62.04}{62.04} \times \text{Ba wt\%} = 0.067 \times 11.4 = 0.76\text{wt\%}$
- Final results: S = 2.67wt%; Ba = 11.4wt%; Ti = 0.76wt%.

[0249] Area ratio <2.2 (No Ti contamination & there are other sources of S apart from $BaSO_4$) #4461:

[0250] For area ratio of peak 3/peak 1 less than 2.2, assume all Ba measured is from $BaSO_4$:

- S_theoretical_area = Ba_area (peak no. 3) ÷ 2.2 =2.8
- S_notBaSO4 = $\frac{\text{S\_area} - \text{S\_theoretical\_area}}{\text{S\_area}} \times \text{S wt\%} = \frac{4.3-2.8}{4.3} \times 0.6 = 0.2\text{wt\%}$
- S_BaSO4 = S wt% - S_notBaSO4 = 0.6 – 0.2 = 0.4wt%
- Therefore Ba wt%= S_BaSO4 x 4.28 = 0.4 x 4.28 = 1.7wt%
- Final results: S_BaSO4 = 0.4wt%; S_notBaSO4 = 0.2wt%; Ba = 1.7wt%; Ti = 0wt%.

[0251] The process is summarized in FIG. 70. References to reading from “data” should be construed as reading the data from any suitable data source such as a database, spreadsheet, or other data structure.

[0252] While some embodiments of the present disclosure relate to using milling fluid to control a wellbore milling operation, other embodiments may relate to other methods or systems. For instance, in some embodiments, a milling fluid may be developed using a test environment. Examples of such methods are described in greater detail U.S. Patent Application No. 62/944,267, filed December 5, 2019, and titled “Efficient Casing Milling Operations”. In other cases, casing may be removed chemically or in other manners. By way of example, a chemical milling operation may include isolating a section of a wellbore and providing a chemical that reacts with and removes the casing. Example chemicals include a solution of cupric chloride or a solution of ferric chloride. In the former, the cupric chloride may react with and dissolve iron in the casing while copper precipitates from the solution onto remaining casing surface. In the example of ferric chloride, the iron may be dissolved without a precipitant. Examples of such chemical milling processes are described in greater detail in U.S. Patent Application No. 62/944,215, filed December 5, 2019, and titled “Electrochemical Corrosion of Downhole Casing”, U.S. Patent Application No. 62/944,122, filed December 5, 2019, and titled “Electrochemical Milling of Casing Using Seawater”, and U.S. Patent Application No. 62/944,302, filed December 5, 2019, and titled “Chemical Milling of Casing Using Ion Solutions”.

[0253] When used in this specification and claims, the terms “comprises”, “comprising”, “includes”, “including,” and similar open-ended language mean that the specified features, steps, or components are included, but do not exclude the presence of other features, steps, or components. Unless clearly indicated otherwise, the conjunction “or” is intended to mean that two or more alternatives are present singly or in combination. Thus, a composition including "A or B" would include a composition that includes A, B, or A and B. In contrast, a composition including "a single one of A or B" or "A or B but not a combination of A and B" would include a composition that includes A, a composition that includes B, but not a composition that includes A and B.

[0254] The features disclosed in the foregoing description, or the following claims, or the accompanying drawings, expressed in their specific forms or in terms of a means for performing the disclosed function, or a method or process for attaining the disclosed result, as appropriate, may, separately, or in any combination of such features, be utilised for realising the disclosure in diverse forms thereof.

CLAIMS

1. A method of controlling wellbore casing milling, the method comprising:

    providing a first milling tool, the first milling tool configured to mill a wellbore casing and deliver a milling fluid to the milling tool;

    using the first milling tool to perform a first milling operation on the wellbore casing according to a first stage of a milling process;

    collecting debris from the wellbore comprising debris generated during the first milling operation;

    measuring at least one physico-chemical property of the collected debris using a first measurement apparatus;

    determining a first condition associated with the first milling operation based on the at least one physico-chemical property;

    devising a second stage of the milling process based on the first condition; and

    performing a second milling operation in relation to the wellbore casing according to the second stage of the milling process.

2. The method of claim 1, wherein the wellbore casing is whipstock, and wherein the milling operation is a sidetracking operation, the stages of the milling process are stages of a sidetracking process, and the first milling tool is a sidetracking tool.

3. The method according to claim 1 or claim 2, wherein measuring the at least one physico-chemical property includes one or more of measuring a size distribution of the debris, measuring an amount of or more constituent parts, subjecting the debris to infra-red spectroscopy, or subjecting the debris to x-ray fluorescence spectroscopy.

4. The method according to any preceding claim, wherein collecting debris from the wellbore comprises collecting a mixture of the debris and the milling fluid from the wellbore, and the method further comprising:

    separating the debris from the milling fluid; and

    removing residual milling fluid from the debris.

5. The method according to claim 4, further comprising providing a filter, wherein separating the debris from the milling fluid comprises using the filter to separate the debris from the milling fluid.

6. The method according to claim 4 or 5, further comprising providing an absorption material configured to absorb milling fluid, wherein removing residual milling fluid from the debris comprises using the absorption material.

7. The method according to any preceding claim, wherein the milling fluid comprises at least one inorganic additive, or only one or more inorganic additives.

8. The method according to any preceding claim, wherein the milling fluid comprises one or more of: a water-based bentonite suspension; a bentonite and mixed metal hydroxide suspension; a bentonite and mixed metal hydroxide suspension without any water-soluble polymer additives; one or more water-soluble polymer additives; one or more water-soluble polymer additives and one or more stabilizers configured to reduce thermo-oxidative degradation of the or each polymer additive; one or more water-soluble polymer additives and one or more stabilizers configured to reduce hydrolytic degradation of the or each polymer additive; an anti-oxidant; an oxygen scavenger; one or more sacrificial compounds which are prone to oxidation; a pH buffer; or combinations of the foregoing.

9. The method according to any preceding claim, further comprising:
mixing the debris with a solvent to remove one or more contaminant components of the debris from a remainder of the debris.

10. The method according to claim 9, wherein the solvent is an organic solvent or mixture of organic solvents.

11. The method according to claim 10, wherein the organic solvent or solvent mixture comprises at least one of chlorinated hydrocarbon, a non-chlorinated solvent, or a mutual solvent.

12. The method according to any of claims 9 to 11, further comprising:
agitating the debris and solvent mixture.

13. The method according to any of claims 9 to 12, further comprising:
extracting the one or more contaminants from the solvent, wherein measuring at least one physico-chemical property of the collected debris comprises analysing the one or more contaminants to determine one or more constituent parts.

14. The method according to claim 13, wherein analysing the one or more contaminants comprises one or more of: subjecting the one or more contaminants to infra-red spectroscopy or subjecting the one or more contaminants to x-ray fluorescence spectroscopy.

15. The method according to claim 13 or 14, wherein determining a first condition associated with the milling operation based on the at least one physico-chemical property, comprises identifying a level of degradation of the milling fluid occurring in the wellbore in relation to the first milling operation, and devising a second stage of the milling process based on the first condition includes selecting a milling fluid based on the identified level of degradation and delivering the selected milling fluid to the first milling tool.

16. The method according to claim 3, further comprising:
comparing one or more constituent parts of the debris to one or more materials used in the wellbore or first milling tool.

17. The method according to claim 16, further comprising:
identifying a milled material as the first condition based on the comparison.

18. The method according to claim 16 or 17, further comprising:
determining a wear characteristic of the first cutting tool as the first condition based on the comparison.

19. The method according to any of claims 16 to 18, further comprising:
determining a temperature associated with the first milling operation as the first condition based on the comparison.

20. The method according to any preceding claim, wherein the second stage of the milling process differs from the first milling process by one or more of a cutting speed, depth, or angle of the first cutting tool.

21. The method according to any preceding claim, wherein the second stage of the milling process uses a second milling tool which is different from the first milling tool.

22. The method according to any preceding claim, further comprising:

providing a camera as at least part of the first measurement apparatus, wherein measuring at least one physico-chemical property of the collected debris includes capturing one or more images of the debris and analysing the one or more captured images.

23. The method according to claim 22, wherein analysing the one or more captured images comprises one or more of determining a debris size from the or each captured image or comparing the or each captured image with at least one stock image representative of debris associated with the first condition.

24. The method according to any preceding claim, wherein the first condition comprises one or more of a ratio of milled casing to cement or a blockage or likely blockage of the wellbore by debris.

25. The method according to any preceding claim, wherein the method is performed at a single geographical location, the method further comprising:

categorizing the first milling operation according to at least one predetermined milling operation category, wherein determining the first condition comprises determining the first condition based at least in part on the at least one predetermined milling operation category.

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Application No:	GB2018427.1	**Examiner:**	Contract Unit Examiner
Claims searched:	1-25	**Date of search:**	2 July 2021

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1-15, 20-25	WO2011/095600 A2 (STATOIL ASA; BREVIK JAN OVE ET AL) the whole document
A	-	US10385619 B2 (SMITH INTERNATIONAL) the whole document
A	-	WO2019/160859 A1 (HALLIBURTON ENERGY SERVICES INC) the whole document
A	-	GB2566068 A (PROSERV UK LTD) the whole document
A	-	US2019/323332 A1 (CUELLAR HUGO FERNANDO OSORIO ET AL) the whole document

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X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

E21B

The following online and other databases have been used in the preparation of this search report

Intellectual
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International Classification:

Subclass	Subgroup	Valid From
E21B	0029/06	01/01/2006
E21B	0021/06	01/01/2006
E21B	0044/00	01/01/2006