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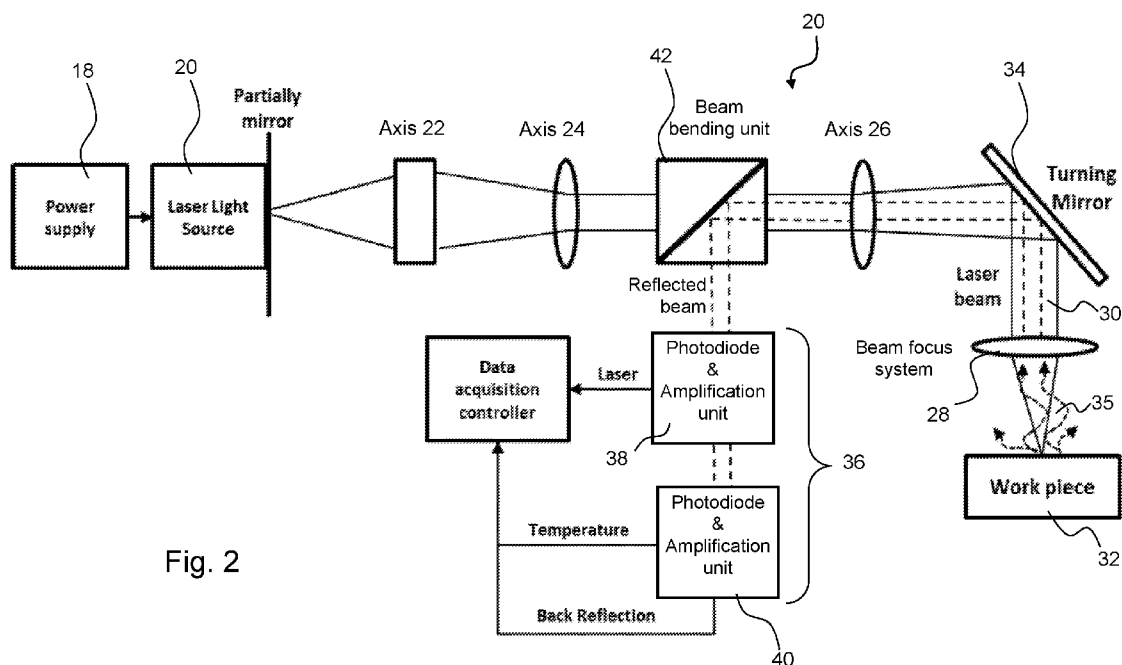


Fig. 2

(57) Abstract: There is disclosed a system and method for evaluating the quality of a joint formed between adjacent parts, for example as part of manufacturing process. The system has an energy emitter for imparting energy to the joint site in the direction of an axis so as form the joint. A non-contact sensor is arranged to sense a signal emanating from the joint site during formation of the joint, wherein the non-contact sensor is arranged to sense reflections from the joint in the direction of said axis. A feature extractor is arranged to identify signal features indicative of joint quality so as to output an indication of the quality of the formed joint.



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Joint Quality Evaluation

This disclosure concerns systems and methods for evaluating the quality of joints formed by a joining process, such as, for example remote laser welding.

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Robotic Remote Laser Welding (RLW) is emerging as a powerful and promising joining technology in automotive manufacturing, amongst other potential fields. By having laser optics embedded into the robot and a scanning mirror head, RLW can remotely create joints at different locations on a product through robot repositioning and laser beam redirection.

10 The non-contact aspect of RLW is particularly beneficial and allows the high power beam to create a weld in a fraction of a second according to the beam intensity. Unlike some other joining technologies, laser welding only requires access to one side of the joint.

The high speed with which welds can be formed makes it suited to production line use.

15 However a high throughput makes it difficult to achieve adequate joint/weld inspection so as to ensure product quality. A thorough analysis of the formed joint conventionally requires a separate inspection stage that would be unsuitable to carry out for all joints since it would significantly reduce throughput. Conventional off-line tests (i.e. X-ray or micro-sectioning), are usually expensive and/or destructive but are considered necessary to provide a clear
20 and comprehensive characterisation of weld performance. However thorough inspection of only a few of the joints/products leaves open the risk that inadequate joints could go undetected.

A solution proposed in the prior art assumes that weld quality can be inferred by measuring
25 a process parameter and inferring weld quality by reference to standard templates or look-up tables that provide a predetermined relationship between the measured parameter and the weld. Although this can be implemented quickly in-process during welding, it is sensitive to operator interpretation and does not provide a direct output of the weld Key Performance Indicators (KPI). Instead such models tend to draw on an alternative understanding of a
30 weld characteristic that can be used to imply weld quality. Certain examples of such parameters in fact represent electrical quantities which do not relate to geometrical parameters of the joints.

D. Y. You, X. D. Gao, S. Katayama, 'Review of laser welding monitoring', Science and
35 Technology of Welding and Joining, Vol 19-3, pp. 181-201, 2014, and Xiangdong Gao, Deyong You, Seiji Katayama, Infrared Image Recognition for Seam Tracking Monitoring

during Fiber Laser Welding, Mechatronics, Vol. 22, pp. 370–380, 2012, each disclose laser weld assessment approaches are based on the common idea of determining the weld indicators based on secondary information, such as the dimension of the melt pool, or the strength of the emissions from the plasma or the metal vapour. However those solutions conform to the above drawback of a template-based solution and suffer by the lack of direct correlation with the weld indicators.

M. Kogel-Hollacher, M. Schoenleber, T. Bautze, Inline Coherent Imaging of Laser Processing - a New Sensor Approach heading for Industrial Applications, 8th International Conference on Photonic Technologies LANE 2014, proposes a new sensor system, which can measure the depth of the keyhole in industrial laser welding applications. This technology relies on a physics-based approach and uses an imaging method based on the low coherence interferometry. The light of low coherence length with the aid of an interferometer is used for distance measurement of scattering materials. This method compares the distance of the reflections of an applied measurement beam with that of a reference beam in an interferometer. That process is only limited to the monitoring of the key-hole penetration only and, whilst providing important weld information, does not assess all potentially-important characteristics of weld quality.

It is an aim of the invention to provide an improved or alternative inline joint assessment system. It may be considered an additional or alternative aim to provide a joint assessment system that can address one or more specific joint KPI, e.g. a plurality of joint KPIs.

According to a first aspect of the invention, there is provided a system for evaluating the quality of a joint formed between two adjacent parts, the system comprising: a non-contact sensor arranged to sense a signal emanating from the joint site during formation of the joint; a feature extractor to identify signal features within the sensed signal indicative of joint quality so as to output for the formed joint a value of one or more of joint penetration into at least one of the adjacent parts, width of the joint, and/or joint surface profile.

The system may allow for inline joint evaluation/inspection with an automated production process.

The sensor may be arranged to sense radiation emanating from the joint during, i.e. caused by or as a result of, the joining process itself. The invention may avoid the need to

wait until the joint is formed before irradiating the joint thereafter with a bespoke radiation source to evaluate the quality of the joint.

5 The sensor may comprise an electromagnetic/radiation signal sensor, e.g. such as an optical/light sensor. A plurality of sensors or sensing units may be used. The sensor(s) may comprise one or more photodiode.

10 The sensor may be arranged to sense reflections off the joint during or immediately following joint formation. The sensed reflections may comprise, at least in part, the reflections of an energy beam and/or reflections of ambient radiation/light occurring during joint forming.

15 The joint may be formed via a surface of one of the parts and the sensor may be arranged to face, or to receive an emanating signal, in a direction substantially normal to the surface at the location of the joint.

20 The joint may be formed by application of a beam, e.g. an energy beam such a laser/electron beam, to a surface of one of the parts. The sensor may be arranged to face, or to receive an emanating signal, in a direction substantially parallel with the direction of the applied beam. The use of an in-axis sensing system is particularly convenient to a laser/beam welding arrangement since it allows the sensing system to be accommodated in a common beam application-and-sensing unit. The system may avoid the need for an additional, e.g. bespoke or off-axis, light/radiation source for joint inspection.

25 One or more signal directing member may be interposed in the signal path between the joint site and the sensor. A signal/beam bending device or splitter may be used. One or more lens and/or reflector may be used. The beam splitter may be interposed in a light path between two beam altering devices, such as lenses, within the path of the welding beam.

30

The sensor may itself be off-axis but may receive a signal emanating from the joint in the direction of the axis by which the beam is applied.

35 The sensor and a beam emitter may or may not share a common signal directing member, such as a beam reflector/mirror, splitter and/or lens.

The system may comprise a beam emitter for directing an energy beam at a joint location. The sensor and the beam emitter may be commonly mounted, supported and/or housed. The system may comprise an actuator for controlling the position and/or orientation of the beam emitter. The sensor may be mounted to the actuator with the beam emitter.

5

The joint may be formed by melting material so as to fuse the adjacent parts. The joint may be a weld.

10 The system may comprise a signal filter arranged to filter the sensed signal, for example prior to feature extraction. The signal filter may be arranged to isolate signal components resulting from distinct phenomena occurring during joint forming, e.g. according to different perceivable properties of the sensed signal. The signal filter may isolate signals according to any or any combination of: different electromagnetic wavelength ranges or bands within the sensed signal; different electromagnetic profiles in the sensed signal;

15 and/or one or more other EM radiation attribute, such as phase or dispersion.

The feature extractor may isolate features resulting from different phenomena occurring during joint formation. At least one feature may concern a thermal property. At least one feature may concern a visible light property. At least one feature may concern a plasma-

20 induced property in the sensed signal. The features may reside in a plurality of different electromagnetic wavelength ranges/bands or in one or more electromagnetic profile within the sensed signal.

According to a second aspect of the invention, there is provided a system for evaluating

25 the quality of a joint formed between two adjacent parts, the system comprising: an energy beam emitter for imparting energy to the joint site along an axis so as to form the joint; a non-contact sensor arranged to sense a signal emanating from the joint site during formation of the joint, wherein the non-contact sensor is arranged to sense reflections from the joint in the direction of said axis; and, a feature extractor arranged to identify

30 signal features indicative of joint quality so as to output an indication of the quality of the formed joint.

The sensed signal features may be used to correlate to one or more physical attribute of the joint, for example comprising one or more of: joint penetration; interface/weld width, s-value or s-distance; part-to-part gap; surface concavity of either or both of a first and/or

35

second opposing joint surfaces, and internal structure/defects. The weld interface width/dimension between the adjacent parts may be determined.

Any of the preferable features defined in relation to any one aspect of the invention may be
5 applied to any further aspect, wherever practicable.

Workable embodiments of the invention are described in further detail below with reference to the accompanying drawings, of which:

10 Fig. 1 shows a an overview of the process of implementing a system according to an example of the invention;

Fig. 2 shows a schematic example of weld forming and inspection equipment according to an example of the invention;

15

Fig. 3 shows charts/plots of attributes or phenomena occurring during weld formation derived from sensed signals using the equipment of Fig. 2;

Fig. 4 shows an example of a weld evaluation process according to the invention making
20 use of the sensed signals; and,

Fig. 5 shows examples of some weld quality assessment parameters;

The examples of the invention described hereinbelow focus on the development of a
25 quality control tool for joint data acquisition, processing and estimating of quality indicators which define the joint quality. The process has been developed for energy beam welding processes, such as remote laser welding (RLW). A significant enabler of the processes described herein was the finding that in-axis monitoring of the signals emanating from a weld site yielded a surprisingly stable signal when compared to off-axis monitoring. This
30 has allowed development of novel techniques for analysing signal data obtained during the weld forming process in order to be able to provide inline weld quality assessment.

Aspects of the invention described herein may thus derive from either or both of (i) in-axis radiation monitoring system development and installation; and (ii) data analytics
35 methodology linking data concerning light emitted from the keyhole during welding with weld KPIs obtained using welding stitch post-processing.

An overview of the process of developing the weld quality monitoring tools is shown in Fig. 1.

- 5 The initial data acquisition process 10 involves setting up hardware for capturing in-axis light/radiation reflected during laser welding from the keyhole in real time.

10 The recorded radiation signal data was processed so as to allow development at stage 12 of analytical models to link the captured signals to weld KPIs obtained through cross-sectional post-processing of weld stitches. To develop the model the in-axis monitoring signal is filtered into plasma, temperature and back-reflection using photodiode sensor. The filtered signal is then used to develop the cross-sectional signal features at the location where the KPIs are estimated. This involves 'training' and validation of the generated models at stage 14 before industrial use and quality monitoring 16. The approach described
15 herein utilizes feature selection via fold validation, feature transformation, and partial least square (PLS) based approach for analytical model development. The approach is validated using multiple KPIs, i.e., penetration, s-value and top-surface concavity on automotive door assembly process. A more complete description of a working system is described below.

20 The RLW process embeds laser optics into the robot creating a synchronous chain of mechanical and optical units. The optical and mechanical moments are utilized to create fast weld into the product with mirror or robot re-positioning. The current study embeds the monitoring sensing device itself within the optical arm of the laser to capture information generated at the weld key-hole during the welding process in real-time.

25

 The schematic representation of the laser and sensing system 20 is shown in Fig. 2. The laser comprises a conventional power supply 18 and laser light source 20 as well as a number of convention laser beam modifying devices 22, 24 and 26 arranged in the beam path upstream of a final lens 28 used to focus the laser beam 30 onto the component to be
30 welded 32. One or more turning mirror 34 may be provided in the laser path, typically upstream of the focussing lens 28 to alter the direction or axis of the laser beam towards the workpiece 32. The components 22-28 and 34 are thus spaced along the path or axis of the beam.

35 In use the laser itself operates in a conventional manner such that the radiation emitted from the laser light source is focussed onto the metal workpiece 32 so as to impart the

required energy to create a weld pool and thereby weld the workpiece to an adjacent component (not shown). Changing the relative position of optical devices 22-28, the focal length for the laser can be changed. The ability to change focal length helps to reduce the robot physical moment during the RLW process thus enhancing the welding speed.

5

During the welding process a so-called keyhole is generated which emanates light/radiation 35 during laser welding process by reflection.

10 The sensor system 36 comprises at least one photodiode and in this example a plurality of photodiodes 38 and 40. In this example, the photodiode devices comprise photodiode and amplification/filtering units. The emitted light 35 is captured and filtered using photodiodes 38, 40 for weld quality monitoring and KPIs estimations.

15 A controller 44, such as a data acquisition controller, comprising one or more processor is arranged to receive the data/signal outputs of the photodiodes 38, 40 to allow processing of the data in a manner to be hereinbelow described. It is to be noted that filtering with reference to the photodiodes or other suitable sensors may refer to optical filtering and/or electronic data/signal filtering as necessary. The use of a plurality of photodiode units 38, 40 may at least in part help achieve a filtering function in that the output of each photodiode 20 unit is distinguishable from the other.

To capture the light emitted from the workpiece 32, beam-bending unit or beam splitter 42 is installed in the path of the emitted laser beam 30 and reflected light 35, e.g. within the optical arm between Axis 24 and Axis 26 as shown in Fig. 2.

25

To embed the beam splitter into optical arm several design modifications are performed within the laser to make the in-line axis monitoring option feasible. The installed beam bending unit is tested for dimensional and optical validation, respectively. The dimension check is performed digitally to identify any potential collision between optical arm, robot and 30 installed beam bending unit. The beam splitter unit is installed between the optical axis 24 and 26. Installation of beam splitter 42 within the optical arm of the laser is followed by testing associated with any optical distortion. Design changes in beam bending unit may be made to eliminate any collision. The installed additional beam-splitter unit affects the laser focal length which is compensated by updating the configuration file for the optical arm to 35 prevent any collisions within the optical chain.

The photodiodes 38, 40 and beam splitter 42 are mounted within/to the laser support structure or housing such that the position/orientation of any or all of those components is fixed/constrained relative to the laser optical equipment.

- 5 The optical validation for the proposed system may be performed by carrying out physical weld with and without the monitoring system. The methodology for the KPIs estimation using the signal obtained from the monitoring system 20, i.e. the photodiodes 38, 40, is described below.
- 10 The radiation/light 35 emanating from the workpiece is filtered into respective wavelengths or wavelength bands using photodiodes into visible light (plasma), temperature and back-reflection as shown in Fig. 3 which shows examples of signal traces obtained using the system for a single weld operation. The traces comprise plots over time.
- 15 KPIs evaluation is performed using the reflected signal 35 captured using the in-axis monitoring system 20. The process of developing KPI estimation model is carried out in 2-steps: (i) Experimentation and data gathering; and (ii) KPIs modelling. The input and output data for developing the KPI evaluation model is captured from different phases of RLW process. During setup and development of the system, weld samples/coupons are
- 20 taken at different stages of the weld process and post-processed by preparation of the physical weld sample, including cutting through weld samples to view internal features where required, for viewing and image capture via a microscope.

The process of KPI modelling/evaluation is achieved using the following techniques.

25

Let I is the set of input parameters $\{P, S, Lt, Ut, Ia, f\}$ used during welding settings and represents the time series signal obtained from the monitoring device such as plasma, temperature and back reflection where m is the number of discrete points obtained from the in-axis device. The number of points m captured during the welding process depends

30 on the weld/stitch length (l), speed (S) and device frequency (f_s) and can be expressed as:

$$m = \frac{l}{S \times f_s}$$

The obtained raw signal T is passed through a low pass filter to remove static noise. The filtered signal is then used to create relevant features relating the KPIs. The obtained KPIs from post-processing is modelled as a response $Y \in \mathbb{R}^{n \times k}$ where n is number of observations and k is number of KPIs. The local features from signal T are generated by binning the time series signal at width w at the specified location where the KPIs are estimated.

Using the localized signals, features are generated to be used for developing model for KPIs estimation. However due to large number of noise sources, the lengths of the stitches are not consistent thus to minimize the error induced due to length compensation is performed by fixing power, speed and sampling frequency. The actual length, l , of the stitch is evaluated using the equation given above. The features are extracted based on localized signal for the estimated length.

Let $\mathbf{X}$ represents the feature space where $\mathbf{X} \in \mathbb{R}^{n \times p}$ and where p is number of parameters and n is number of samples. The polynomial transformation is performed with respect to KPIs to optimize the relationship between the KPIs and input features given above is

$$f(x) = f(x; a_0, a_1, \dots, a_m) = a_0 + a_1x + a_2x^2 + \dots + a_mx^m$$

The polynomial order is optimized using cross-validation error using objective function as given below

$$\min_{a_i} (y - f(x; a_0, a_1, \dots, a_m))^2 \quad \text{where } i=1, 2, \dots, m$$

where, y is the KPI for which the transformation is performed and x is the feature extracted from the signal. The feature or relationships extracted from the polynomial are augmented with the current features thus the features utilized for modelling can be represented as $\mathbf{X}' = [\mathbf{X}, \mathbf{X}^p]$ where $\mathbf{X} \in \mathbb{R}^{n \times p}$ are initial extracted features; and $\mathbf{X}^p \in \mathbb{R}^{n \times p'}$ is polynomial transformed features. The new feature set $\mathbf{X}' \in \mathbb{R}^{n \times 2p}$ is utilized to develop relationship between KPIs and input features using Partial Least Square (PLS) approach. The PLS approach is suited to predicting linear models especially when the number of predictor is very large with less number of observations making systems ill-conditioned. The partial least square develops the model by projecting the feature space and response into new space represented by the equations below. The independent variables in PLS is decomposed as

10

$$\mathbf{X}^t = \mathbf{T}\mathbf{P}^T + \varepsilon$$

Where $\mathbf{T} \in \mathbb{R}^{m \times l}$ is score with $\mathbf{T}^T \mathbf{T} = \mathbf{I}$ and $\mathbf{P} \in \mathbb{R}^{m \times l}$ as loading matrix with l representing the number of loading factors. Similarly, the response in PLS in can be represented as

$$\mathbf{y} = \mathbf{U}\mathbf{Q}^T + \zeta$$

5

Where $\mathbf{U} \in \mathbb{R}^{m \times l}$ are scores of $\mathbf{y}$ and $\mathbf{Q} \in \mathbb{R}^{m \times l}$ is the loading matrix. The vector ε and ζ are errors assumed to be *i.i.d* following normal distribution. The PLS search for scores $\mathbf{t} = \mathbf{X}^T \mathbf{W}$ and $\mathbf{u} = \mathbf{y} \mathbf{c}$ with the constraints $\mathbf{w}^T \mathbf{w} = 1$, $\mathbf{t}^T \mathbf{t} = 1$ and $\mathbf{t}^T \mathbf{u}$ is maximum. The identified

10 latent vectors are subtracted from both $\mathbf{X}$ as shown below

$$\mathbf{X}^{(l+1)} = \mathbf{X}^{(l)} - \mathbf{t}^{(l)} \mathbf{p}^{(l)T}$$

The score $\mathbf{t}^{(l)}$ can be determined as

$$\mathbf{t}^{(l)} = \mathbf{X}^{(l)} \mathbf{w}^{(l)}$$

15 where, $\mathbf{w}^{(l)}$ is the weight of l th column and is estimated as

$$\mathbf{w}^{(l)} = \frac{\mathbf{X}^{(l)T} \mathbf{y}}{\|\mathbf{X}^{(l)T} \mathbf{y}\|}$$

The three preceding steps are re-iterated until $\mathbf{X}$ becomes a null matrix. The cross validation error is utilized to optimize the number of latent variables (l) with root mean square error (RMSE) as an objective function.

20

3.3 KPIs estimation and Confidence Interval Evaluation

The above model is utilized to estimate the gap and KPIs such as weld penetration, S-value, top-surface concavity, and bottom surface concavity. The approach utilized to evaluate the KPIs is shown in Fig. 4, by which KPIs are determined directly from the data generated from sensors. Here it can be seen that model development stages are performed offline and feed into the final form of the transformations and KPI prediction tools used in the operation/inline system.

25

To improve the model stability and determine the confidence interval for the prediction a bootstrapping approach is integrated with PLS. Let, **B** represent the bootstrapped sample drawn using Monte Carlo algorithm from the dataset from the empirical distribution with replacement. Each bootstrap sample is n-tuples (x, y) from original dataset and the bootstrap pair is represented as

$$(\mathbf{X}^*, \mathbf{y}^*) = \{(x_{1i}, y_{1i}), (x_{2i}, y_{2i}), \dots, (x_{ni}, y_{ni})\}$$

The confidence interval is estimated from the bootstrapped pairs using bias corrected and accelerated (BC_α) method. Let $(\hat{y}_{low}, \hat{y}_{up})$ be the lower and upper bound of prediction. The bias correction on the method is performed by taking quartiles for the intended interval $(1 - 2\alpha)$ as shown below

$$(\hat{y}_{low}, \hat{y}_{up}) = (\hat{y}_{low}^{*(\alpha_1)}, \hat{y}_{up}^{*(\alpha_2)})$$

Where α_1 and α_2 are corrected percentile and determined as in

$$\alpha_1 = \Psi\left(\hat{z}_0 + \frac{\hat{z}_0 + \hat{z}^{(\alpha)}}{1 - \hat{a}(\hat{z}_0 + \hat{z}^{(\alpha)})}\right)$$

$$\alpha_2 = \Psi\left(\hat{z}_0 + \frac{\hat{z}_0 + \hat{z}^{(1-\alpha)}}{1 - \hat{a}(\hat{z}_0 + \hat{z}^{(1-\alpha)})}\right)$$

- 15 where $\hat{z}_0$ is the bias correction parameter and $\hat{a}$ is acceleration factor which correct for prediction skewness. The $z^{(\alpha)}$ represents the 100α percentile of the standard normal distribution and Ψ is the cumulative normal distribution function. The bias correction and acceleration factor are estimated using

$$\hat{z}_0 = \Psi^{-1}\left(\frac{\#\{y^* < \bar{\bar{y}}\}}{\# \text{ of paired samples in } \mathbf{B}}\right)$$

$$\hat{a} = \frac{\sum_i (\bar{\bar{y}} - \bar{y})^3}{6 \left(\sum_i (\bar{\bar{y}} - \bar{y})^2 \right)^{3/2}}$$

20

where, Ψ^{-1} is inverse of cumulative normal distribution function, $\bar{\bar{y}}$ is the mean of each bootstrap sample and $\bar{y}$ is global mean of all bootstrap sample prediction.

The above described processes for signal processing, feature extraction and KPI estimation may be performed using suitable conventional computational equipment comprising one or more data processor having machine readable instructions containing suitable algorithms and/or modules of code for implementing the above equations.

5 Based on the results, the null hypothesis in-axis signal processing is not rejected for within stitch and across stitches for same power, speed and gap parameter, whereas corresponding off-axis results are rejected. Thus the signal obtained from in-axis monitoring system is more stable and repeatable. Due to higher repeatability of the signal, the
10 predictive models are used to predict the KPIs using the real-time data captured using in-axis monitoring system.

Fig. 5 shows some examples of KPIs that can be assessed using the invention. The KPIs may generally concern the geometry/structure of the weld, for example a plurality of different
15 aspects of the weld geometry/structure. The weld penetration into a workpiece, i.e. the depth of the weld below the workpiece surface may be assessed. The weld surface profile on one or more opposing weld surface, typically an exposed or external weld surface, may be assessed, e.g. according to the shape/concavity/curvature of the weld face. Whilst not shown in Fig. 5 the weld width, e.g. at the interface between the adjoining parts may be
20 assessed and/or the location/dimension of a space within or adjacent the weld, such as the part-to-part gap or a void/defect in the weld itself.

Claims:

1. A system for evaluating the quality of a joint formed between adjacent parts, the system comprising: an energy emitter for imparting energy to the joint site in the direction
5 of an axis so as to form the joint; a non-contact sensor arranged to sense a signal emanating from the joint site during formation of the joint, wherein the non-contact sensor is arranged to sense reflections from the joint in the direction of said axis; and, a feature extractor arranged to identify signal features indicative of joint quality so as to output an indication of the quality of the formed joint.
10
2. A system according to claim 1, wherein the emitter comprises a beam emitter focussed onto the joint site.
3. A system according to claim 1 or 2, wherein the feature extractor derives from the
15 identified signal features a value for one or more of joint penetration depth, width of the joint, and/or joint surface profile.
4. A system according to any preceding claim, wherein the sensor is arranged to sense radiation reflected by the joint during the joining process, at least a component of
20 said sensed radiation being due to the energy imparted by the energy emitter.
5. A system according to any preceding claim, wherein the sensor is arranged to sense radiation reflected by the joint in a molten and/or resolidifying state.
- 25 6. A system according to any preceding claim, comprising a plurality of photodiode sensors.
7. A system according to any preceding claim, comprising a signal filter arranged to filter the sensed signal according to signal wavelength prior to feature extraction.
30
8. A system according to claim 7, wherein the signal filter is arranged to filter the sensed signal so as to isolate signal components corresponding to a plurality of: a heat signature; a visible light signature; and/or a plasma signature, and wherein the feature extractor is arranged to process each of those signal components in order to derive a
35 plurality of different indicators of the quality of the joint.

9. A system according to any preceding claim, comprising one or more signal directing member interposed in the signal path between the joint site and the sensor, the signal directing member a lens and a reflector.

5 10. A system according to any preceding claim, wherein the sensor and emitter are commonly mounted and/or housed and a common signal directing member is mounted so as to be both in a path of an emitted signal between the emitter and joint site and also in a return path of the sensed signal between the joint site and the sensor.

10 11. A system according to claim 10, wherein the common signal directing member comprises a beam splitter.

12. A system according to claim 11, wherein the beam splitter is located between two focussing devices of the emitter.

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13. A system according to any preceding claim, wherein the emitter and sensor are mounted to a common support arm structure, the support arm structure having an actuator, such as a robotic actuator, for movement of the emitter relative to either or both of the parts to be joined.

20

14. A system according to any preceding claim, wherein the joint is formed via a surface of one of the parts and the sensor is arranged to receive an emanating signal from the joint, in a direction substantially normal to the surface at the joint site.

25 15. A data carrier comprising machine readable instructions for operation of one or more processor to receive data signals from one or more electromagnetic sensor relating to sensed radiation emanating from a joint between to adjacent parts during formation of the joint, the instructions causing the one or more processor to process different filtered components of the received data signals so as to extract data features corresponding to
30 the quality of the joint and to output for the joint a value of two or more of joint penetration into at least one of the adjacent parts, width of the joint, and/or joint surface profile.

16. A system for evaluating the quality of a joint formed between two adjacent parts, the system comprising: a non-contact sensor arranged to sense a signal emanating from
35 the joint site during formation of the joint; a feature extractor to identify signal features within the sensed signal indicative of joint quality so as to output for the formed joint a

value of one or more of joint penetration into at least one of the adjacent parts, width of the joint, and/or joint surface profile.

17. A method of evaluating the quality of a joint formed between adjacent parts, the
5 method comprising:
- operating a non-contact energy emitter so as to impart energy to the joint site in the direction of an axis so as form the joint;
 - sensing a signal emanating from the joint site during formation of the joint using a non-contact sensor, wherein the non-contact sensor is arranged to sense reflections from
10 the joint in the direction of said axis; and,
 - identifying in the sensed signal data features indicative of joint quality so as to output an indication of the quality of the formed joint from the sensed signal during formation of the joint.

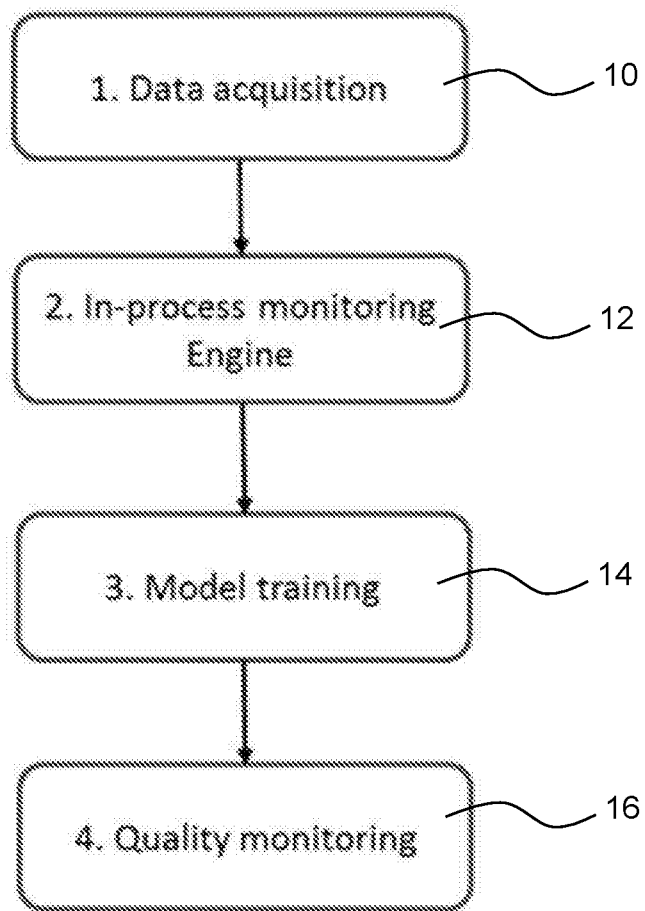
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Fig. 1

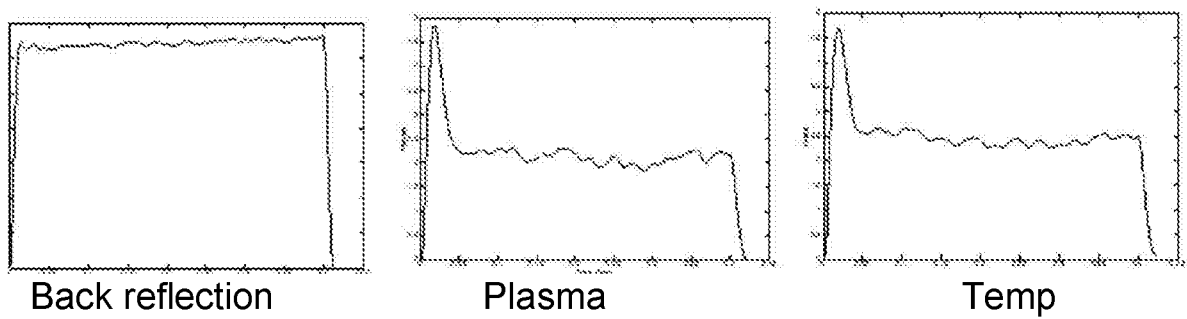


Fig. 3

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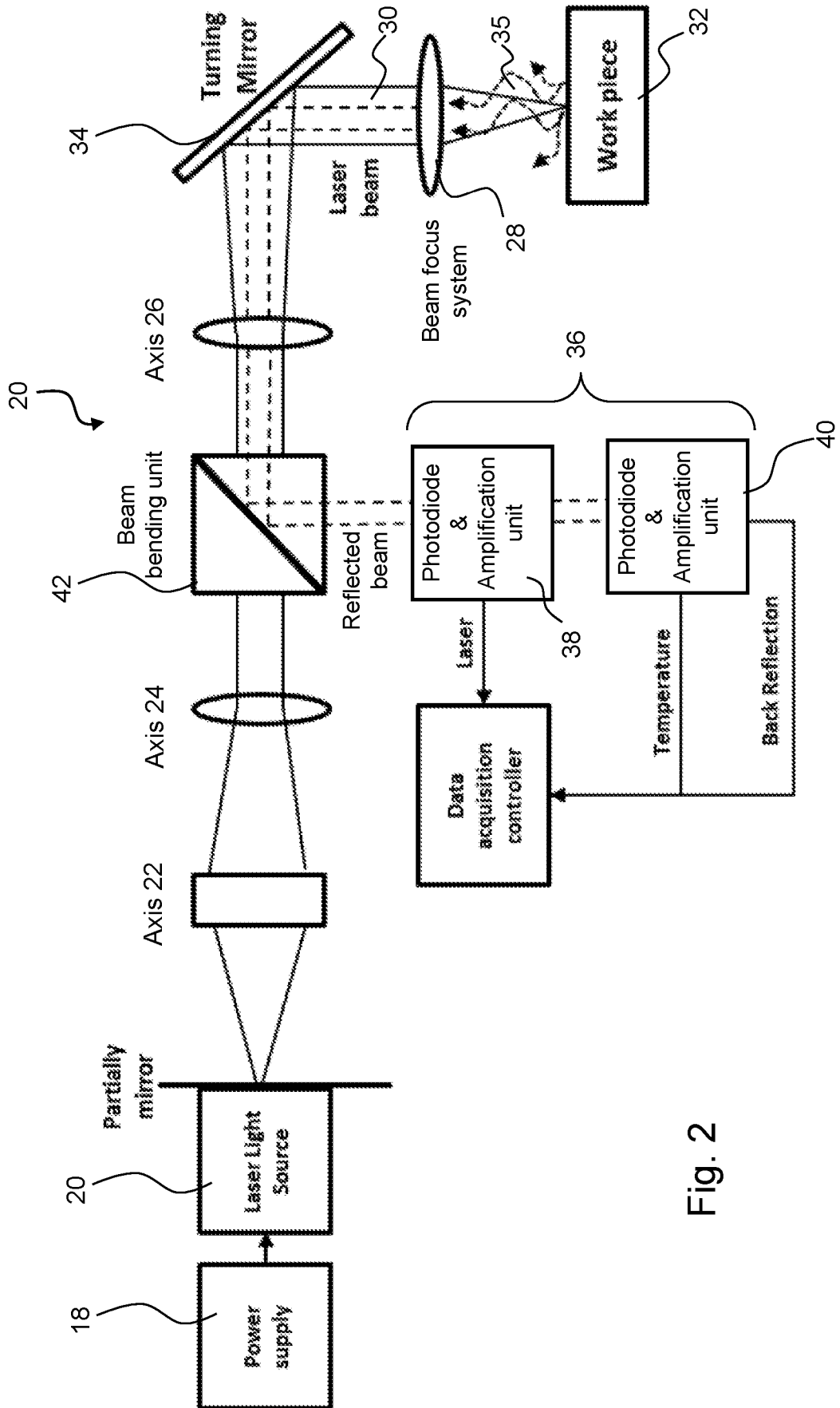


Fig. 2

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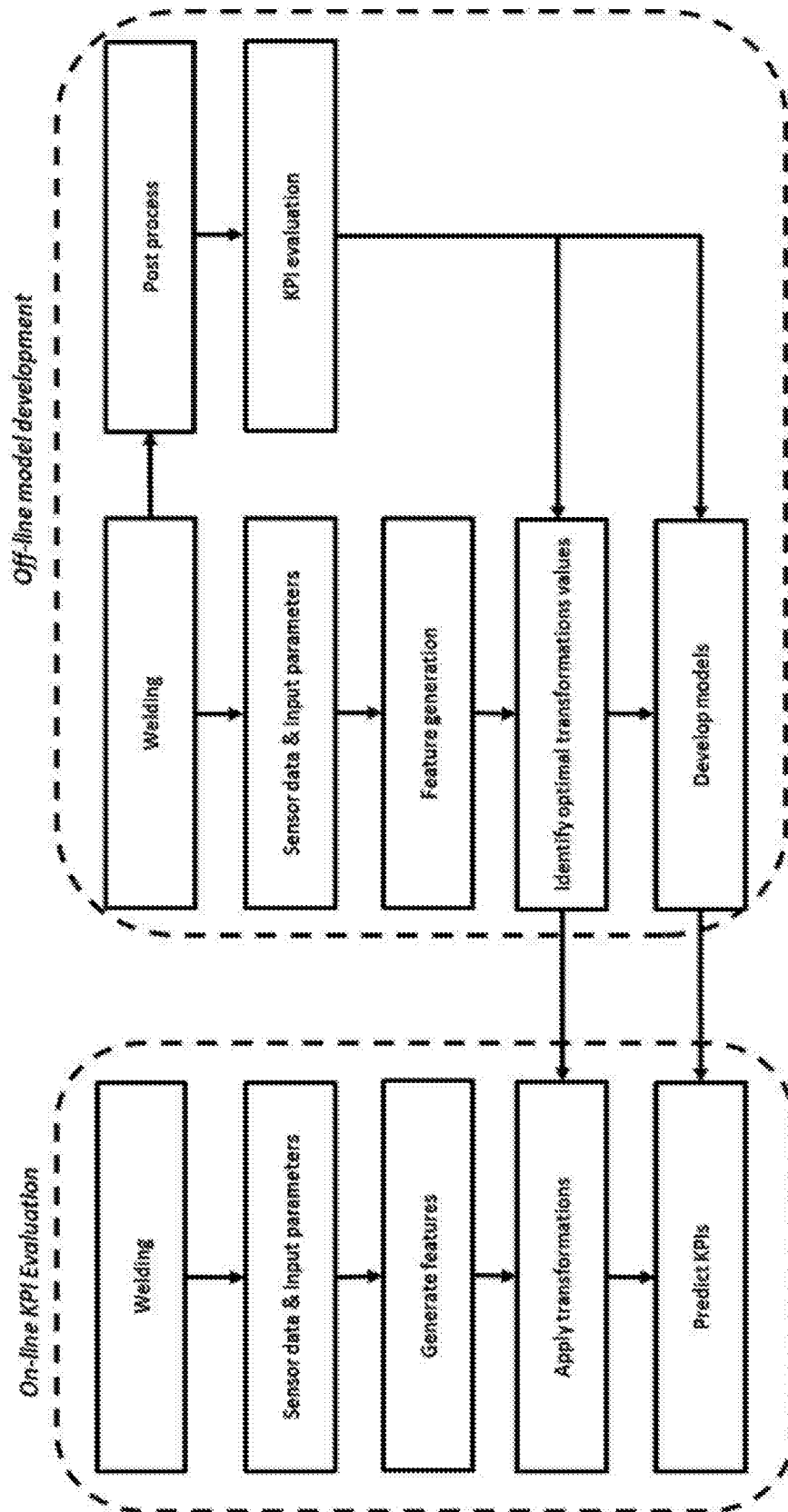


Fig. 4

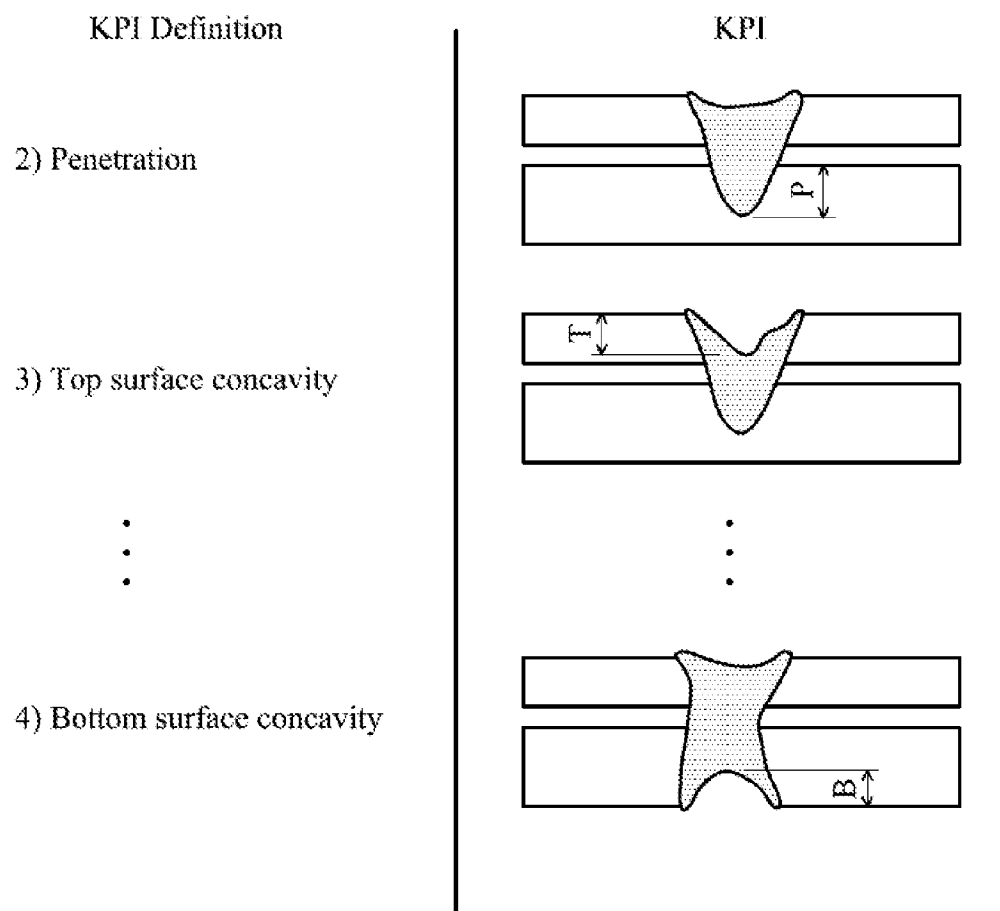
4/4

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2017/052640

A. CLASSIFICATION OF SUBJECT MATTER
INV. B23K26/03 B23K31/12
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8 653 407 B2 (OH KWANG MIN [KR]; HYUNDAI MOTOR CO LTD [KR]; KIA MOTORS CORP [KR]) 18 February 2014 (2014-02-18) column 6, lines 56-64; figures 2,6,7,10a column 7, lines 38-43 column 7, line 52 - column 8, line 43 column 8, line 53 - column 9, line 36 column 11, lines 27-35,59-63 -----	1-17
X	DE 10 2006 028250 A1 (ZEISS CARL MICROIMAGING GMBH [DE]; ZEISS CARL AG [DE]) 27 December 2007 (2007-12-27) paragraphs [0001], [0002], [0020], [0023], [0024], [0031], [0033], [0041]; figure 1 ----- -/-	1-12,14,16,17

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

2 February 2018

Date of mailing of the international search report

16/02/2018

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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/052640

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2006 015383 A1 (BOSCH GMBH ROBERT [DE]) 4 October 2007 (2007-10-04) paragraphs [0003], [0004], [0006], [0007], [0009], [0015]; figures 1,3 -----	1-11,14,16
X	DATABASE WPI Thomson Scientific, London, GB; AN 2006-245991 XP002777855, -& JP 2006 082129 A (TOYOTA) 30 March 2006 (2006-03-30) abstract; figure 1 -----	1-5,7,14,16,17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2017/052640

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 8653407 B2	18-02-2014	CN 102463419 A KR 20120053558 A US 2012125899 A1	23-05-2012 29-05-2012 24-05-2012
DE 102006028250 A1	27-12-2007	NONE	
DE 102006015383 A1	04-10-2007	NONE	
JP 2006082129 A	30-03-2006	JP 4179558 B2 JP 2006082129 A	12-11-2008 30-03-2006