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Resistance Spot Weld Quality Inference From Electrode Displacement

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Abstract

This disclosure describes a system for inferring the quality of a resistance spot weld by analyzing the displacement of a welding electrode during the welding process. Unlike traditional methods that rely solely on electrical parameters like current and time, this system directly monitors the material consolidation at the faying surfaces. By tracking the dynamic changes in electrode position, the system identifies characteristic displacement signatures corresponding to adequate nugget formation, and flags deviations indicative of weld defects such as cold welds or expulsion events. The system also incorporates mechanisms for compensating for electrode wear over time.

1. Technical Field

[0001] The technical field relates to methods and apparatus for monitoring and controlling resistance spot welding processes, particularly focusing on the inference of weld quality through real-time measurement of electrode displacement.

2. Technical Context

[0002] Resistance spot welding is a widely used joining process in various industries. Conventionally, weld quality is inferred primarily from electrical parameters such as welding current, weld time, and voltage, or through post-process destructive testing. While current and time parameters define the energy delivered to the weld, they do not directly provide information about the actual material consolidation or metallurgical changes occurring at the faying surfaces of the workpieces. Fluctuations in workpiece surface condition, shunting paths, electrode wear, or material stack-up variations can lead to inconsistent weld quality even when electrical parameters are held constant. These inconsistencies can result in defects such as cold welds (insufficient fusion), expulsion (molten metal ejection), or undersized nuggets, which compromise joint strength and integrity. There is a need for a more direct, non-destructive method to assess weld quality in real time during the process itself, providing a more accurate indication of nugget formation and defect occurrence.

3. System Overview

[0003] The disclosed system infers resistance spot weld quality by monitoring the dynamic displacement of at least one welding electrode (22, 24) during the welding cycle. As depicted in FIG. 1, a welding controller (12) orchestrates the welding process, communicating with a power supply (10) and a weld head (14). A displacement sensor (16) is integrated into the weld head (14) to measure the relative movement of the electrodes (22, 24) or the movement of one electrode relative to a fixed reference. The sensor data is captured by a data acquisition unit (18) and transmitted to an inference module (20). The inference module (20) analyzes characteristic features within the displacement signature to determine weld quality and provides feedback to the welding controller (12). This feedback enables real-time process adjustment or flagging of defective welds. The system aims to correlate specific patterns in electrode displacement, particularly the collapse phase, with the formation and growth of the weld nugget, as well as with potential defects.

4. Components

[0004] The system comprises several key components:

[0005]

- **Power Supply (10):** Delivers the high current required for resistance welding, typically controlled by the welding controller (12).
- **Welding Controller (12):** A programmable logic controller or dedicated welding control unit that manages the timing and magnitude of welding current, electrode force, and overall welding sequence. It receives inputs from the inference module (20) and can initiate appropriate responses.
- **Weld Head (14):** Comprises the mechanisms for applying force to the electrodes (22, 24) and for holding the electrodes themselves. This typically includes pneumatic or servo-electric actuation.
- **Upper Electrode (22) and Lower Electrode (24):** Conduct the welding current to the workpieces and apply the necessary forging force. The upper electrode (22) is typically movable, while the lower electrode (24) may be fixed or also movable.
- **Displacement Sensor (16):** Measures the relative displacement between the upper and lower electrodes (22, 24), or between one electrode and a fixed reference point on the weld head (14). This can be an inductive transducer, a linear variable differential transformer (LVDT), an optical encoder, or a similar device capable of high-resolution, high-speed displacement measurement. The sensor should have a linearity error not exceeding 0.5% of the full measurement range, and a response bandwidth sufficient to capture rapid changes in displacement, typically at least 1 kHz.
- **Data Acquisition Unit (18):** Receives analog or digital signals from the displacement sensor (16), converts them to a digital format if necessary, and samples the data at a high rate, for example, 5 kHz to 20 kHz. It may include filtering and amplification stages to prepare the signal for analysis.
- **Inference Module (20):** A computational unit, which may be integrated into the welding controller (12) or operate as a separate processing unit. It executes algorithms to analyze the displacement data, compare it to established reference profiles, and determine weld quality.

5. Operation

[0006] The operation of the system during a welding cycle proceeds as follows:

[0007] **Start-up and Pre-weld:** The welding controller (12) initiates the process. The weld head (14) advances the upper electrode (22) to contact the workpieces, applying a predetermined electrode force. The displacement sensor (16) begins recording the initial position.

[0008] **Steady Running (Weld Phase):**

[0009]

- **Compression and Heating:** As shown in FIG. 2, once the electrodes (22, 24) contact the workpieces, the electrode force compresses the workpieces. The power supply (10) delivers welding current. Electrical resistance at the faying surfaces generates heat, causing the material to soften and expand. This initial expansion may manifest as a slight, temporary increase in the measured electrode gap or a reduction in the rate of collapse, depending on the setup.
- **Nugget Growth and Collapse:** As heating continues, the material at the faying surfaces reaches its melting point, forming a molten nugget. The applied electrode force causes the softened and molten material to collapse, resulting in a measurable reduction in the electrode gap. This collapse, represented by Δx in FIG. 2, is the primary indicator of nugget formation and growth. A typical displacement signature shows a relatively sharp, continuous collapse phase as the nugget forms and expands. The rate of collapse and total collapse amount are critical features.
- **Hold Phase:** After the welding current is terminated, the electrode force is maintained for a hold time. During this phase, the molten nugget solidifies under pressure. The displacement typically stabilizes, with minimal further collapse or expansion.

[0010] **Fault or Interruption:**

[0011]

- **Cold Weld (Insufficient Collapse):** If insufficient heat is generated or the weld time is too short, the material may not fully melt or the nugget may not grow adequately. The displacement signature will show a collapse phase that is significantly shorter in duration, smaller in magnitude (below a predefined threshold), or slower in rate compared to a reference profile. The inference module (20) flags this as a cold weld.
- **Expulsion (Excessive Collapse or Rapid Change):** If excessive heat is generated or the electrode force is too low, molten metal can be ejected from the weld interface. This event is characterized by a sudden, rapid, and often abrupt increase in the rate of collapse, sometimes followed by an unstable displacement profile. The inference module (20) identifies this signature as expulsion and flags the weld as potentially defective.
- **Electrode Stick:** If the electrode (22) sticks to the workpiece, the displacement sensor (16) may show a lack of retraction or an abnormal retraction profile after the hold time.
- **Shunting:** While not directly visible in displacement, shunting can lead to reduced heat at the intended weld and thus a cold weld signature.

[0012] The inference module (20) continuously compares the real-time displacement signature against a set of predetermined reference profiles and thresholds. These profiles are established based on known good welds for specific material combinations and thicknesses. Deviations from these profiles trigger an inference of a defect and can initiate corrective actions by the welding controller (12), such as increasing weld current for subsequent welds, or generating an alarm for the current weld.

6. Example Embodiments

[0013] **Embodiment 1** This embodiment utilizes a single, high-resolution LVDT as the displacement sensor (16), mounted to measure the relative vertical movement between the upper electrode holder and the fixed lower arm of the weld head (14). The data acquisition unit (18) samples the LVDT output at 10 kHz. The inference module (20) calculates the instantaneous collapse velocity by differentiating the displacement signal. A good weld is characterized by a collapse velocity profile that remains within a specified envelope for a minimum duration. An abrupt spike in collapse velocity exceeding a high threshold, followed by a plateau or recovery, indicates expulsion. A collapse velocity that remains below a low threshold throughout the weld phase indicates a cold weld.

[0014] **Embodiment 2** This configuration employs two optical encoders as displacement sensors (16), one measuring the movement of the upper electrode (22) and another providing a reference from a fixed point on the weld head (14) that compensates for machine frame deflection. The inference module (20) uses a neural network model, trained on displacement profiles from known good and defective welds, to classify the quality of each weld. The model processes features such as total displacement, maximum collapse rate, time to peak collapse rate, and integral of the collapse rate over the weld duration. This allows for more nuanced defect detection and classification beyond simple thresholding.

[0015] **Embodiment 3** In this embodiment, the displacement sensor (16) is a high-speed laser triangulation sensor directed at a reflective target on the upper electrode holder. The data acquisition unit (18) incorporates a real-time digital signal processor (DSP) that performs wavelet transform analysis on the displacement signal. Specific frequency components and amplitudes within the wavelet coefficients are correlated with nugget formation and defect characteristics. For instance, high-frequency oscillations during the collapse phase may indicate localized material instability or micro-expulsion, even before a major expulsion event occurs. Electrode wear compensation is performed by adjusting the nominal start position based on a periodic reference weld on a test coupon.

7. Alternative Configurations

[0016] Instead of measuring vertical displacement, the system could be configured to measure acoustic emissions or vibration signatures, which are also related to material behavior during welding, and correlate these with displacement data for enhanced inference. Another alternative involves integrating a force sensor into the weld head (14) to simultaneously monitor electrode force alongside displacement, allowing for calculation of dynamic workpiece stiffness as an additional quality indicator. The displacement sensor (16) could also be located closer to the electrode tip, for example, within the electrode holder itself, to minimize the influence of machine compliance. Furthermore, the inference module (20) could utilize a Kalman filter to estimate the true displacement profile, reducing noise and improving the accuracy of feature extraction from the sensor data.

8. Parameter Variations

Parameter	Range	Effect of Moving Towards Low End	Effect of Moving Towards High End
Electrode Force	100 to 500 daN	Insufficient material forging, increased expulsion risk	Excessive indentation, potential for cold welds due to shunting
Weld Current	5 to 20 kA	Insufficient heat, small nugget, cold weld	Excessive heat, large nugget, high risk of expulsion
Weld Time	5 to 50 cycles (50 Hz)	Insufficient heat input, small nugget, cold weld	Excessive heat input, larger nugget, increased expulsion risk
Hold Time	5 to 30 cycles (50 Hz)		

Parameter	Range	Effect of Moving Towards Low End	Effect of Moving Towards High End
		Premature electrode separation, porosity, reduced strength	No significant benefit beyond adequate cooling, cycle time increase
Material Thickness	0.5 to 3.0 mm	Faster heating, smaller collapse, higher risk of burn-through	Slower heating, larger collapse, higher current/time needed
Electrode Tip Diameter	5 to 12 mm	Higher current density, localized heating, faster collapse	Lower current density, broader heating, slower collapse
Displacement Sample Rate	1 kHz to 20 kHz	Loss of high-frequency detail, missed rapid events (expulsion)	Increased data volume, higher processing load, minimal added detail
Tolerance for Collapse	±10% to ±30% of reference	Higher rejection rate for minor deviations, potentially good welds	Lower rejection rate, acceptance of marginal or defective welds

9. Additional Implementations

[0018] The system can be expanded to include adaptive process control. If the inference module (20) repeatedly detects a trend towards cold welds, the welding controller (12) can be configured to automatically increase the welding current or weld time for subsequent welds within a predefined adjustment window. Conversely, if expulsion is repeatedly detected, the welding current could be incrementally reduced or the electrode force increased. This closed-loop feedback mechanism allows the system to self-optimize and maintain consistent weld quality over production runs, compensating for gradual changes like electrode wear or minor variations in incoming material properties. Furthermore, the stored displacement signatures for each weld can serve as a comprehensive quality record, providing traceability and supporting statistical process control initiatives. The system may also integrate pre-weld displacement measurements, such as workpiece stack height variation, to predict potential welding issues before current application and adjust initial parameters accordingly.

10. Figures

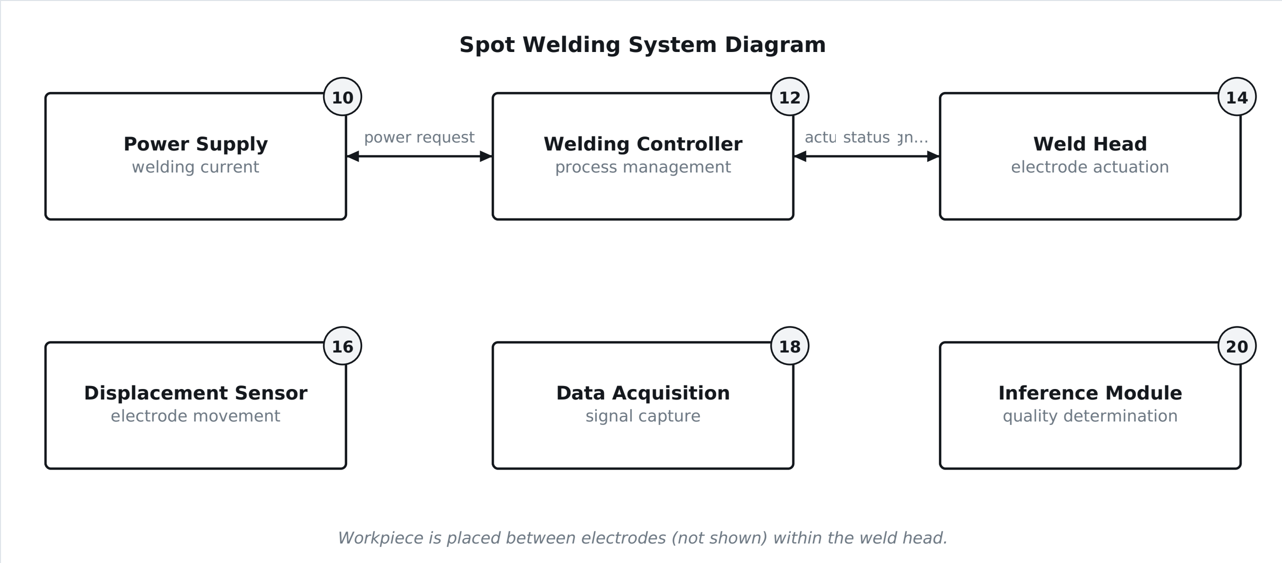

FIG. 1 A simplified block diagram illustrating the primary components of a resistance spot welding system with displacement monitoring. PNG

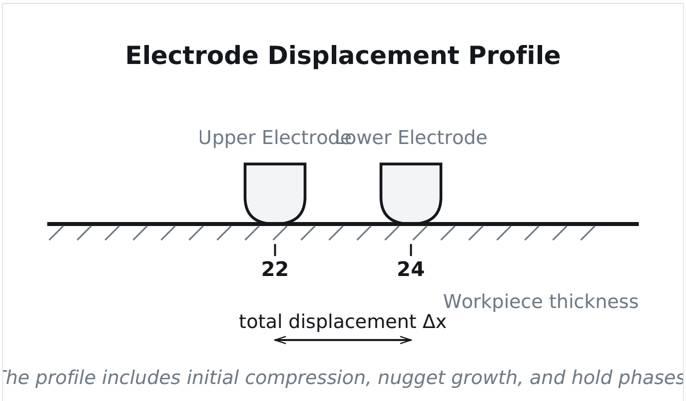

FIG. 2 An idealized representation of electrode displacement over time during a typical resistance spot welding cycle. PNG

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