In a resistance welding method, by controlling the power amount from a melting start time onward, the weld quality may be stabilized efficiently, even when a disturbance is present, because of the correlation between the amount of power input from the melting start time and a resulting nugget. The resistance welding method includes: pressing an electrode against a workpiece; inputing power to the workpiece through the electrode to subject the workpiece to Joule heating; detecting the melting start time, which is the time at which at least a portion of the faying portion of a workpiece starts to melt when subjected to Joule heating; calculating a first power amount input into the workpiece from the melting start time; and determining whether the first power amount has reached a first set value; and continuing the Joule heating until the first power amount reaches the first set value.
FIG. 1

<table>
<thead>
<tr>
<th>TYPES OF DISTURBANCES</th>
<th>NO DISTURBANCE</th>
<th>SURFACE TILT</th>
<th>GAP BETWEEN PLATES</th>
<th>ELECTRODE WEAR</th>
<th>DIVERGENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- No Disturbance
- Surface Tilt
- Gap Between Plates
- Electrode Wear
- Divergence

- Joint Gap
- Electode Wear
- Divergence
- Current Path
- Welded Spot
FIG. 2

NO DISTURBANCE
SURFACE TILT 3°
GAP BETWEEN PLATES 1 mm
ELECTRODE WEAR
DIVERGENCE

INPUT POWER AMOUNT Q FROM START OF ENERGIZATION (kWs)

NUGGET DIAMETER D (mm)
**FIG. 4**

- **NUGGET DIAMETER D (mm)**
- **INPUT POWER AMOUNT Q (kWs)**

- **NO DISTURBANCE**
- **SURFACE TILT 3°**
- **GAP BETWEEN PLATES 1 mm**
- **ELECTRODE WEAR**
- **DIVERGENCE**
FIG. 7

START

SET WELDING CONDITION S11

APPLY PRESSURE TO WORK PIECE USING ELECTRODES S12

HEATING ENERGIZATION S13

CALCULATE SECOND POWER AMOUNT Q2 (t) S14

NO

Q2(t) ≥ X2(t) ?

YES

SPECIFY MELTING START TIME t0 S16

CALCULATE FIRST POWER AMOUNT Q1 S17

NO

Q1 ≥ X1 ?

YES

HALT ENERGIZATION, SEPARATE ELECTRODES FROM WORK PIECE FOLLOWING FIXED COOLING PERIOD S19

END
BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The invention relates to a method relevant to resistance welding such as spot welding, a resistance-welded member, a resistance welder, a control apparatus for the resistance welder, a control method and a control program for the resistance welder, a resistance welding evaluation method, and a resistance welding evaluation program.

[0003] 2. Description of the Related Art

[0004] Welding is often employed when joining a plurality of materials because of its low cost and the ease with which strength can be secured. Spot welding, which is a type of resistance welding, is often employed to weld overlapped steel plates (a plurality of workpieces) efficiently at a plurality of locations (spots), for example, in an automobile body or the like. Spot welding typically joins the workpieces by passing a large current through the workpieces for a short time from electrodes that sandwich outer side of each workpiece such that the faying portion on the respective inner sides of each workpiece is melted and solidified.

[0005] Incidentally, spot welding differs from other types of welding, such as arc welding, in that the faying portion is positioned on the inner side of the workpieces, making it difficult to observe the welding location directly. Furthermore, in a mass production process, it is not realistic for an operator to inspect the condition of the spot weld point by point in detail using a jig or the like. Therefore, various methods have been proposed to stabilize the weld quality by equalizing the size of nuggets (melted and solidified portions of the workpieces) formed during the spot welding process. For example, Japanese Patent Application Publication No. 62-64483 (JP-A-62-64483), describes this problem.

[0006] JP-A-62-64483 describes a resistance welding process in which a welding current is applied until the amount of energy applied reaches a target total energy value. On an actual welding site, however, welding is performed under various unexpected conditions (disturbances). For example, if two steel plates serve as the workpieces that are resistance-welded, a gap may separate the steel plates; the steel plates may tilt, and a tip end portion of an electrode pressed against the steel plates may become worn. When such disturbances are present, alignment condition of the steel plates (in particular, a faying surface area) varies. As a result, a Joule heat amount and a radiation amount generated in the faying portion are varied by the disturbances, leading to variation in an amount of heat used effectively during the welding. According to the welding process described in JP-A-62-64483, it is difficult to stabilize the weld quality without taking disturbances into account and simply focusing on the total energy (total amount of power) input into the workpieces from the start of energization.

SUMMARY OF THE INVENTION

[0007] The invention provides a resistance welding method with which a resistance welding quality can be stabilized even when a disturbance occurs in a condition of a faying portion (a joint between workpieces), a contact condition between the workpieces and electrodes, and so on while actually welding the workpieces, and a resistance-welded member obtained thereby. The invention also provides a resistance welder suitable for implementing this resistance welding method as well as a control method, a control apparatus, and a control program thereof. The invention further provides a resistance welding evaluation method and a resistance welding evaluation program.

[0008] As a result of committed research and repeated trial and error with the aim of solving the aforesaid problems, the inventor has newly discovered that even when various disturbances exist on a welding site, these disturbances have substantially no effect once Joule-heated workpieces begin to melt, and therefore, by advancing resistance welding in accordance with an input energy (an input power amount) and adjusting the input energy (input power amount), a desired nugget can be formed. By developing this discovery, the inventor arrived at various inventions relating to resistance welding, to be described below.

[0009] An aspect of the invention provides a resistance welding method including: pressing an electrode against the workpiece; subjecting the workpiece to Joule heating by inputting power through the electrode into the workpiece; detecting a melting start time, which is a time at which at least a portion of a faying portion of a workpiece starts to melt (i.e., detection process); calculating a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time (i.e., calculation process); determining whether the first power amount or a welding index value that indexes a welding condition of the faying portion corresponding to the first power amount has reached at least a first set value (i.e., a first determination process); and continuing the Joule heating from the melting start time until the first power amount or the welding index value reaches at least the first set value (i.e., heating process), wherein formation of the nugget through melting and solidification of the faying portion can be stabilized.

[0010] According to the resistance welding method described above, after resistance welding of the workpiece has begun, or in other words after the electrode has been energized in order to Joule-heat the workpiece, first, the time (melting start time) at which at least a part of the faying portion of the workpiece starts to melt while being Joule-heated is detected. An energy (input power amount) input into the workpiece is then calculated using the melting start time as a starting point. By focusing on the first power amount, i.e., the amount of power input from the melting start time onward, the size of the nugget formed in the faying portion of the workpiece can be controlled appropriately even in a condition where various disturbances exist. More specifically, by performing Joule heating until the first power amount obtained by integrating the input power amount from the melting start time onward or the welding index value obtained by converting the first power amount into a nugget size (nugget diameter) or the like reaches at least a predetermined set value (the first set value), the welding quality can be stabilized even on a welding site where various disturbances exist.

[0011] Note that in this specification, the term “reaches at least the set value” includes a case in which a subject value is contained within a specific range. Accordingly, the set value may be an upper limit value (a final target value) or a minimum reach value (a lower limit value). In the case of the invention, the heating process may be stopped when the cal-
culated first power value or the corresponding welding index value reaches the first set value or continued for as long as the first power value or welding index value remains within a certain range exceeding the first set value. Further, the “welding index value” may be any value that indexes the condition of the resistance welding accurately, a representative example thereof being the nugget diameter. Furthermore, there are no limitations on the method of calculating the “power amount” according to this specification. Specific numerical values of the respective power amounts described in this specification are not important in themselves as long as they serve as accurate indices correlating with the melting start time of the workpiece, the diameter of the formed nugget, and so on.

[0012] In the resistance welding method according to the invention, detection or specification (estimation) of the melting start time is important for achieving stability in the welding quality of the workpiece on the basis of the first power amount calculated from the melting start time. The melting start time is basically the point at which the faying portion of the workpiece starts from a solid phase to a liquid phase, and therefore the melting start time may be detected by focusing on variation in physical property values of the workpiece such as variation in the temperature, the volume, and so on of the melting portion. The inventor has discovered a new method of detecting the melting start time precisely and easily even when various disturbances exist in the vicinity of the melting subject and the electrode, regardless of the type of disturbance. More specifically, the inventor has discovered that the melting start time may be detected by performing a second power amount calculation process for calculating a second power amount, by integrating the total power input into the workpiece, in accordance with an elapsed time from an energization start time, which is a time at which energization of the electrode for Joule-heating the faying portion begins; and a second determination process for determining the melting start time as a time at which the second power amount reaches at least a melting start power amount, which is a power amount input until at least a portion of the faying portion actually begins to melt and is determined in advance in accordance with the elapsed time from the energization start time, or a second set value set on the basis of the melting start power amount (in other words, the constitution of the aforementioned detection process). The reasons for this are as follows.

[0013] When a “disturbance” occurs such that a disposal condition of the workpiece to be welded, a contact condition between the workpiece and the electrode, and so on deviate from their originally envisaged conditions (standard conditions), the actual melting start time varies. This fact is corroborated by test results obtained from an investigation into the input power amount integrated from the start of energization of the electrode and the diameter of the formed nugget (see FIG. 2). Hence, at first glance, it appears to be difficult to detect the melting start time with a high degree of precision in conditions where an unspecified disturbance exists. However, after investigating the melting start time of the workpiece under various disturbances, it was found that a correlative relationship exists between the energization period up to the melting start time and the input power amount (melting start power amount) up to the melting start time. In other words, it was found that a cumulative power amount (melting start power amount) required for the workpiece to start melting is expressed by a function of the elapsed time following the start of energization (an initial energization period). More specifically, when the workpiece starts to melt after a short period following energization, the input power amount is small, and when the workpiece starts to melt after a long period following energization, the input power amount increases. Hence, it was learned that the melting start power amount has a monotonically increasing relationship with the initial energization period. Therefore, by detecting the point at which a power amount (the second power amount) calculated in accordance with the elapsed time from the start of energization (the initial energization period) reaches at least the melting start power amount determined likewise in accordance with the elapsed time from the start of energization (the initial energization period), it can be determined that the workpiece starts to melt at this point, and therefore this point can be determined as the melting start time without the need to specify the type of disturbance.

[0014] Incidentally, the reason why the initial energization period and the melting start power amount have the above relationship may be described simply as follows. When a disturbance exists, a contact resistance and a current density of the faying portion vary, leading to corresponding variation in an amount of heat generated in the melting portion per unit time (a heat generation rate). Therefore, when the contact resistance and current density are large such that the heat generation rate of the faying portion is also large, for example, the faying portion increases in temperature and melts quickly. Conversely, when the contact resistance and current density are small such that the heat generation rate is also small, a long time is required for the faying portion to increase in temperature and melt.

[0015] In the invention, a current value and a voltage value employed to energize the electrode that contacts the workpiece during the resistance welding do not necessarily have to be fixed. The current value and voltage value applied to the workpiece may be modified appropriately before the first power amount reaches the first set value set in accordance with the desired nugget diameter or the like, and for each welding spot. Hence, the heating process according to the invention may include a heating modification process for modifying a heating condition of the workpiece on the basis of a determination result obtained in the first determination process. This may be applied similarly to detection of the melting start time of the workpiece. When detecting the melting start time, the relationship between the energization period until the workpiece starts to melt, the second power amount calculated in accordance with the energization period, and the melting start power amount determined in accordance with the energization period is important. Therefore, the current value and voltage value applied to the workpiece may be modified appropriately during calculation of the second power amount and for each welding spot.

[0016] Note that the content described here may be applied appropriately to a resistance welder, a control apparatus thereof, a control method thereof, a control program thereof, a resistance welding evaluation method, a resistance welding evaluation program, and so on, to be described below. In this case, the “processes” included in the constitution of the invention described above should be read as “steps” or “units” as required.

[0017] By employing the resistance welding method described above, a product in which welding defects are suppressed and the welding quality is stabilized can be obtained. Therefore, the invention may be understood not only as a resistance welding method, but also as a resistance-
welded member having stable nugget shapes and so on, which is not available in the related art.

[0018] The invention may also be understood as a resistance welder and a control apparatus thereof for realizing the resistance welding method described above. More specifically, the invention may be a control apparatus for a resistance welder having an electrode that contacts an external surface of a workpiece and a power supply apparatus that supplies a heating current for Joule-heating a faying portion of the workpiece to the electrode, including: a melting start time detection unit that detects a melting start time, which is a time at which at least a part of the faying portion starts to melt while being subjected to Joule heating by a power input into the workpiece from the electrode; a first power amount calculation unit that calculates a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time; a first determination unit that determines whether or not the first power amount or a welding index value that indexes a welding condition of the faying portion corresponding to the first power amount has reached at least a first set value; and a heating unit that performs the Joule heating from the melting start time until the first power amount or the welding index value reaches at least the first set value.

[0019] Further, the invention may be a resistance welder including: an electrode that is pressed against a workpiece; a power supply apparatus that supplies a heating current for Joule-heating a faying portion of the workpiece to the electrode; and the control apparatus described above for controlling the power amount input into the workpiece from the power supply apparatus.

[0020] Furthermore, the invention may be understood as a control method or a control program for the resistance welder described above. More specifically, the invention may be a control method for a resistance welder having an electrode that contacts an external surface of a workpiece and a power supply apparatus that supplies a heating current for Joule-heating a faying portion of the workpiece to the electrode, including the following steps: a melting start time detecting step of detecting a melting start time, which is a time at which at least a part of the faying portion starts to melt while being subjected to Joule heating by a power input into the workpiece from the electrode; a first power amount calculating step of calculating a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time; a first determining step of determining whether or not the first power amount or a welding index value that indexes a welding condition of the faying portion corresponding to the first power amount has reached at least a first set value; and a heating step of performing the Joule heating from the melting start time until the first power amount or the welding index value reaches at least the first set value.

[0021] The invention may also be a control program for a resistance welder that causes a computer to execute this control method for a resistance welder.

[0022] In addition, the invention may be understood as a resistance welding evaluation method and a resistance welding evaluation program. More specifically, the invention may be a resistance welding evaluation method including the following steps: a melting start time detecting step of detecting a melting start time, which is a time at which at least a part of a faying portion of a workpiece starts to melt while being subjected to Joule heating by a power input from an electrode pressed against the workpiece; a first power amount calculating step of calculating a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time; and an estimating step of estimating a welding condition of the faying portion on the basis of the first power amount.

[0023] In addition to the resistance welding evaluation method described above, the invention may be a resistance welding evaluation method including the following steps: a second power amount calculating step of calculating a second power amount, by integrating the total power input into a workpiece from an electrode pressed against the workpiece, in accordance with an elapsed time from an energization start time, which is a time at which energization of the electrode for Joule-heating a faying portion of the workpiece using the power input from the electrode begins; and a second determining step of determining a melting start time as a time at which the second power amount reaches at least a melting start power amount, which is a power amount input until at least a part of the faying portion actually begins to melt and is determined in advance in accordance with the elapsed time from the energization start time, or a second set value set on the basis of the melting start power amount, wherein the melting start time at which at least a part of the workpiece to be resistance-welded begins to melt can be detected. The latter resistance welding evaluation method may be incorporated into the "melting start time detecting step" of the former resistance welding evaluation method.

[0024] Moreover, the invention may be a resistance welding evaluation program for causing a computer to execute these resistance welding evaluation methods.

[0025] Note that the estimating step described above may be an evaluating step of evaluating the welding condition according to whether or not the calculated first power amount or the welding index value indexing the welding condition of the faying portion, which is determined from the first power amount, is within a predetermined range. Further, the estimating step is more preferably a nugget estimating step of estimating, on the basis of the first power amount, a size of the nugget formed when the melting portion melts and solidifies.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The features, advantages, and technical and industrial significance of this invention will be described in the following detailed description of example embodiments of the invention with reference to the accompanying drawings, in which like numerals denote like elements, and wherein:

[0027] FIG. 1 illustrates the various disturbances that may occur during resistance welding;

[0028] FIG. 2 is a graph showing the correlation between the input power amount from the start of energization of a workpiece existing under various disturbances and a diameter of a formed nugget;

[0029] FIG. 3 is a graph showing the correlation between the energization period and the input power amount applied to the workpiece existing under various disturbances;

[0030] FIG. 4 is a graph showing the correlation between the input power amount applied to the workpiece from a melting start time of the workpiece and the diameter of the formed nugget;

[0031] FIG. 5 is a schematic view showing a spot welder according to an embodiment of the invention;

[0032] FIG. 6 is a schematic view showing the vicinity of a faying portion on the workpiece;
FIG. 7 is a flowchart of a welding method employed by the spot welder according to an embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

The invention will now be described in detail in the context of an embodiment thereof. The following description focuses mainly on a resistance welding method according to the invention, but the content of the description may be applied appropriately not only to the resistance welding method, but also to a resistance-welding member, a resistance welder, a control apparatus for the resistance welder, a control method for the resistance welder, a control program for the resistance welder, a resistance welding evaluation method, and a resistance welding evaluation program. The invention further encompasses a configuration obtained by adding one or more constitutions selected as desired from the constitutions cited hereinafter to the constitutions described above. The configuration to be added may be selected concomitantly or arbitrarily regardless of category. Note that the decision as to which embodiment is optimal will differ according to subject, required performance, and so on.

First, resistance welding and disturbances, which are important prerequisites to understanding the invention, will be described. In resistance welding, a joint is formed by energizing an electrode pressed against a workpiece. Resistance heat (Joule heat) is generated due to various types of resistance existing in a faying portion. Then, the temperature of the faying portion of the workpiece is increased in accordance with a heat amount difference, which is obtained by subtracting an amount of radiation generated. A part of the amount of generated resistance heat is radiated to the workpiece itself, the electrode, and so on from the resistance heat generation amount. Then, the faying portion melts, and the faying portion is cooled until the faying portion solidifies. For example, a set of metal plates may be subjected to resistance welding. First, the set of plates that serves as the workpieces are pressed into close contact by electrodes or the like. The electrodes are then energized and Joule heat is generated between contact surfaces (joints) of adjacent plates. Accordingly, the area near the contact surfaces melts preferentially. When energization is complete, the workpieces are cooled so that the melted portion solidifies, thereby forming a nugget. The resistance welding is then terminated.

The reason the area near the contact surfaces of the workpieces to be joined melts preferentially during the resistance welding is that a contact resistance in this region is higher than the resistance in other parts. However, the contact resistance is greatly affected by a contact condition between the workpieces, and furthermore, on an actual welding site, deviations (disturbances) from an ideal contact condition (a standard condition) often occur. Therefore, even if conditions such as the applied current value, the energization period, and so on remain constant, the form of the resulting weld of the faying portion may vary. It is of course possible to perform welding with stability even when disturbances are present by calculating the radiation amount and so on accurately if the required amount of heat to melt the faying portion is input in real time during the welding process. In reality, however, this type of energization heating is difficult. Hence, in conventional resistance welding, irregularities of the faying portion and excessive input power amounts make it difficult to form a stable weld efficiently.

However, the effect of disturbances continues to be either small or substantially non-existent until the faying portions of the workpiece begin to melt, and the effect of disturbances is negligible after the faying portions of the workpieces begin to melt. Hence, by focusing on the point at which the workpiece begins to melt onward, the amount of power input into the workpiece may be optimized in accordance with the desired welding parameter (a nugget size, for example), and as a result, a stable weld may be formed. However, these prerequisites, i.e. the melting start time of the workpiece and the amount of power input up to the melting start time, vary according to the type of disturbance, and it is therefore difficult to determine or specify the melting start time of the workpiece precisely based only on the amount of power input into the workpiece from the start of energization.

For example, if the disturbance illustrated in Pattern III of FIG. 1 is present, the contact area of the faying portion is smaller than that of the disturbance illustrated in Pattern IV, and therefore the contact resistance is greater. Even if the total current value passed through the electrode is identical in both cases, resistance in the faying portion is lower in the former case, leading to an increase in a density of the current flowing through the faying portion, and as a result, heat is generated rapidly by the faying portion (in other words, the rate of heat generation is greater), causing the temperature of the faying portion to increase rapidly. Further, due to the temperature increase, a temperature-dependent specific resistance value also increases rapidly. As a result, melting begins much earlier in the former case than in the latter, leading to reductions in wasteful radiation and the amount of power input up to the start of melting.

In a power amount calculation process according to the invention, the power amount is calculated based on the magnitude of the current passed through the electrode pressed against the workpiece and so on. The power amount is determined as an integrated value of the current, voltage, and time, but may be determined from a transformed formula. The current passed through the electrode may be a direct current or an alternating current, and when an alternating current is applied, the power amount may be calculated based on an effective value.

A determination process according to the invention is performed by comparing the power amount calculated in the power amount calculation process or an index value corresponding to the power amount with a set value. The set value is appropriately selected depending on whether the subject of the comparison is the power amount or the index value. A representative index value is the size of the nugget (the nugget diameter) formed by melting and solidifying the faying portion of the workpiece. Since the nugget is not formed until the workpiece starts to melt, the input power amount calculated as needed in accordance with an energization period is preferably compared directly with a melting start power amount determined in accordance with the energization period or a set value based on the melting start power amount.

There are no limitations on the shape, material, and so on of the workpieces. Representative workpieces may be overlapped steel plates. For example, soft steel plates having a thickness of approximately 0.5 to 3 mm and a carbon content (C) of 0.05% to 0.2% by weight are commonly subjected to. Alternatively, suitable workpieces may also be made from materials such as high strength (high tension) steel, galvanized steel, stainless steel, aluminum (Al), Al alloy, copper
(Cu), Cu alloy, nickel (Ni), and Ni alloy. Furthermore, the workpieces may be constituted by a combination of different materials. The power amount and so on required to obtain a faying portion having a desired form vary according to the material of the workpieces. Accordingly, the set value, melting start power amount, and so on that are compared to the power amount calculated during the resistance welding differ according to the material and form of the workpieces, the manner in which the workpieces are arranged, the pressure applied by the electrodes, and so on.

There are no limitations on the shape, material, and so on of the electrode. The electrode is typically made of a column or cylinder of copper. If the electrode is cylindrical, coolant is preferably supplied to the interior of the electrode to cool the electrode, thereby suppressing wear. An end surface of the electrode that contacts the external surface of the workpiece is often circular or gently conical. If the resistance welding is performed favorably, the nugget in the weld is generally formed in the same shape as that of the electrode end surface, so that the nugget is substantially circular. In this case, the size of the nugget is represented by its diameter (the nugget diameter). In this specification, the size of the nugget will be referred to as the nugget diameter for convenience.

A power supply apparatus may be an alternating current power supply or a direct current power supply. In the case of an alternating current power supply, it may be a single-phase power supply, a three-phase power supply, and so on. Further, the power supply apparatus may be a constant current power supply or a constant voltage power supply. If a constant current power supply is used, the amount of generated Joule heat increases as the workpiece is heated to a steadily higher temperature. As a result, the nugget obtained through melting and solidification of the workpiece is formed more reliably, and therefore a constant current power supply is preferable. Note that a favorable current value and so on supplied to the workpiece from the electrode differs according to the material of the workpiece, the desired nugget diameter, the energization period, and so on.

A specific embodiment of the invention will now be described. Resistance welding (spot welding) on a cut model of a workpiece (the workpiece) constituted by two overlapped steel plates under various disturbances was performed, and the welding process was photographed using a high-speed camera. The formation process of a nugget formed by the spot welding was thus observed. More specifically, (1) spot welding was performed by setting five representative patterns I to V as shown in FIG. 1. In Pattern I, in FIG. 1, the two overlapped steel plates were pressed together by the electrodes so that a central axis of the electrodes is normal to the faying portion of the workpiece. In Pattern II, the workpiece was tilted 3° from the horizontal direction, relative to the standard condition of Pattern I. In Pattern III, a gap was formed on the periphery of the faying portion. More specifically, a spacer having a thickness of 1 mm was interposed in positions located 15 mm (30 mm) on either side of the welding center of the overlapped steel plates. In Pattern IV, the circular shape on the tip end surface (the surface that contacts the workpiece) of the electrode was enlarged from a diameter of 5 mm to a diameter of 7 mm. Here, d is a diameter of the circle formed on the tip of the electrode. It should be noted that the tip end surface of the electrode is connected to a peripheral side face of the electrode by a curved surface having a curvature radius of 40 mm. In Pattern V, the current supplied from the electrode flowed to a point that has already been welded other than the present welding spot, in which welding had been completed in the previous process.

After setting the workpiece and the electrode in the respective patterns described above, the workpiece was spot-welded. At this time, an integrated value of the power input into the workpiece was calculated as an input power amount Q. Further, the diameter D of the resulting nugget formed in the workpiece in accordance with the input power amount Q was measured. The input power amount Q and the nugget diameter D were then plotted in a graph, as shown in FIG. 2. The workpiece subjected to spot-welding was constituted by two overlapped cold-rolled soft steel plates (JIS: SPC270 having a thickness of 2 mm. The employed electrode was cylindrical, and the spot welding was performed while cooling the interior thereof. The tip end portion of the electrode was shaped as described above.

Further, the spot welding was performed while pressing the electrode against the respective outer sides of the workpiece. The pressure applied to the workpiece by the electrode was set at 3430N. A 60-cycle, single-phase alternating current was used as the power supply. An effective current value was set at 11 kA. An application period of the heating current was controlled in cycle time Ct (1/60 sec) units.

The input power amount Q calculated here is an integrated value of the current applied to the electrodes vs. voltage between the electrodes (between the two ends of the workpiece) vs. time. Hence, the input power amount Q is also a function of time. FIG. 3 shows the relationship between the elapsed time after the start of energization (the energization period), for each of the patterns described above, and the input power amount Q. Note that in FIG. 3, the energization period is indicated by the number of energization cycles (one cycle time Ct: 1/60 sec). Further, a point (melting start point) at which the workpiece starts to melt in each of the aforesaid patterns was estimated using FIG. 2 and superimposed on FIG. 3. The melting start point is specified as the timing at which the flow of melted material could be confirmed on the cut model.

By connecting the five melting start points obtained in each pattern, a melting start curve is obtained (indicated by a thick solid line in FIG. 3). Conversely, the intersection between a curve (an energization period-input power amount curve) indicating the relationship between the energization period and the input power amount during an actual spot welding operation and the melting start curve serves as the melting start point. Hence, the melting start point is given by the intersection between the energization period-input power amount curve and the melting start curve, without the need to consider the presence of a disturbance or specify the disturbance type. Further, the energization period at this time serves as a melting start time and the input power amount at this time serves as a melting start power amount. More specifically, for each energization period (number of energization cycles), the calculated input power amount is compared to the melting start power amount stored in association with the energization period, without taking the disturbance pattern into consideration, and a point at which the input power amount reaches or exceeds the melting start power amount is determined as the melting start time.

FIG. 4 shows the relationship between the nugget diameter D and a first power amount Q1 (Q - Qm), which is calculated by subtracting a melting start power amount Qm
from the input power amount Q (the power amount calculated at the start of energization) when the respective workpieces are spot-welded. In other words, FIG. 4 shows the respective curves shown in FIG. 2 moved horizontally by an amount corresponding to the melting start power amount Qm. As is evident from FIG. 4, the relationship between the first power amount Q1 after the start of melting and the diameter D of the formed nugget remains substantially constant regardless of the disturbance pattern. In other words, once the workpiece has started to melt, the diameter D of the resulting nugget is substantially determined by the first power amount Q1 with negligible effect from the disturbance.

[0050] FIG. 5 shows a spot welder 100 serving as an embodiment of the resistance welder according to the invention. The spot welder 100 includes an articulated welding robot 20, a control apparatus 30 for controlling the welding robot 20, and a power supply apparatus 40.

[0051] The welding robot 20 is a six-axis vertical articulated robot having a base 21 that is fixed to the floor to be capable of rotating about a vertical direction first axis, an upper arm 22 connected to the base 21, a forearm 23 connected to the upper arm 22, a wrist element 24 coupled to a front end portion of the forearm 23 to be free to rotate, and a spot welding gun 10 attached to the end of the wrist element 24. The upper arm 22 is coupled to the base 21 to be capable of rotating about a horizontal direction second axis. The forearm 23 is coupled to an upper end portion of the upper arm 22 to be capable of rotating about a horizontal direction third axis. The wrist element 24 is coupled to a tip end portion of the forearm 23 to be capable of rotating about a fourth axis parallel to an axis of the forearm 23. The spot welding gun 10 is attached, via an additional wrist element (not shown) that is capable of rotating about a fifth axis perpendicular to the axis of the forearm 23, to a tip end portion of the wrist element 24 to be capable of rotating about a sixth axis perpendicular to the fifth axis.

[0052] The spot welding gun 10 is constituted by an inverted L-shaped gun arm 12 and a servo motor 13. A pair of electrodes 11 (a movable electrode 11a and an opposing electrode 11b) are disposed on the gun arm 12.

[0053] The movable electrode 11a is driven by the servo motor 13 to move towards and away from a workpiece W. Thus, the movable electrode 11a works in cooperation with the opposing electrode 11b, which is disposed coaxially with a thickness direction of the workpiece W, to sandwich the workpiece W at a desired pressure. Further, the movable electrode 11a and the opposing electrode 11b are closed-end cylinders formed from a copper alloy, and are cooled by circulating coolant through the interiors of each electrode 11.

[0054] The control apparatus 30 includes a robot drive circuit (not shown) that controls driving of the welding robot 20 and the spot welding gun 10. The control apparatus 30 also includes a power circuit (not shown) to control at least one of the voltage and the current supplied to the workpiece W via the electrodes 11. The magnitude of the current applied to the workpiece W, the energization period, an energization timing, the sandwiching force applied to the workpiece W by the electrodes 11, and so on are controlled by these circuits. Parameters required for this control are input from an operating panel 31.

[0055] The power supply apparatus 40 is an alternating current constant current apparatus that can stably supply a high constant current by boosting a single-phase power supply or a three-phase power supply. The power supply apparatus 40 is controlled by the control apparatus 30.

[0056] The spot welder 100 is operated as follows. The workpiece W to be spot-welded is disposed on a carrying table (not shown). Welding parameters such as welding spots of the workpiece W, physical property values of the workpiece W, the sandwiching force to be applied to the workpiece W by the electrodes 11, the magnitude of current to be supplied to the electrodes 11, the energization period, and a target value (first set value) corresponding to the first set value are set and input into the control apparatus 30.

[0057] The spot welder 100 is then activated to move the welding robot 20, which is controlled by the control apparatus 30, so that the spot welding gun 10 successively placed at the respective welding spots. The electrodes 11 provided on the spot welding gun 10 are then driven by the servo motor 13, which is controlled by the control apparatus 30, to sandwich the workpiece W by the set pressure. In this state, a predetermined constant current is supplied to the workpiece W from the power supply apparatus 40. By repeating this operation at each welding spot, the workpiece W (a welded member) is appropriately spot-welded.

[0058] FIG. 6 is a schematic view of a weld formed by the spot welding. If the spot welding is performed favorably, the workpiece W melts and solidifies so that the nugget N is formed in the interior at the faying portion of the workpiece W (a workpiece Wa and a workpiece Wb), constituted by, for example, soft steel plates. Note that the part that is heated and pressed by the electrodes 11 serves as a faying portion Y, and the nugget N is normally enveloped by the faying portion Y. Further, a maximum diameter of the nugget N is set as the nugget diameter.

[0059] The control apparatus 30 according to this embodiment of the invention further includes a monitoring circuit (not shown) that monitors the welding condition of the welded spots. The monitoring circuit includes a melting start time detection unit that detects the melting start time, i.e., the point at which at least a part of the workpiece W starts to melt; a first power amount calculation unit that calculates the first power amount Q1 into the workpiece W via the electrodes 11; and a first determination unit that determines whether the integrated first power amount Q1 has reached a first set value X1 (in other words, whether Q1≥X1). Further, the monitoring circuit supplies power to the workpiece W via the power circuit to Joule-heats the working piece W until the first power amount Q1 reaches the first set value X1 (a heating unit).

[0060] The melting start time detection unit of the monitoring circuit includes a second power amount calculation unit that calculates a second power amount Q2 (t) input into the workpiece W via the electrodes 11 for an initial energization period t, which is the energizing period from the start of energization of the workpiece W by the electrodes 11, and a second determination unit that determines whether the second power amount Q2 (t) has reached a melting start power amount X2 (t) (second set value), which is determined in accordance with the initial energization period t, at which the workpiece W actually starts to melt (in other words, whether Q2≥X2).

[0061] FIG. 7 is a flowchart of the control method employed by the control apparatus 30 to control the spot welder 100. By executing the control method shown in FIG. 7, each process of the resistance welding method according to the invention is realized, and as a result, the resistance-welded
workpiece W is manufactured. First, in step S11, various welding conditions are set and input (setting step). More specifically, the material and plate thickness of the workpieces Wa, Wb; the number and position of welding spots; the chip shape of the electrodes 11a, 11b; the pressure to be applied to the workpiece W by the electrodes 11; the current magnitude I1 to be employed during the spot welding; the cycle time Ct; the first set value X1 corresponding to the desired nugget diameter; the melting start power amount X2 (t), which is a function of the initial energization period t; and so on are set and input. As long as the melting start power amount X2 (t) is derived from the melting start curve shown in FIG. 3, it (i.e., the melting start power amount X2 (t)) may take the form of an empirical formula or numeric data (array data) of the melting start power amount X2 (t) correlated with the initial energization period t.

In step S12, the welding robot 20 and the spot welding gun 10 are operated so that they end (electrode chips) of the electrodes 11a, 11b contact the outer sides of the workpiece W. The electrodes 11 press the workpiece W based on the settings of step S11 (pressing step). In step S13, the electrodes are energized for the spot welding. In other words, the heating current I1 is supplied to the electrodes, whereby the spot welding begins (heating step, heating process).

In step S14, the second power amount Q2 (t) input into the workpiece W is calculated in accordance with the energization period (initial energization period) t from the start of energization (second power amount calculating step, second power amount calculation process). More specifically, if the current is an alternating current, the second power amount Q2 (t) is calculated at each cycle time Ct of the energization operation based on the effective current supplied through the electrodes 11 and the effective voltage thereof. Note that 1 Ct is equal to one period of the supplied alternating current, and therefore, in the case of a 60 Hz alternating current, for example, 1 Ct=1/60 sec.

In step S15, the melting start power amount X2 (t) corresponding to the cycle time Ct, in which the second power amount Q2 (t) was calculated, is compared to the second power amount Q2 (t) calculated in step S14 (second determination step, second determination process). If the second power amount X2 (t) is below the melting start power amount X2 (t), in other words if the second power amount Q2 (t) has not yet reached the melting start power amount X2 (t), the heating energization of step S13 is continued. When the second power amount Q2 (t) has reached the melting start power amount X2 (t), however, the routine advances to step S16, in which a melting start time t0 is specified (melting start time detecting step, melting start time detection process).

In step S17, similarly to step S14, the first power amount Q1 input into the workpiece W is calculated in accordance with the energization period (melting energization period: t=0) from the melting start time t0 (first power amount calculating step, first power amount calculation process). In step S18, the first power amount Q1, calculated from the melting start time t0 onward, is compared to the first set value X1, corresponding to the desired nugget diameter (first determining step, first determination process).

If the first power amount Q1 is less than the first set value X1, energization of the workpiece W is continued. When the first power amount Q1 has reached the first set value X1, however, the routine advances to step S19, in which energization of the workpiece W is halted, the electrodes 11 separated from the workpiece W, and spot welding in that position is terminated (heating step, heating process).

Although not shown in the flowchart of FIG. 7, the conditions of the heating energization may be amended or modified when steps S17 and S18 have been repeated at least a predetermined number of times or for a predetermined period (number of cycle times) (heating modifying step, heating modification process).

The condition of the spot weld may be evaluated using steps S14 to S18 in FIG. 7. The quality of the weld alone may be evaluated by comparing the magnitude of the first power amount Q1 and the first set value X1, as shown in step S18 (estimating step, evaluating step). Further, by preparing a database, such as that shown in FIG. 4, that associates the first power amount Q1 with the nugget diameter D, the diameter D of the nugget formed in the weld may be estimated based on the actually integrated first power amount Q1 (nugget estimating step).

Furthermore, the melting start time may be detected by performing steps S13 to S16 of FIG. 7. In other words, the melting start time may be determined by comparing magnitude of the second power amount Q2 (t) and the melting start power amount X2 (t) in each energization period, as shown in step S15 (estimating step, evaluating step).

1. A resistance welding method for forming a nugget by causing a faying portion to melt and solidify, comprising:
   - pressing an electrode against a workpiece;
   - subjecting the workpiece to Joule heating by inputting power through the electrode into the workpiece;
   - detecting a melting start time, which is a time at which at least a portion of a faying portion of the workpiece starts to melt;
   - calculating a first power amount, which is an integrated value of the power input into the workpiece via the electrode from the melting start time;
   - determining whether the first power amount or a welding index value that indexes a welding condition of the faying portion corresponding to the first power amount has reached at least a first set value; and
   - continuing the Joule heating from the melting start time until the first power amount or the welding index value reaches at least the first set value.

2. The resistance welding method according to claim 1, wherein detecting the melting start time further comprises:
   - calculating a second power amount, by integrating the total power input into the workpiece, in accordance with an elapsed time from an energization start time, which is a time at which energization of the electrode for Joule-heating the faying portion begins; and
   - determining the melting start time as a time at which the second power amount reaches at least a melting start power amount, which is a power amount input until at least a part of the faying portion actually begins to melt and is determined in advance in accordance with the elapsed time from the energization start time, or a second set value set on the basis of the melting start power amount.

3. The resistance welding method according to claim 1, wherein the Joule heating of the workpiece includes modifying a heating parameter of the workpiece based on whether the first power amount or the welding index value has reached at least the first set value.
5. A control apparatus for a resistance welder that includes an electrode that contacts an external surface of a workpiece and a power supply apparatus that supplies a current to the electrode for Joule-heating a faying portion of the workpiece, the control apparatus comprising:
   a melting start time detection unit that detects a melting start time, which is a time at which at least a portion of the faying portion starts to melt when subjected to Joule heating;
   a first power amount calculation unit that calculates a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time;
   a first determination unit that determines whether the first power amount or a welding index value that indexes a welding parameter of the faying portion that corresponds to the first power amount has reached at least a first set value; and
   a heating unit that performs the Joule heating from the melting start time until the first power amount or the welding index value reaches at least the first set value.

6. A resistance welder comprising:
   an electrode that is pressed against a workpiece;
   a power supply apparatus that supplies a current to the electrode for Joule-heating a faying portion of the workpiece; and
   the control apparatus according to claim 5.

7. A control method for a resistance welder that includes an electrode, which contacts an external surface of a workpiece and a power supply apparatus that supplies a current to the electrode for Joule-heating a faying portion of the workpiece, the method comprising:
   detecting a melting start time, which is a time at which at least a portion of the faying portion starts to melt while being subjected to Joule heating by a power input into the workpiece from the electrode;
   calculating a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time;
   determining whether the first power amount or a welding index value that indexes a welding condition of the faying portion corresponding to the first power amount has reached at least a first set value; and
   continuing the Joule heating from the melting start time until the first power amount or the welding index value reaches at least the first set value.

8. A control program for a resistance welder that controls a computer to execute the control method for a resistance welder according to claim 7.

9. A resistance welding evaluation method, comprising:
   pressing an electrode against a workpiece;
   subjecting the workpiece to Joule heating by inputting power through the electrode into the workpiece;
   detecting a melting start time, which is a time at which at least a portion of a faying portion of the workpiece starts to melt;
   calculating a first power amount, by integrating the total power input into the workpiece via the electrode from the melting start time; and
   estimating a welding parameter of the faying portion based on the first power amount.

10. The resistance welding evaluation method according to claim 9, wherein the welding parameter estimated is a size of a nugget, which is formed when the faying portion melts and solidifies, the size of the nugget is estimated based on the first power amount.

11. The resistance welding evaluation method according to claim 9, wherein detecting the melting start time further comprises:
   calculating a second power amount, by integrating the total power input into the workpiece, in accordance with an elapsed time from an energization start time, which is a time at which energization of the electrode for Joule-heating the faying portion begins; and
   determining the melting start time as a time at which the second power amount reaches at least a melting start power amount, which is a power amount input until at least a part of the faying portion actually begins to melt and is determined in advance in accordance with the elapsed time from the energization start time, or a second set value set on the basis of the melting start power amount.

12. A resistance welding evaluation method, comprising:
   calculating a second power amount, by integrating the total power input into a workpiece from an electrode pressed against the workpiece, in accordance with an elapsed time from an energization start time, which is a time at which energization of the electrode for Joule-heating a faying portion of the workpiece using the power input from the electrode begins; and
   determining a melting start time as a time at which the second power amount reaches at least a melting start power amount, which is a power amount input until at least a part of the faying portion actually begins to melt and is determined in advance in accordance with the elapsed time from the energization start time, or a second set value set based on the melting start power amount,
   wherein the melting start time at which at least a portion of the workpiece to be resistance-welded begins to melt is detected.

13. A resistance welding evaluation program that controls a computer to execute the resistance welding evaluation method according to claim 9.

14. A resistance welding evaluation program that controls a computer to execute the resistance welding evaluation method according to claim 12.