(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
22 October 2020 (22.10.2020)

WIPO | PCT

(10) **International Publication Number**
WO 2020/212741 A1

(51) **International Patent Classification:**
B23K 11/11 (2006.01) ***C22C 38/06*** (2006.01) ***B23K 11/16*** (2006.01) *B23K 101/00* (2006.01) ***B23K 11/30*** (2006.01) *B23K 101/18* (2006.01) ***C22C 38/02*** (2006.01) *B23K 103/04* (2006.01) ***C22C 38/04*** (2006.01)

(21) **International Application Number:**
PCT/IB2019/053252

(22) **International Filing Date:**
19 April 2019 (19.04.2019)

(25) **Filing Language:** English

(26) **Publication Language:** English

(71) **Applicant: ARCELORMITTAL** [LU/LU]; 24-26, Boulevard d'Avranches, 1160 Luxembourg (LU).

(72) **Inventor: BENLATRECHE, Yacine**; 17 rue de la Cerisière, 57070 Metz (FR).

(74) **Agent: PLAISANT, Sophie**; ArcelorMittal France, Research & Development, Intellectual Property, 6 rue André Campra, 93200 Saint-Denis (FR).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

(54) **Title:** A METHOD FOR RESISTANCE SPOT WELDING OF ZINC-COATED HIGH STRENGTH STEELS

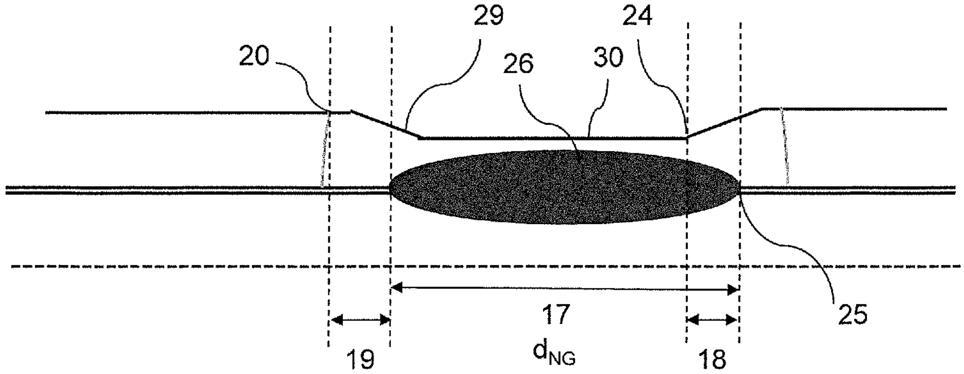

Figure 7

(57) **Abstract:** A resistance spot welding electrode with a tip zone (Z) having an active diameter d_{EL} allowing current flow during resistance spot welding, comprising a circular central zone (C) (1) with a flat or hemispherical surface, the diameter of the central zone (C) (1) being dc, an annular peripheral circular zone (P) (2) concentric with the circular zone (C) (1), having a flat surface, the width of annular peripheral zone (P) (2) being d_P, the central zone (C) protruding with respect to the peripheral zone (P) (2), the protrusion height (5) between the central zone (C) (1) and the external part (22) of the annular peripheral zone (P) being h, an annular circular transition zone (T) (3) concentric with the central zone (C) (1), located between the central zone (C) (1) and the peripheral zone (P) (2), the width (31) of the annular transition zone (T) (3) being d_T, wherein d_C, d_P, d_T, h, are such as: $d_{EL}= d_C+2d_T+2d_P$, $d_c>0$, $d_p>0$, $d_T\geq 0$, $h>0$, $0.20 < d_c/d_{EL} < 0.60$, $0.05 < (d_p-h)/ (d_{EL}\leq 0.25$.

WO 2020/212741 A1

A METHOD FOR RESISTANCE SPOT WELDING OF ZINC-COATED HIGH STRENGTH STEELS

The invention relates to a resistance spot welding process making it possible to suppress or reduce the cracks formation due to Liquid Metal Embrittlement, particularly in the industrial conditions required by the automotive industry.

Zinc or Zinc-alloy coated steel sheets are very effective for corrosion resistance and are thus widely used in the automotive industry. However, it has been experienced that the welding of certain steels can cause the apparition of particular cracks due to a phenomenon called Liquid Metal Embrittlement ("LME") or Liquid Metal Assisted Cracking ("LMAC"). This phenomenon is characterized by the penetration of liquid Zn along the grain boundaries of underlying steel substrate, under applied stresses or internal stresses resulting from restraint, thermal dilatation and/or phases transformations. It has been recognized that a higher stress level increases the LME risk. Since the stresses that are present during the welding itself depend in particular of the strength level of the base metal, it is experienced that welds made out of steels with higher strength are in general more sensitive to LME.

Document JP2005002415 proposes to interpose between the coating and the steel substrate, a nickel-based layer for minimizing the diffusion of zinc and thus suppressing the generation of LME cracks in the Heat affected Zone. However, the fabrication of such coated steel sheet is more complex and costly.

Document WO2018163017 teaches to limit the indentation due to welding, as a function of Zn solubility in the steel substrate at 750°C. However, this document does not teach about modification of the electrode shape for increasing the resistance to LME.

Thus, it is desirable to have a resistance spot welding process of Zn-coated sheets that would meet stringent requirements:

- to weld steel sheets with tensile strength TS higher than 800MPa in the base metal sheet. This high level of tensile strength in the steel substrate requests the addition of alloying elements, some of them causing a potential increase risk of LME cracks generation.

- to manufacture a resistance spot weld having a high Tensile Shear stress, which is usually obtained with high welding intensity. Such high intensity range is also recognized to increase potentially the risk of LME cracks generation.

More particularly, it is desired to manufacture spot welds with a small number of LME deep cracks so not to reduce the mechanical performance of the welds. In particular, it is desired that the spot welds fabricated by such process have:

- no Liquid Metal Embrittlement cracks with crack depth greater than half of the thickness of the Zn-coated steel sheet.
- a proportion of less than 20% of spot welds with a crack depth comprised between 0.2mm and half of the thickness of the Zn-coated steel sheet.

In order to solve the aforementioned problems, the invention relates to a resistance spot welding electrode with a tip zone (Z) having an active diameter d_{EL} allowing current flow during resistance spot welding, comprising:

- a circular central zone (C) with a flat or hemispherical surface, the diameter of the central zone (C) being d_C,
- an annular peripheral circular zone (P) concentric with the circular zone (C) , having a flat surface, the width of annular peripheral zone (P) being d_P, the central zone (C) protruding with respect to the peripheral zone (P), the protrusion height between the central zone (C) and the external part of the annular peripheral zone (P) being h ,
- an annular circular transition zone (T) concentric with the central zone (C), located between the central zone (C) and the peripheral zone (P), the width of the annular transition zone (T) being d_T,
- wherein d_C, d_P, d_T, h, are such as:
- $d_{EL}= d_C+2d_T+2d_P$,
- $d_c>0$, $d_P>0$, $d_T\geq0$, $h>0$,
- $0.20 < d_C/d_{EL} < 0.60$,
- $0.05 \leq (d_P-h)/ d_{EL} \leq 0.25$.

According to an embodiment, the circular central zone (C) has a hemispherical surface with a curvature radius higher than 30 mm.

According to another embodiment, the annular transition zone (T) is flat.

In another embodiment, the annular transition zone (T) comprises at least two distinct surfaces.

Preferably, the resistance spot welding electrode is such as d_{EL} is comprised between 4 and 12 mm.

According to an embodiment, the circular central zone (C) and the annular peripheral circular zone (P) are parallel planes.

According to another embodiment, the circular central zone (C) and the annular peripheral circular zone (P) are non-parallel planes forming a dihedral with an angle 23 less than 30°.

Another object of the invention is a process for resistance spot weld comprising the steps of :

- providing at least two partially superimposed steel sheets S1 and S2 with respective thickness t_1 and t_2, at least one of the steel sheets having a zinc-coating or a zinc-alloy coating,
- providing a pair of resistance spot welding electrodes as described above, then
- welding said steel sheets S1 and S2, each of said sheets S1 and S2 being in contact with one electrode of the pair of spot welding electrodes, with a current flow of intensity I comprised between I_1 and I_2, wherein:
- I_1 is the intensity making it possible to obtain a nugget diameter d_{NG} higher than 3.5 x $t^{1/2}$, t being the thickness of the thinnest sheet of the at least two steel sheets S1 and S2,
- I_2 is comprised between 0.9 and 1.1 x I_{exp}, wherein I_{exp} is the intensity at which expulsion appears during welding.

In an embodiment, the indentation depth ID after spot welding is such as:

$0 < (h - ID) < 0.03$mm.

Preferably, the force applied during welding through the said pair of electrodes placed sensibly perpendicular and on the outer sides of the said at least two superimposed steel sheets S1 and S2, is comprised between 170 and 750 daN.

Also preferably, the thickness t_1 and t_2 of the at least two steel sheets S1 and S2 is comprised between 0.5 and 3mm.

At least one of the sheets S_1 or S_2 is preferably a High Formable steel sheet with a tensile strength (TS) higher than 800 MPa and a total elongation (TEL) such as (TS)x(TEL)>14000MPa%.

In an embodiment, the composition of the High Formable steel substrate of at least one of the sheets S_1 or S_2 contains, in weight: 0.05% ≤ C ≤ 0.4%, 0.3% ≤ Mn ≤ 8%, 0.010% ≤ Al ≤3%, 0.010% ≤ Si ≤ 2.09%: with 0.5% ≤ (Si+Al) ≤ 3.5%, and optionally 0.001% ≤ Cr ≤ 1.0%, 0.001% ≤ Mo ≤ 0.5%, 0.005% ≤ Nb ≤0.1% , 0.005% ≤ V ≤ 0.2%, 0.005% ≤ Ti ≤ 0.1%, 0.0003% ≤ B ≤ 0.005%, 0.001% ≤ Ni ≤ 1.0%, the remainder being Fe and unavoidable impurities.

The high Formable steel has preferably a retained austenite surface fraction between 5 and 30%.

In an embodiment, the zinc-coating or zinc-alloy coating is obtained by hot-dip coating, or electrodeposition, or vacuum deposition.

According to an embodiment, the process for resistance spot welding is such as the spot welds fabricated by such process have:

- no Liquid Metal Embrittlement cracks in sheet S1 deeper than $t_1/2$,
- no Liquid Metal Embrittlement cracks in sheet S2 deeper than $t_2/2$,
- less than 20% of spot welds with a crack depth in sheet S1 comprised between 0.2mm and $t_1/2$,
- less than 20% of spot welds with a crack depth in sheet S2 comprised between 0.2mm and $t_2/2$,

In a preferred embodiment, the average value $(L_m)_{av}$ of maximum cracks depths in the spot welds is less than 0.15mm.

Another object of the invention is a resistance spot weld comprising at least two partially superimposed steel sheets S1 and S2, at least one of the steel sheets having a zinc-coating or a zinc-alloy coating, the nugget having a diameter (17) d_{NG}, the distance between the extremity P_{notch} (25) of the weld nugget forming a notch, and the position P_{Ac3} (20) of Ac3 isotherm in steel S1 and S2, being $d_{(notch\text{-}Ac3)}$, the distance between the extremity P_{notch} (25) of the weld nugget forming a notch, and the extremity $P_{indentation}$ (24) of the flat portion of the indentation zone, being $d_{(notch-indentation)}$, wherein:

- $d_{(notch-Ac3)}/d_{NG} > 0.125$
- $d_{(notch-indentation)}/d_{NG} > 0.20$

Preferably, the thickness t_1 and t_2 of the at least two steel sheets S1 and S2 is comprised between 0.5 and 3mm.

Also preferably, at least one of the sheets S_1 or S_2 is a High Formable steel sheet with a tensile strength (TS) higher than 800 MPa and a total elongation (TEL) such as (TS)x(TEL)>14000MPa%.

In an embodiment, the composition of the High Formable steel substrate of at least one of the sheets S_1 or S_2 contains, in weight: 0.05% ≤ C ≤ 0.4%, 0.3% ≤ Mn ≤ 8%, 0.010% ≤ Al ≤3%, 0.010% ≤ Si ≤ 2.09%:, with 0.5% ≤ (Si+Al) ≤ 3.5%,and optionally, 0.001% ≤ Cr ≤ 1.0%, 0.001% ≤ Mo ≤ 0.5%, 0.005% ≤ Nb ≤0.1%, 0.005% ≤ V ≤ 0.2%, 0.005% ≤ Ti ≤ 0.1%, 0.0003% ≤ B ≤ 0.005%, 0.001% ≤ Ni ≤ 1.0%, the remainder being Fe and unavoidable impurities.

The High Formable steel has preferably a retained austenite surface fraction comprised between 5 and 30%.

In a preferred embodiment, the zinc-coating or zinc-alloy coating is obtained by hot-dip coating, or electrodeposition, or vacuum deposition.

In an embodiment, the spot weld has no Liquid Metal Embrittlement cracks in sheet S1 deeper than $t_1/2$, no Liquid Metal Embrittlement cracks in sheet S2 deeper than $t_2/2$, less than 20% of spot welds with a crack depth in sheet S1 comprised between 0.2mm and $t_1/2$, less than 20% of spot welds with a crack depth in sheet S2 comprised between 0.2mm and $t_2/2$.

In a preferred embodiment, the average value $(L_m)_{av}$ of maximum cracks depths in the spot weld is less than 0.15mm.

Another object of the invention is the use of a spot weld fabricated according to the method described above, for the manufacturing of structural part of automotive vehicle.

Another object of the invention is the use of a spot weld as described above for the manufacturing of structural part of automotive vehicle.

The invention will now be described in details and illustrated by examples without introducing limitations, with reference to the appended figures among which:

- the figure 1 presents schematically a cross-cut of the tip of a welding electrode illustrating characteristic geometrical features of the invention.
- the figure 2 presents schematically a cross-cut of the tip of a variant of welding electrode illustrating characteristic geometrical features of the invention.
- the figure 3 presents schematically a cross cut-of the tip of another variant of welding electrode illustrating characteristic geometrical features of the invention.
- the figure 4 illustrates LME cracks that can appear after the welding of a Zn-coated sheet.
- the figures 5 and 6 are schematic presentation of possible mechanisms and phenomena occurring in the welding process of the invention and in a reference process, respectively.
- the figure 7 is a schematic cross-cut of a spot weld illustrating some characteristic geometrical features.
- the figure 8 illustrates how a specific combination of geometrical features defined in figure 7 makes it possible to obtain high LME resistance.

It is underlined that the figures 1-3 and 5-8 are schematic figures for sake of clarity and do not intend to reproduce the relative scale of the constitutive elements each one in proportion with the other.

First, at least two steel sheets S1 and S2 with respective thickness t_1 and t_2 are provided and superimposed at least partly, in order to be in contact. These sheets may have the same thickness or different thicknesses. In particular, t_1 and t_2 are comprised between 0.5 and 3mm, which is a typical thickness range used in the automotive industry.

At least one of these sheets S1 and S2 is a zinc or zinc-alloy coated sheet, the latter expression designating coatings wherein the Zn content is higher than 50% in weight. In particular, the coating can be obtained by Hot-Dip-

Galvanizing ("GI") or by hot-dip galvanizing immediately followed by a heat-treatment at about 500-570°C so to cause diffusion of iron in the coating and to obtain "galvannealed" or "GA" coating containing about 7-14%Fe. It can be also a zinc or zinc-alloy coating obtained by an electroplating process or by a Vacuum deposition process, the latter being possibly a Jet Vapor Deposition process. The Zn-alloy can be also a Zn-Mg-Al coating such as for example a Zn-3%Mg-3.7%Al, or a Zn-1,2%Al-1.2%Mg coating.

The Zn or Zn-alloy coated sheet is made out of a High-Formable steel with a tensile strength (TS) higher than 800 MPa and a total elongation (TEL) such as (TS)x(TEL)>14000MPa%. Depending on the composition and the fabrication process, the microstructure of the Zn-coated sheet or sheets contains, in surface fraction between 5 and 30% of retained austenite, such constituent making it possible to increase the formability of the steel sheet.

The composition and the microstructural features of the coated steel sheets will be now explained. According to the thermomechanical cycle on the industrial line, these coated steels may be for example TRIP (Transformation Induced Plasticity) steels, CFB (Carbides Free Bainite) steels, or Q-P (Quenched and Partitioned) steels. In particular, the composition of the High-Formable steel sheets may contain:

- Carbon: between 0.05% and 0.4% by weight. If the carbon content is below 0.05%, the tensile strength is insufficient and the stability of the retained austenite which is present in the steel microstructure for achieving sufficient elongation, is not obtained. Above 0.4%C, weldability is reduced because low toughness microstructures are formed in the Heat Affected Zone or in the molten zone of the spot weld. In one preferred embodiment, the carbon content is in the range between 0.13 and 0.25%, which makes it possible to achieve a tensile strength higher than 1180 MPa.

- Manganese is a solid solution hardening element which contributes to obtain a tensile strength higher than 800 MPa. Such effect is obtained when Mn content is at least 0.3% in weight. However, above 8%, its presence contributes to the formation of a structure with excessively marked segregation bands which can adversely affect the hardenability of the welds and the use properties of the automobile structural part. The coatability is also adversely reduced. Preferably, the manganese content is in the range between 1.4% and 4% to achieve these effects. This makes it possible to achieve satisfactory mechanical strength without increasing the difficulty of industrial fabrication of the steel and without increasing the hardenability in the welded alloys which would adversely affect the weldability of the sheet claimed by the invention.

- Silicon must be comprised between 0.010 and 2.09% to achieve the requested combination of mechanical properties and weldability: silicon reduces the carbides precipitation during the annealing after cold rolling of the sheet, due to its low solubility in cementite and due to the fact that this element increases the activity of carbon in austenite. Thus, the enrichment of austenite in carbon leads to its stabilization at room temperature and to the apparition of a Transformation Induced Plasticity ("TRIP") behavior which means that the application of a stress, during forming for example, will lead to the transformation of this austenite into martensite. When Si is higher than 2.09%, strongly adhering oxides could be formed during annealing before hot dip galvanizing, which could lead to surface defects in the coating. Silicon content above 0.5% contributes to an efficient stabilization of austenite, while Si content above 0.7% contributes to obtain a surface fraction of retained austenite comprised between 7 and 30%.

- Aluminum must be comprised between 0.010 and 3.0%. With respect to the stabilization of retained austenite, aluminum has an influence that is relatively similar to the one of the silicon. However, since aluminum promotes efficiently the formation of ferrite at high temperature, an excessive aluminum addition would increase the Ac3 temperature (i.e. the temperature of complete steel transformation into austenite during heating) during the annealing step, and would therefore make the industrial process expensive in terms of electric power required for annealing. Thus, Al content is less than 3.0%.

- Among the microstructural constituents of the steel, retained austenite between 5 and 30% at room temperature makes it possible to obtain high total elongation. The formability is particularly high when the surface fraction of retained austenite is comprised between 7 and 30%. A sufficient stabilization of the austenite is obtained through the addition of silicon and/or aluminum in the steel composition, in quantities such as : (Si+Al) ≥ 0.5%. If (Si+Al)<0.5%, the fraction of retained austenite could be below 5%, thus the ductility and strain hardening properties in cold-forming are insufficient. However, if (Si+Al)>3.5%, the coatability and the weldability are impaired.

The steel may also contain optional elements:

- Chromium hardens and refines the microstructure and makes it possible to control the formation of proeutectoid ferrite during the cooling step after holding at the maximal temperature during the annealing cycle. In the case of steels that do not contain more than 2.8%Mn, ferrite, when present in surface fraction higher than 40%, increases the risk that the tensile strength is lower than 800 MPa. Thus, the chromium content is higher than 0.001% and less than 1.0% for reasons of cost and for preventing excessive hardening.

- As chromium, molybdenum in quantity comprised between 0.001% and 0.5% is efficient for increasing the hardenability and stabilizing the retained austenite since this element delays the decomposition of austenite.

- The steels may optionally contain elements susceptible to precipitate under the form of carbides, nitrides, or carbonitrides, thus able to provide precipitation hardening. For this purpose, the steels may contain niobium, titanium or vanadium: Nb and Ti in quantity comprised between 0.005 and 0.1%, and V in quantity comprised between 0.005 and 0.2%.

- The steels may optionally contain nickel, in quantity comprised between 0.001% and 1.0% so to improve toughness.

- The steels may optionally content also boron, in quantity comprised between 0.0003 and 0.005%. By segregating at the grain boundary, B decreases the grain boundary energy and is thus beneficial for increasing the resistance liquid metal embrittlement.

- The balance in the composition consists in iron and residual elements resulting from the steelmaking. In this respect, Cu, S, P and N at least are considered as residual elements or unavoidable impurities. Therefore, their contents are less than 0.03% for Cu, 0.003% for S, 0.02% for P and 0.008% for N.

The geometry of the pair of electrodes used in the welding process will now be described: The electrodes are made out of copper or copper-alloy, i.e. copper with a small amount of alloy such as Cr, Zr, Mo... so to modify hardness or conductivity of the electrode. The electrodes are water-cooled in order to limit their progressive shape deformation because of the successive heat welding thermal cycles, and to efficiently cool the weld nugget during the holding step of the welding cycle. The electrodes have a tip zone (Z) with an active diameter d_{EL} in contact with the steel sheet during the welding cycle. According to the usual thickness of Zn-coated steel sheets implemented in the automotive industry, the active diameter d_{EL} is generally comprised between 4 and 12 mm.

The figure 1 illustrates the schematic cross-cut of the tip of an electrode which is axisymmetric and comprises different zones:

- a circular central zone (C) numbered 1 in figure 1, with a diameter d_C >0 (numbered 11 in figure 1) Although figure 1 illustrates the case of a flat zone, it is understood that the zone (C) can have also an hemispheric shape. In this case, the radius curvature of the hemispheric zone is larger than 30mm so to avoid a contact zone with the sheet, with a surface which would be too much reduced.

- an annular peripheral zone (P) (numbered 2 in figure 1) concentric with the circular zone (C) This zone has a flat surface, its width is d_P (numbered 21 in figure 1) and such as: d_P>0. The central zone (C) protrudes with respect to the peripheral zone (P), the protrusion height between the central zone (C) and the annular peripheral zone (P) being h (referenced as 5 in figure 1) and such as: h>0. The protrusion is measured by the difference between the height of the highest portion of the central zone (C) and the height of the external part of the peripheral zone (numbered 22 in figure 1)

As illustrated in figures 1 and 2, the zones (C) and (P) can be parallel planes.

In an alternative variant, the planes (P) and (C) form a dihedral as illustrated in figure 3. The angle 23 between these planes is less than 30°. If the angle 23 is higher, there is a risk that for some steels, the strain at external part of the zone (P) is too high, thus inducing deep LME cracks.

- an annular transition zone (T) (numbered 3 in figure 1) which is concentric with the central zone (C) and located between the central zone (C) and the peripheral zone (P), the width of the annular transition zone (T) being d_T (numbered 31 in figure 1) The transition zone may be flat, as illustrated in figure 1. This geometry offers the advantage of simplicity for mechanical machining. However, in a variant illustrated in figure 2 referring to the same numberings as in figure 1, (T) can comprise at least two distinct flat surfaces, and in particular a staircase geometry. Figure 2 illustrates the case wherein two horizontal flat surfaces are present in the annular transition zone.

The total active diameter of the electrode tip is therefore: $d_{EL}= d_C+2d_T+2d_P$.

The functions of the different zones and the relationships between their respective geometrical features will be now described.

The inventor has put into evidence that the LME cracks appear mainly in the zones located at the peripheral part of the nugget created by the welding operation. These cracks appear more likely in some Zn-coated steels with a tensile stress higher than 800MPa because higher tensile stress increases the level of applied stresses or strains during welding, thus the probability of LME occurrence is higher. Steels with higher carbon and silicon contents have been found more susceptible to LME. Figure 4 illustrates an example of LME crack (numbered as 9 in figure 4) which has occurred at the periphery of the indented zone in a Zn-coated steel with tensile stress higher than 800MPa. The initiation site (numbered as 10) of the deep crack corresponds to a highly strained zone, due to the use of a conventional electrode which has sensibly a flat tip surface.

Through numerous experiments, the inventor has searched to reduce the level of applied stress or strains during spot welding through the kinematics of geometrical, mechanical and thermal interactions between the electrodes and the Zn-coated sheets during the welding sequence.

It has been found that this result can be achieved if, during the welding cycle, a central part, with specific geometrical features, of the pair of electrodes comes earlier than the peripheral part in contact with the sheet.

Without wishing to be bound by a theory, the figures 5 and 6 illustrate schematically the possible succession of phenomena that occur when welding according to the invention (figure 5) by comparison with a reference electrode (figure 6) For sake of clarity, the welding cycle can be presented in five successive steps (I-V) The figures 5 and 6 illustrate schematically the sequence of two sheets 27 and 28 that are spot welded. At least sheet 27 is a zinc-coated or a zinc-alloy coated steel sheet. Although only one electrode is represented at the upper side in figures 5-6 (I-V), it is understood that another electrode is also present in contact with the lower sheet symmetrically, so to obtain current flow between the electrodes.

In the stage (I) (figure 5 and 6), the sheets are pressed together with the electrodes. No current flow occurs at his stage.

In the stage (II) the current begins to flow, heat generation is mainly initiated at the interface between the sheets since the electric resistance is the highest in this contact zone. In the process of the invention, the current flows mainly through the central part (C) of the electrode (figure 5. II) Thus, a nugget (15, 16) formation starts.

When current continues to flow (stage III), the nugget volume increases and an indentation, i.e. a depression at the surface of the weld under the electrode surface in contact with the sheet, appears progressively. In the invention (figure 5. III) the transition zone (T) of the electrodes, sloped or staircase shaped, comes progressively into contact with the sheet and increases the surface for current flow, making it possible the nugget to grow with limited amount of strain in the steel sheet.

In a further stage (figure 5. IV), the peripheral part of the electrodes comes in contact with the Zn-coated sheet under the effect of the applied electrode force. As compared to the reference electrode (figure 6. IV), the surface in contact between the electrode and the steel sheet is higher, thus the strains created in the steel are lower.

In a further and final stage of the welding cycle (Figure 5. V), a moderate indentation occurs at the external portion 12, which is a zone more prone to eventual LME. However, the strain occurring at this stage is limited and is reduced as compared to the Figure 6. V related to the reference electrode, wherein there is the possibility of crack occurrence 14 in the zone 13.

Furthermore, since the strain is applied more progressively in the case of the invention, the strain rate experienced in the final contact zone 13 is also reduced, which further contributes to restriction or prevention of LME.

As related to the active diameter d_{EL} of the tip, the central zone diameter d_C must not be such as: $d_C/d_{EL} \leq 0.20$, otherwise, the intensity may not be sufficient to create a nugget of sufficient diameter, and the current density may be too high, increasing thermal gradient which favours LME.

When $d_C/d_{EL} \geq 0.60$, the annular and transition zones are too narrow in the electrode tip, thus, the zone of maximum indentation caused by the central part (C) is too close to the potential initiation site 13, and LME is more likely to occur.

For fixed values of d_P and d_{EL}, the obtention of $(d_P\text{-}h)/d_{EL}>0.25$ corresponds to situations wherein the value of h is too much limited, i.e. that the effect of the protrusion is insufficient since the other portions of the electrode come too rapidly in contact with the sheet during the welding cycle.

On the other hand, for fixed values of d_P and d_{EL}, the obtention of $(d_P\text{-}h)/d_{EL}<0.05$ corresponds to situations wherein h is too high, thus the potential initiation site 13 is too much strained and the probability of cracking is increased.

The inventor has also put into evidence that the average size of the maximum depth in the different welds, is further depending on the value of (h- ID) :

When (h-ID) is less than or equal to 0, the indentation is due to a too large extent to the external part of the electrode tip, and the strain amount in the potential initiation site 10 can be too high.

when (h-ID) is higher than or equal to 0.03mm, the peripheral zone of the electrode may not have been in sufficient contact with the steel sheet in order to cause a smooth transition zone, thus very high levels of LME resistance may not be attained.

In addition, the welding parameters are chosen in order to avoid interfacial failure during shear tensile test of the spot welds. A satisfactory pullout mode is obtained when the nugget diameter d_{NG} of the spot weld is higher than $3.5 \times t^{1/2}$, t being the thickness of the thinnest sheets in a stackup weld. Thus, this result is achieved by using a current intensity of not less than I_1, I_1 being the intensity for obtaining a nugget diameter d_{NG} of $3.5 \times t^{1/2}$.

Furthermore, the intensity is comprised between 0.9 and 1.1 I_{exp}, I_{exp} being the intensity at which expulsion of liquid metal starts to be observed in resistance spot welding. The selection of intensity in industrial conditions is often made around I_{exp} since it corresponds to a large weld nugget diameter d_{NG} which makes it possible to obtain high weld tensile properties.

According to the thickness of the sheets and the intensity ranges, the force applied during welding through the pair of electrodes placed sensibly perpendicular on the steel sheets, is comprised between 170 and 750 daN.

The inventor has also evidenced that the welding process of the invention is associated to specific geometrical features in the spot weld, making it possible to obtain high resistance to LME cracking.

The figure 7 illustrates schematically a resistance spot weld joining two superposed steel sheets. For sake of simplicity, the lower part of the weld beyond the non-continuous line, is not represented and only the upper part will be described. The nugget 26 is the zone that has been melted and thereafter solidified during the welding process. This nugget has a diameter d_{NG} referred as 17 in figure 7. The location P_{notch} corresponds to the extremity of the nugget intersecting with the planes of the steel sheets and is referred as 25 in this figure. The location P_{Ac3} corresponds to the position of the isotherm Ac3 in the steel sheet, i.e. to the location 20 of complete transformation into austenite during the heating in the welding cycle. Its position can be determined through polishing of the cross-cut of the weld and further appropriate etching with a reagent such as Nital, by means which are known per se.

An indentation zone is present at the surface of the weld which includes a flat central zone 30 and a peripheral zone 29 forming the transition with the steel sheet. The limit $P_{indentation}$ between the central and the peripheral part of the indentation is referred as 24 in figure 7.

Thus, it is possible to define

- $d_{(notch-Ac3)}$: the distance 19 between P_{notch} and P_{Ac3}.
- $d_{(notch-indentation)}$: the distance 18 between P_{notch} and $P_{indentation}$.

The inventor has put in evidence that high resistance to LME cracking is obtained in the weld when the following conditions are simultaneously met:

- $d_{(notch-Ac3)}/d_{NG} > 0.125$
- $d_{(notch-indentation)}/d_{NG} > 0.20$

Figure 8 illustrates the influence of such features, obtained by welding High Formable steels, 1.4mm thick, with Zn coating obtained by electrodeposition or

Jet-Vapor Deposition. The steels have a tensile strength (TS) higher than 800 MPa and a total elongation (TEL) such as (TS)x(TEL)>14000MPa%, and a retained austenite surface fraction of 12%.

In the figure 8, the domain with high resistance to LME cracking is defined as:

- (C1) : no Liquid Metal Embrittlement occurs with a crack depth greater than half of the thickness of the Zn-coated steel sheet.
- (C2): among the ten spot welds series, less than 20% of the welds have a crack depth comprised between 0.2mm and half of the thickness of the Zn-coated steel sheet.

When $d_{(notch\text{-}Ac3)}/d_{NG} \leq 0.125$, the location of Ac3 is too close to the zone of maximal strain due to indentation, and LME occurs in the zone combining high temperature gradient and plastic strain.

When $d_{(notch\text{-}indentation)}/d_{NG} \leq 0.20$, the transition portion 29 is too steep, thus intense strain is present and causes LME.

Examples

High Formable steels with compositions according to table 1 have been elaborated. The compositions are expressed in weight, the remainder being Fe and unavoidable impurities.

Steel	Thickness (mm)	C	Mn	Si	Al	Si+Al	Cr	Ni
A	1.4	0.225	2.07	1.48	0.035	1.515	0.349	0.018
B	1.4	0.192	2.47	1.74	0.040	1.78	0.028	0.011

Table 1: Compositions of Zn coated steels

Steel A is a Carbide-Free-Bainite steel with an electrodeposited Zn coating, 7µm thick. Its tensile strength UTS and total elongation are respectively 1235 MPa and 14.4% (JIS Standard) in the transverse direction. Its microstructure contains 12% of residual austenite, 7% of martensite and 81% of bainite in surface fraction.

Steel B is obtained by a Quenching and partitioning treatment and has a Zn coating of 8 µm deposited by Jet Vapor Deposition. Its tensile strength UTS and total elongation are respectively 1131 MPa and 14.1 % (JIS standard) in the transverse direction. Its microstructure contains 12% of residual austenite, 67% bainite, 16% partitioned martensite and 5% of fresh martensite, in surface fraction.

A mild steel sheet coated with Zn (GI coating) has been used for welding together with the steels A or B. Geometrical and welding parameters have been chosen so as to exacerbate the eventual occurrence of Liquid Metal Embrittlement and to evidence clearly the phenomena: by the spot welding of three superposed sheets and the creation of a stackup configuration with increased thickness, the sensitivity to LME cracking is raised. Thus, heterogeneous welding is performed by using one steel sheet A or B partially superposed to two sheets of Zn-coated mild steel, 1.75mm thick, with a composition containing: 0.032%C, 0.008%Si, 0.222%Mn, 0.052%Al, 0.039%Cr and 0.012%N, the remainder being Fe and unavoidable impurities.

Mild steel is chosen because its spot welding requires higher current level to get proper welds than the steels having a tensile stress higher than 800MPa. This higher current level induces higher heat input and as a consequence an increase of probability of LME occurrence during the welding of high resistance steels. Thus, the severity of the welding conditions is increased. In the stackups, the welding is performed in such a way that the Zn-coated steel sheet having a tensile strength higher than 800 MPa has one surface in contact with a welding electrode. The eventual cracks are more prone to occur in the indentation zone created by the welding electrode at the sheet surface.

The figure 4 shows an example of such crack: 7 and 8 in the figure are mild steel sheets, while 6 is steel A. A LME crack (referenced by 9) has been initiated at the outer part of the indented zone, here referenced as 10.

Example 1

Resistance spot welding of steel A has been performed by using various geometries of copper-alloy water-cooled electrodes. Characteristic features of the geometry of the electrodes (d_c, d_p, d_T, h) are reported in table 2.

The surfaces of zones (T) and (P) are flat whereas the zone (C) has an hemispherical shape with a curvature radius of 50mm.

Electrode N°15 is a reference electrode with a hemispherical surface of 50mm radius, without protrusion, which comes immediately in full contact with the sheet during the welding cycle.

Ten spot welds have been performed with each of these electrodes geometries for assessing the sensitivity to LME cracking.

The welding conditions were selected accord to ISO-18278-2 standard, using the following parameters:

- alternate current with a frequency of 50 Hz.
- welding time: 3 cycles of (0.2s of current flow followed by 0.04s of non-flow)
- Welding intensity : I
- welding force: 500 daN
- holding time, i.e. duration wherein the cooled electrodes have been maintained on the sheets to cool the weld : 0.32 s.

<table>
<tr><th>Electrode reference N°</th><th>Protrusion h (mm)</th><th>Diameter of central part d_c (mm)</th><th>Width of annular transition zone d_T (mm)</th><th>Width of annular peripheral zone d_p (mm)</th></tr>
<tr><td>1</td><td rowspan="7">0.5</td><td>2</td><td>3</td><td rowspan="3">1</td></tr>
<tr><td>2</td><td>6</td><td>1</td></tr>
<tr><td>3</td><td>8</td><td>0</td></tr>
<tr><td>4</td><td rowspan="4">4</td><td>3</td><td>0</td></tr>
<tr><td>5</td><td>2</td><td>1</td></tr>
<tr><td>6</td><td>3</td><td>2</td></tr>
<tr><td>7</td><td>0</td><td>3</td></tr>
<tr><td>8</td><td rowspan="7">0.2</td><td>2</td><td>3</td><td rowspan="4">1</td></tr>
<tr><td>9</td><td>4</td><td>2</td></tr>
<tr><td>10</td><td>6</td><td>1</td></tr>
<tr><td>11</td><td>8</td><td>0</td></tr>
<tr><td>12</td><td rowspan="3">4</td><td>3</td><td>0</td></tr>
<tr><td>13</td><td>1</td><td>2</td></tr>
<tr><td>14</td><td>0</td><td>3</td></tr>
<tr><td>15</td><td>0</td><td>8</td><td>0</td><td>0</td></tr>
</table>

Table 2: Geometrical features of electrodes for resistance spot welding

Underlined: not according to the invention

For the different geometries, the value of intensity I_{exp}, i.e. the intensity beyond which expulsion appears during welding, has been determined and reported in table 3. Then welding has been performed by using a current I comprised between 0.9 and 1.1 I_{exp}. According to ISO standard 18278-2, it has been checked in all these welds that the nugget diameter d_{NG} is greater than 3.5 x $t^{1/2}$, t being the thinnest of the two thickest sheets of the assembly. Thus, the welding intensity I is higher than I_1, and lower than I_2 as defined previously.

Atop of this nugget, a circular depression, i.e. indentation, is present on the surface of the sheets, and corresponds to a deformation of the surface of the spot weld caused by the electrode. The indentation depth (ID) has been measured at its center and reported in table 3.

Electrode reference N°	I (kA)	I_{exp} (kA)	I/I_{exp}	Nugget diameter d_{NG} (mm)	Indentation ID (mm)
1	12.4	12.4	1.0	8.5	0.37
2	12.1	12.2	0.99	8.2	0.54
3	12.4	12,4	1.0	8.3	0.53
4	12.4	12.4	1.0	8.3	0.43
5	12.4	12.36	1.0	8.4	0.50
6	11.4	11.4	1.0	7.6	0.48
7	11.9	12,1	0.98	7.9	0.43
8	13.1	13,1	1.0	8.6	0.34
9	12.3	12.6	0.97	8.1	0.27
10	13.1	13.1	1.0	8.5	0.35
11	12.9	13.1	0.98	8.7	0.35
12	13.4	13.5	1.0	8.8	0.28
13	12.9	13	0.99	8.5	0.27
14	13.1	13.1	1.0	8.6	0.27
15	12	12	1	8.2	0.52

Table 3- Welding conditions and results obtained for nugget diameter and indentation

The location and quantification of eventual LME cracks in spot welds has been assessed by dye penetrant. When a crack was detected, the spot weld was cut at the middle of the crack location and fine-polished. The weld sections have been thereafter observed through optical microscope with magnification between 10 and 1000, and the crack depth was measured. The maximum crack depth L_m has been determined in each observed weld, and the average crack depth $(L_m)_{av}$ for each series of ten welds.

High resistance to LME cracking is obtained when two criteria (C1) and (C2) are simultaneously met:

- (C1) : no Liquid Metal Embrittlement occurs with a crack depth greater than half of the thickness of the Zn-coated steel sheet.
- (C2): among the ten spot welds series, less than 20% of the welds have a crack depth comprised between 0.2mm and half of the thickness of the Zn-coated steel sheet.

“Yes” in table 4 below means that criteria (C1) and (C2) are fulfilled, “No” means that at least one of criteria (C1) or (C2) is not fulfilled.

In addition, a special high resistance to LME cracking is obtained when the average crack depth $(L_m)_{av}$ is less than 0.15mm. This is referred as criterion (C3) and reported also in table 4.

Test reference N°	0.20< (dc/d_{EL}) <0.60?	0.05 ≤($dp-h)/d_{EL}$ ≤0.25 ?	LME results: (C1) and (C2) met ?	ID (mm)	(h- ID) (mm)	Average of max. crack depths $(L_m)_{av}$ (C3) (mm)
1	0.20	0.05	No	0.37	0.12	0,26
2	0.60	0.05	No	0.54	-0.04	0,42
3	0.80	0.05	No	0,53	-0,03	0,89
4	0.40	-0.05	No	0.42	0.07	0,29
5	0.40	0.05	Yes	0.50	0.00	0.13
6	0.40	0.15	Yes	0.47	0.02	0.10
7	0.40	0.25	Yes	0.43	0,07	0.11
8	0.20	0.08	No	0.33	0.16	0.19
9	0.40	0.08	Yes	0.26	0.07	0.15
10	0.60	0.08	No	0.35	0.15	0.27
11	0.80	0.08	No	0.27	0.15	0.47
12	0.40	-0.02	No	0.27	0.08	0.33
13	0.40	0.18	Yes	0.27	0,07	0.13
14	0.40	0.28	No	0.27	0,07	0.30
15	1.00	0	No	0.52	1.43	0.77

Table 4 : Results of tests concerning LME on steel A

Underlined: not according to the invention

Conditions of the tests n°5-7, 9 and 13 correspond to the invention : thus no Liquid Metal Embrittlement occurs with a crack depth greater than half of the thickness of the Zn-coated steel sheet (criterion (C1) fulfilled) and less than 20% of the welds have a crack depth comprised between 0.2mm and half of the thickness of the Zn-coated steel sheet (criterion (C2) fulfilled)

As appears also from table 3, the conditions of the invention (5-7, 9,13) make it possible to obtain nugget diameters which are comparable with the one obtained with the reference electrode 15, and which are largely higher than 3.5 x $t^{1/2}$.

Among the tests n°5-7, 9 and 13, it can be observed that only tests 5 and 6 satisfy to an additional requirement expressed by criterion (C3): for tests 5 and 6 which are such as 0 <(h- ID) <0.03mm, the average crack depth $(L_m)_{av}$ is less than 0.15mm, while for tests 7, 9 and 13, the average crack depth $(L_m)_{av}$ is not less than 0.15mm.

In the tests n°1 and 8, the diameter of the central zone is too small with respect to the active diameter of the electrode, thus LME occurs because criterion (C2) is not fulfilled.

In the tests n° 2, 3, 10, 11, the diameter of the central zone is too large with respect to the active diameter of the electrode, thus the strain in the external portion of the indented zone is too high.

The same result is obtained for the reference electrode n°15: Since the indentation has not proceeded in the external portion 13 in a sufficiently progressive manner, LME occurs.

<u>Example 2</u>

Welding tests have been performed on steels A and B of table 1 according to a methodology generally similar than the one described in Example 1. However, the welding has been performed with electrodes having the geometrical features described in table 5. The electrodes 16 and 17 have an annular transition zone 31 with a general shape similar to figure 2, however with four individual horizontal surfaces in the transition zone, each of 0.5mm wide. Electrode n°18 is a reference electrode with a central surface without protrusion.

The central surface of all electrodes has hemispherical shape with a curvature radius of 50mm.

Electrode reference N°	Protrusion h (mm)	Diameter of central part d_c (mm)	Width of annular transition zone d_T (mm)	Width of annular peripheral zone d_p (mm)	$0.20 < (dc/d_{EL}) < 0.60$?	$0.05 \leq (dp-h)/d_{EL} \leq 0.25$?	Staircase geometry in zone (T) ?	Angle α between central and peripheral zone (°)
16	0.5	4	2	1	0.4	0.05	Yes (4 steps)	0
17	1.08	4	2	1	0.4	-0.08	Yes (4 steps)	30
18	0	8	0	0	1.00	0	-	-

Table 5: Geometrical features of electrodes for resistance spot welding

Underlined : not according to the invention

Welding parameters and results obtained on nugget diameter and indentation depth are presented in table 6. For example, Test reference 16A refers to the spot weld manufactured from steel A with electrode n°16. Other welding conditions are:

- alternate current with a frequency of 50 Hz.
- welding time: 3 cycles of (0.2s of current flow followed by 0.04s of non-flow)
- welding force: 500 daN
- holding time : 0.32 s

Test reference N°	I (kA)	I_{exp}	I/I_{exp}	Nugget diameter d_{NG} (mm)	Indentation ID (mm)
16A	10.8	10.9	0.99	7.7	0.36
16B	10.7	10.9	0.98	7.7	0.33
17A	11.6	11.7	0.99	8.3	0.43
17B	10.7	10.7	1.0	7.0	0.41
18A	12	12	1.0	7.9	0.22
18B	11.7	11.7	1.0	8.2	0.25

Table 6- Welding conditions and results obtained for nugget diameter and indentation

Referring to the criteria (C1), (C2) and (C3) defined above, the results obtained on the eventual presence of LME cracks are presented in table 7.

Test Reference°	LME results: (C1) and (C2) met ?	Average of max. crack depths $(L_m)_{av}$ (C3) (mm)
16A	Yes	0.17
16B	Yes	0.16
17A	No	0.47
17B	Yes	0.12
18A	No	0.83
18B	No	0.44

Table 7 : Results of tests concerning LME on steels A and B
Underlined: not according to the invention

For all testing conditions, the nugget diameter d_{NG} is greater than 3.5 x $t^{1/2}$, t being the thinnest of the two thickest sheets of the assembly.

As seen from tests 18A and 18B, the reference electrode does not provide satisfactory results since LME cracks are initiated at the location 13 (see figure 6) due the high strain amount and strain rate in this zone.

Replacing electrode 18 by electrode 17, with a central zone and a transition zone including staircase geometry, brings an improvement for the steel B since the LME cracks are reduced to such an extent that criteria (C1) and (C2) are fulfilled. However this result is not achieved with steel A, the composition of which is more sensitive to LME cracking than steel B. In this case, the dihedral angle α (23) between the central and the peripheral zone is too high, which causes the value of (dp-h) to be outside of the range of the invention.

By comparison, the electrode 16 has a transition staircase zone which contributes to the progressiveness of the indentation, together with an angle α less than 30°. Thus, resistance spot welding in such conditions corresponds to the invention and generates welds of satisfactory quality with criteria (C1) and (C2) which are met for both steels A and B.

Thus, the coated steel parts manufactured according to the invention can be used with profit for the fabrication of structural or safety parts of vehicles.

CLAIMS

1 A resistance spot welding electrode with a tip zone (Z) having an active diameter d_{EL} allowing current flow during resistance spot welding, comprising :

- a circular central zone (C) (1) with a flat or hemispherical surface, the diameter of the central zone (C) (1) being d_C,
- an annular peripheral circular zone (P) (2) concentric with the circular zone (C) (1), having a flat surface, the width of annular peripheral zone (P) (2) being d_P, the central zone (C) protruding with respect to the peripheral zone (P) (2), the protrusion height (5) between the central zone (C) (1) and the external part (22) of the annular peripheral zone (P) being h ,
- an annular circular transition zone (T) (3) concentric with the central zone (C) (1), located between the central zone (C) (1) and the peripheral zone (P) (2), the width (31) of the annular transition zone (T) (3) being d_T,
- wherein d_C, d_P, d_T, h, are such as:
  - $d_{EL}= d_C+2d_T+2d_P$,
  - $d_c>0$, $d_P>0$, $d_T \geq 0$, $h>0$,
  - $0.20 < d_C/d_{EL} < 0.60$,
  - $0.05 \leq (d_P-h)/ d_{EL} \leq 0.25$.

2 A resistance spot welding electrode according to claim 1, wherein the circular central zone (C) (1) has a hemispherical surface with a curvature radius higher than 30 mm.

3 A resistance spot welding electrode according to claim 1 or 2, wherein the annular transition zone (T) (3) is flat.

4 A resistance spot welding electrode according to any one of claims 1 to 3, wherein the annular transition zone (T) (3) comprises at least two distinct surfaces.

5 A resistance spot welding electrode according to any one of claims 1 to 4, wherein d_{EL} is comprised between 4 and 12 mm.

6 A resistance spot welding electrode according to any one of claims 1 to 5, wherein the circular central zone (C) (1) and the annular peripheral circular zone (P) (2) are parallel planes.

7 A resistance spot welding electrode according to any one of claims 1 to 5, wherein the circular central zone (C) (1) and the annular peripheral circular zone (P) (2) are non-parallel planes forming a dihedral with an angle (23) less than 30°.

8 A process for resistance spot welding comprising the steps of :

- providing at least two partially superimposed steel sheets S1 and S2 with respective thickness t_1 and t_2, at least one of the steel sheets having a zinc-coating or a zinc-alloy coating,
- providing a pair of resistance spot welding electrodes according to any one of claims 1 to 7, then
- welding said steel sheets S1 and S2, each of said sheets S1 and S2 being in contact with one electrode of the pair of spot welding electrodes, with a current flow of intensity I comprised between I_1 and I_2, wherein:
- I_1 is the intensity making it possible to obtain a nugget diameter d_{NG} higher than 3.5 x $t^{1/2}$, t being the thickness of the thinnest sheet of the at least two steel sheets S1 and S2,
- I_2 is comprised between 0.9 and 1.1 x I_{exp}, wherein I_{exp} is the intensity at which expulsion appears during welding.

9 A process for resistance spot welding according to claim 8, wherein the indentation depth ID after spot welding is such as:

$$0 < (h - ID) < 0.03mm.$$

10 A process for resistance spot welding according to claims 8 or 9, wherein the force applied during welding through the said pair of electrodes placed sensibly perpendicular and on the outer sides of the said at least two superimposed steel sheets S1 and S2, is comprised between 170 and 750 daN.

11 A process for resistance spot welding according to any one of claims 8 to 10, wherein the thickness t_1 and t_2 of the at least two steel sheets S1 and S2 is comprised between 0.5 and 3mm.

12 A process for resistance spot welding according to any one of claims 8 to 11 wherein at least one of the sheets S_1 or S_2 is a High Formable steel sheet with a tensile strength (TS) higher than 800 MPa and a total elongation (TEL) such as (TS)x(TEL)>14000MPa%.

13 A process for resistance spot welding according to any one of claims 8 to 12 wherein the composition of the High Formable steel substrate of at least one of the sheets S_1 or S_2 contains, in weight:

0.05% ≤ C ≤ 0.4%

0.3% ≤ Mn ≤ 8%

0.010% ≤ Al ≤3%

0.010% ≤ Si ≤ 2.09%:

with 0.5% ≤ (Si+Al) ≤ 3.5%,

and optionally

0.001% ≤ Cr ≤ 1.0%

0.001% ≤ Mo ≤ 0.5%

0.005% ≤ Nb ≤0.1%

0.005% ≤ V ≤ 0.2%

0.005% ≤ Ti ≤ 0.1%

0.0003% ≤ B ≤ 0.005%

0.001% ≤ Ni ≤ 1.0%

the remainder being Fe and unavoidable impurities.

14 A process for resistance spot welding according to claims 12 or 13, wherein the High Formable steel has a retained austenite surface fraction between 5 and 30%.

15 A process for resistance spot welding according to any one of claims 8 to 14, wherein said zinc-coating or zinc-alloy coating is obtained by hot-dip coating, or electrodeposition, or vacuum deposition.

16 A process for resistance spot welding according to any one of claims 8 to 15, wherein the spot welds fabricated by such process have:

- no Liquid Metal Embrittlement cracks in sheet S1 deeper than $t_1/2$,
- no Liquid Metal Embrittlement cracks in sheet S2 deeper than $t_2/2$,
- less than 20% of spot welds with a crack depth in sheet S1 comprised between 0.2mm and $t_1/2$,
- less than 20% of spot welds with a crack depth in sheet S2 comprised between 0.2mm and $t_2/2$,

17- A process for resistance spot welding according to claim 16 wherein the average value $(L_m)_{av}$ of maximum cracks depths in the spot welds is less than 0.15mm.

18- A resistance spot weld comprising at least two partially superimposed steel sheets S1 and S2, at least one of the steel sheets having a zinc-coating or a zinc-alloy coating,

- the nugget having a diameter (17) d_{NG},
- the distance between the extremity P_{notch} (25) of the weld nugget forming a notch, and the position P_{Ac3} (20) of Ac3 isotherm in steel S1 and S2, being $d_{(notch-Ac3)}$
- the distance between the extremity P_{notch} (25) of the weld nugget forming a notch, and the extremity $P_{indentation}$ (24) of the flat portion of the indentation zone, being $d_{(notch-indentation)}$,

wherein :

$d_{(notch\text{-}Ac3)}/d_{NG} > 0.125$

$d_{(notch\text{-}indentation)}/d_{NG} > 0.20$

19 A resistance spot weld according to claim 18, wherein the thickness t_1 and t_2 of the at least two steel sheets S1 and S2 is comprised between 0.5 and 3mm.

20 A resistance spot weld according to claim 18 or 19 wherein at least one of the sheets S_1 or S_2 is a High Formable steel sheet with a tensile strength (TS) higher than 800 MPa and a total elongation (TEL) such as (TS)x(TEL)>14000MPa%.

21 A resistance spot weld according to any one of claims 18 to 20 wherein the composition of the High Formable steel substrate of at least one of the sheets S_1 or S_2 contains, in weight:

$0.05\% \leq C \leq 0.4\%$

$0.3\% \leq Mn \leq 8\%$

$0.010\% \leq Al \leq 3\%$

$0.010\% \leq Si \leq 2.09\%$:

with $0.5\% \leq (Si+Al) \leq 3.5\%$,

and optionally

$0.001\% \leq Cr \leq 1.0\%$

$0.001\% \leq Mo \leq 0.5\%$

$0.005\% \leq Nb \leq 0.1\%$

$0.005\% \leq V \leq 0.2\%$

$0.005\% \leq Ti \leq 0.1\%$

$0.0003\% \leq B \leq 0.005\%$

$0.001\% \leq Ni \leq 1.0\%$

the remainder being Fe and unavoidable impurities.

22 A resistance spot weld according to any one of claims 18 to 21, wherein the High Formable steel has a retained austenite surface fraction between 5 and 30%.

23 A resistance spot weld according to any one of claims 18 to 22, wherein said zinc-coating or zinc-alloy coating is obtained by hot-dip coating, or electrodeposition, or vacuum deposition.

24 A resistance spot weld according to any one of claims 18 to 23, wherein the spot weld has:

- no Liquid Metal Embrittlement cracks in sheet S1 deeper than $t_1/2$,
- no Liquid Metal Embrittlement cracks in sheet S2 deeper than $t_2/2$,
- less than 20% of spot welds with a crack depth in sheet S1 comprised between 0.2mm and $t_1/2$,
- less than 20% of spot welds with a crack depth in sheet S2 comprised between 0.2mm and $t_2/2$.

25- A resistance spot weld according to claim 24 wherein the average value $(L_m)_{av}$ of maximum cracks depths in the spot weld is less than 0.15mm.

26 Use of a spot weld fabricated according to any one of claims 8 to 17, for the manufacturing of structural part of automotive vehicle

27 Use of a spot weld according to any one of claims 18 to 25, for the manufacturing of structural part of automotive vehicle

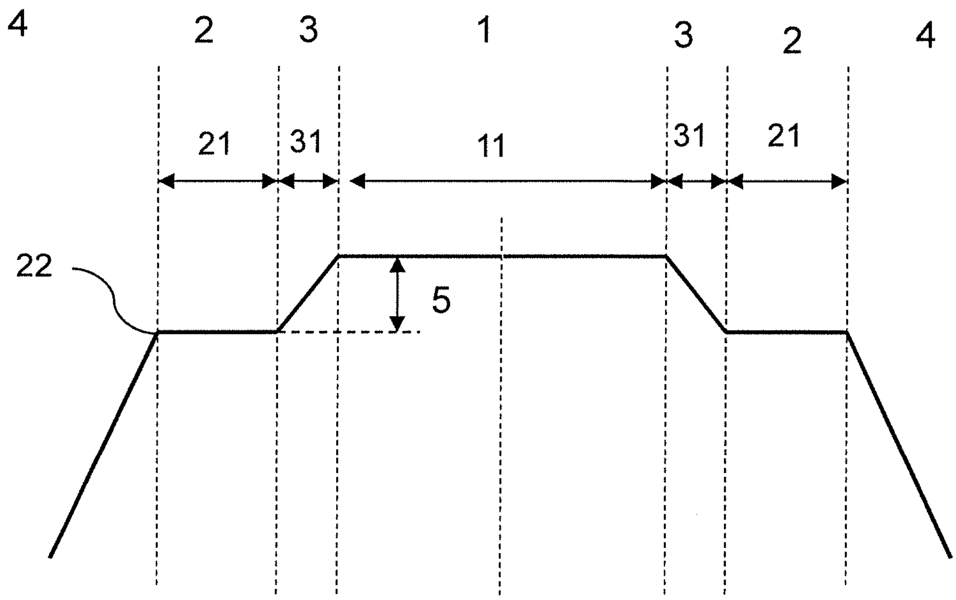

Figure 1

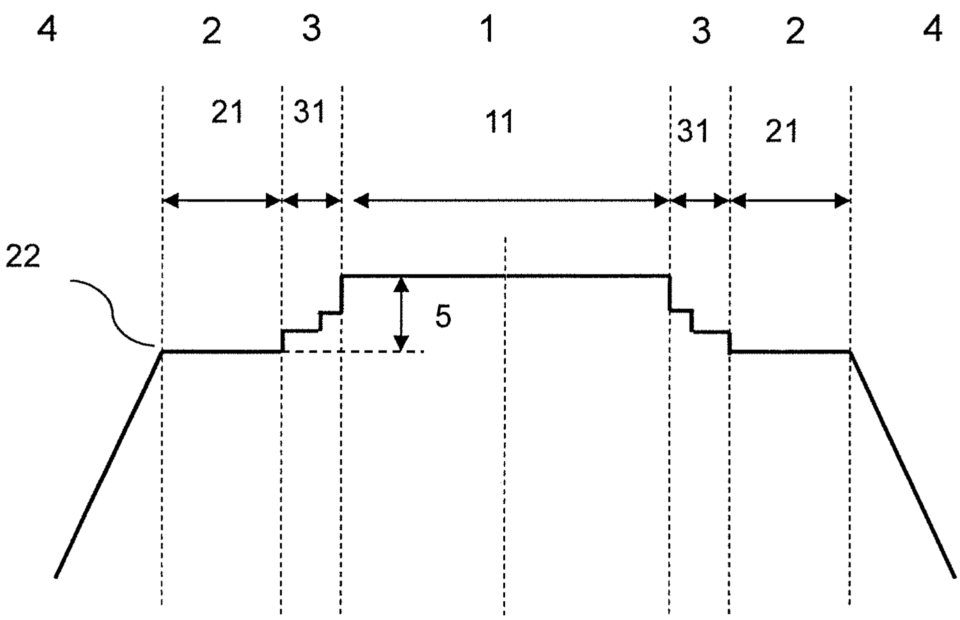

Figure 2

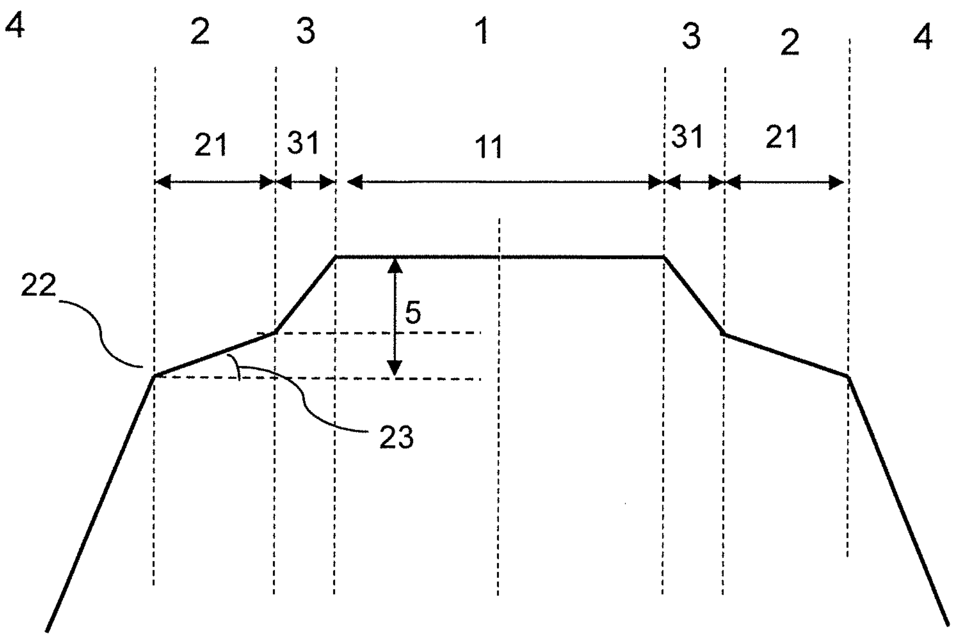

Figure 3

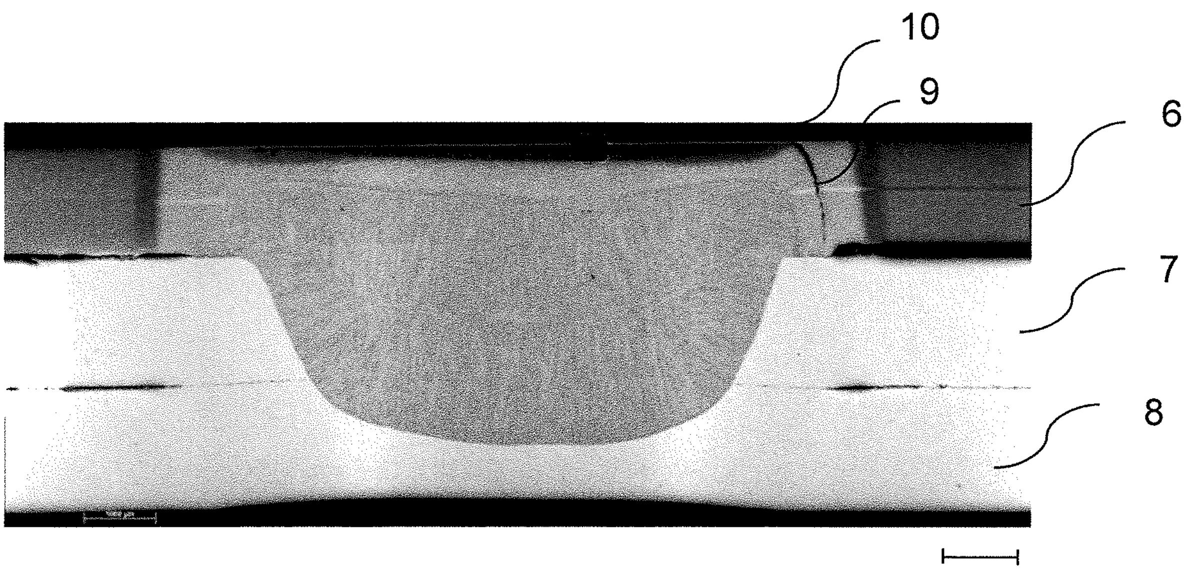

Figure 4

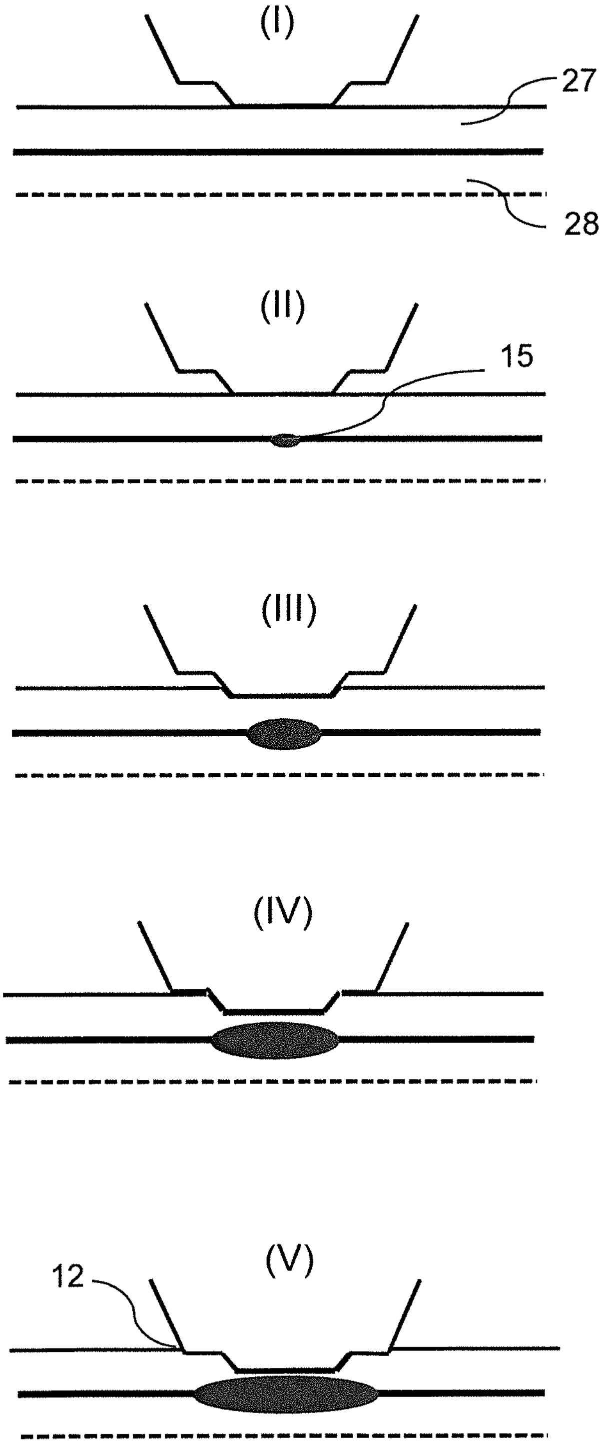

Figure 5

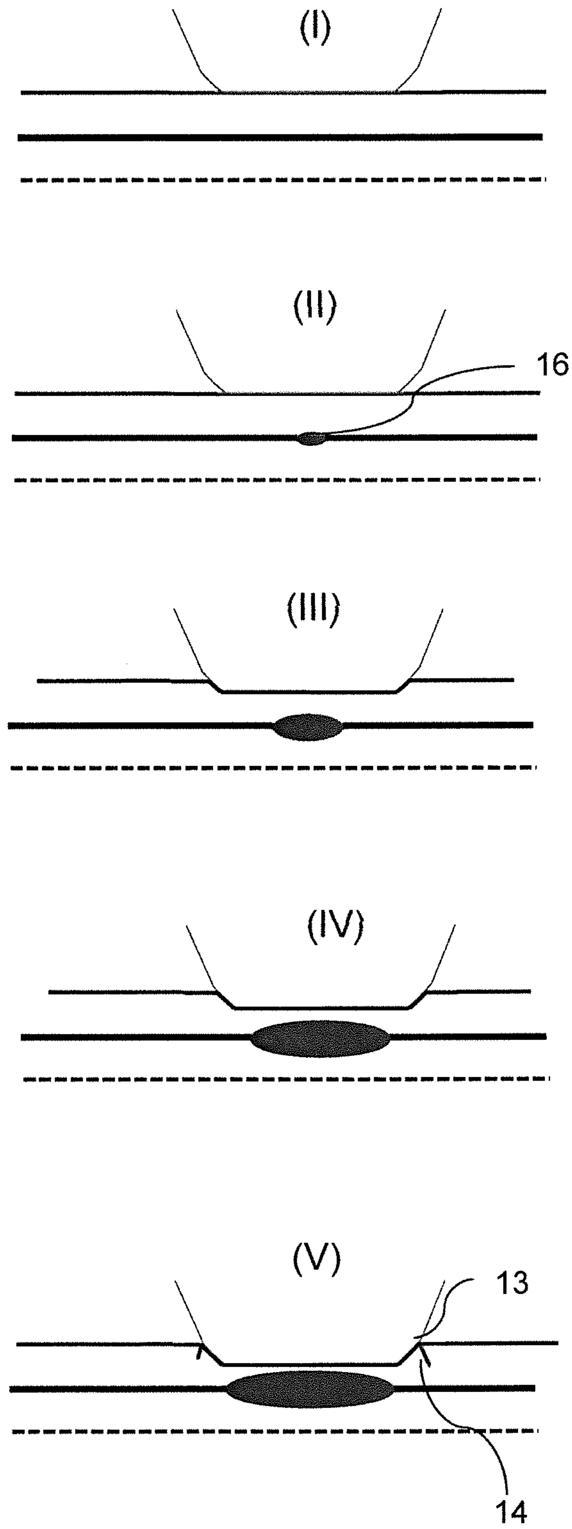

Figure 6

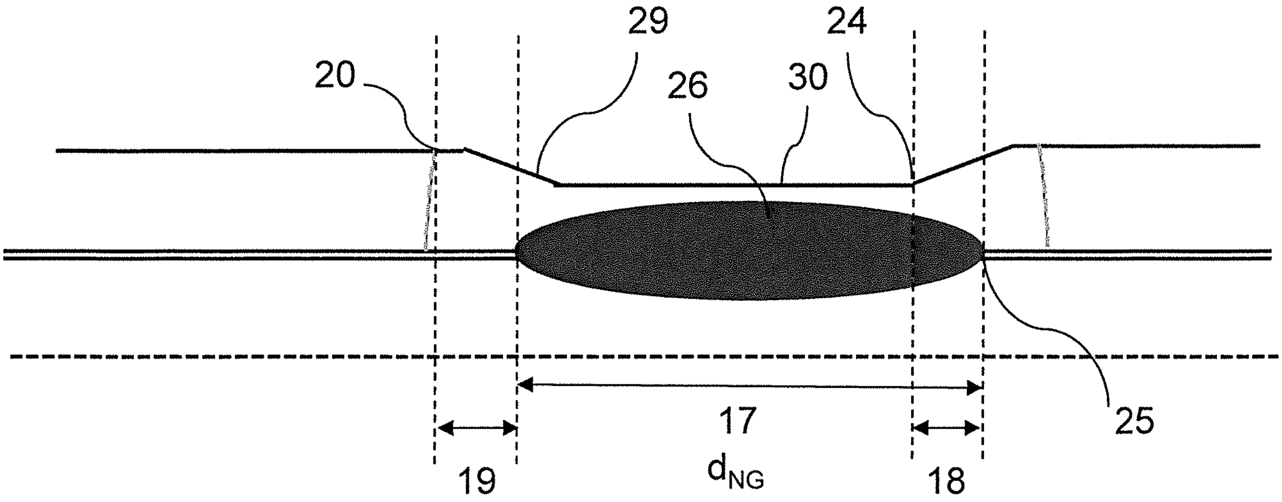

Figure 7

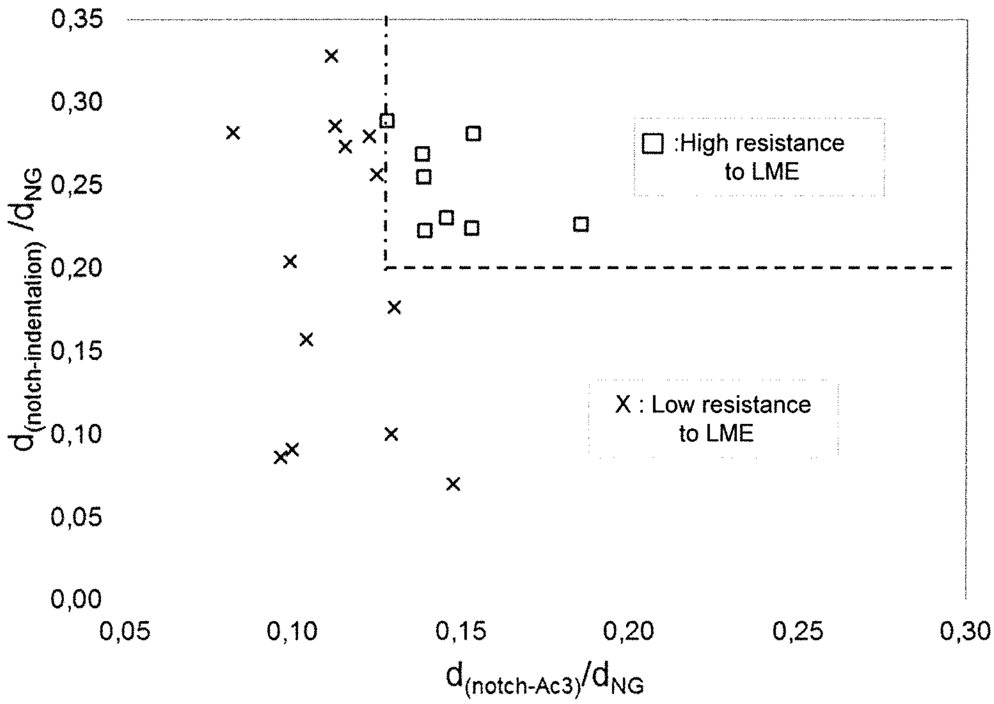

Figure 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2019/053252

A. CLASSIFICATION OF SUBJECT MATTER
INV. B23K11/11 B23K11/16 B23K11/30 C22C38/02 C22C38/04 C22C38/06
ADD. B23K101/00 B23K101/18 B23K103/04

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 C22C

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 Y	US 2017/361392 A1 (SIGLER DAVID R [US] ET AL) 21 December 2017 (2017-12-21) paragraphs [0002], [0003], [0037], [0040] - [0044], [0051], [0052], [0059], [0071]; figures 1,2,12 -----	1-5,7 6,8-17, 26
X Y	US 2009/302009 A1 (SIGLER DAVID R [US] ET AL) 10 December 2009 (2009-12-10) paragraphs [0002], [0005], [0012], [0013], [0026], [0031] - [0039], [0043] - [0047]; claims 3,12; figure 7 -----	1-4,7 6,8-17, 26
Y	US 2019/084074 A1 (BRANAGAN DANIEL JAMES [US] ET AL) 21 March 2019 (2019-03-21) paragraphs [0002] - [0007], [0109] - [0115], [0131], [0131], [0164] - [0167]; claims 21,25,26; table 44 -----	8-17,26
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 March 2020	27/05/2020

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Schloth, Patrick

4

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KR 2012 0017955 A (POSCO [KR]) 29 February 2012 (2012-02-29) paragraphs [0001] - [0003], [0015] - [0021], [0069], [0070]; figure 7 -----	18-25,27
X	WO 2018/082425 A1 (BAOSHAN IRON & STEEL [CN]) 11 May 2018 (2018-05-11) paragraphs [0009], [0013], [0029], [0088]; figure 6; table 2 -----	18-21, 23-25,27
X	Lutz-Alexander Pepke ET AL: "Untersuchung der Anlagenkonfiguration beim Widerstandspunktschweißen von Stahlfeinblechen", , 17 March 2015 (2015-03-17), XP055681323, DOI: 10.14279/depositonce-4299 Retrieved from the Internet: URL:https://depositonce.tu-berlin.de/handle/11303/4596?mode=full [retrieved on 2015-03-17] pages 24,61-64 -----	18-25,27

4

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2019/053252

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017361392 A1	21-12-2017	CN 107520550 A	29-12-2017
		US 2017361392 A1	21-12-2017
US 2009302009 A1	10-12-2009	US 2009302009 A1	10-12-2009
		US 2013306604 A1	21-11-2013
US 2019084074 A1	21-03-2019	NONE	
KR 20120017955 A	29-02-2012	NONE	
WO 2018082425 A1	11-05-2018	AU 2017352642 A1	16-05-2019
		BR 112019008699 A2	08-10-2019
		CN 108015401 A	11-05-2018
		EP 3536435 A1	11-09-2019
		JP 2019536631 A	19-12-2019
		US 2019321907 A1	24-10-2019
		WO 2018082425 A1	11-05-2018

INTERNATIONAL SEARCH REPORT

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☒ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-17, 26

   A resistance spot welding electrode with an improved design and a process of resistance spot welding that uses a pair of resistance spot welding electrodes with that improved design.

   ---

2. claims: 18-25, 27

   A resistance spot weld of superimposed steel sheets with a specific relationship of the heat affected zone (AC3 isotherm) and the extremity (outer edge) of the weld nugget and a specific relationship of the extremity (outer edge) of the weld nugget and the extremity of the indentation zone of the electrode.
