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(19) **United States**(12) **Patent Application Publication****Kurz et al.**(10) **Pub. No.: US 2005/0028897 A1**(43) **Pub. Date: Feb. 10, 2005**(54) **PROCESS FOR AVOIDING CRACKING IN WELDING**(52) **U.S. Cl. 148/525**

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(57) **ABSTRACT**

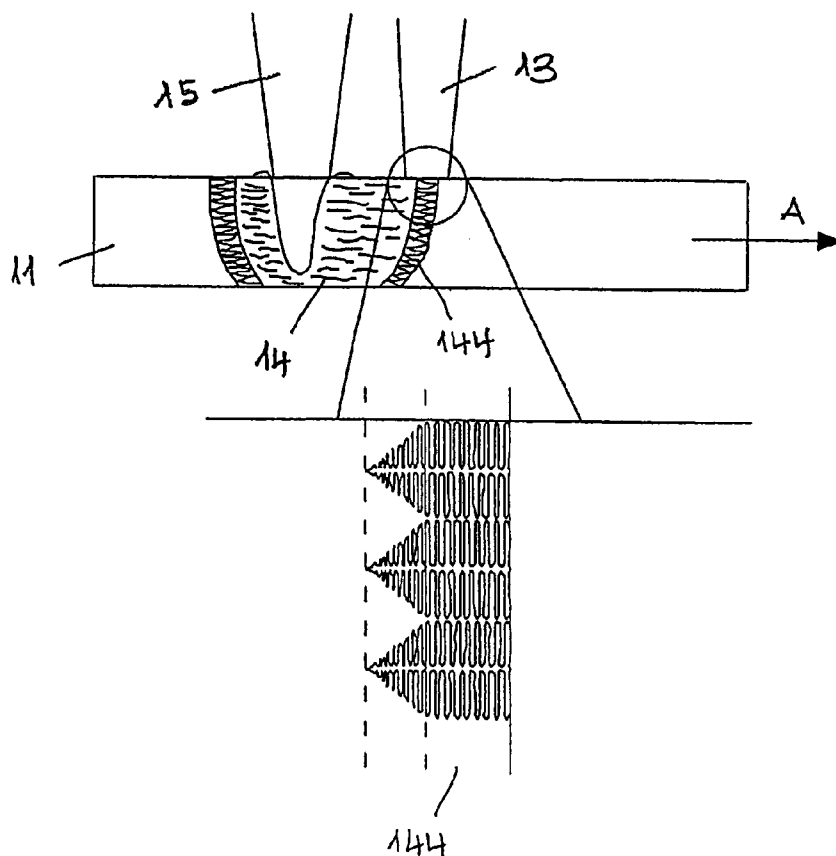
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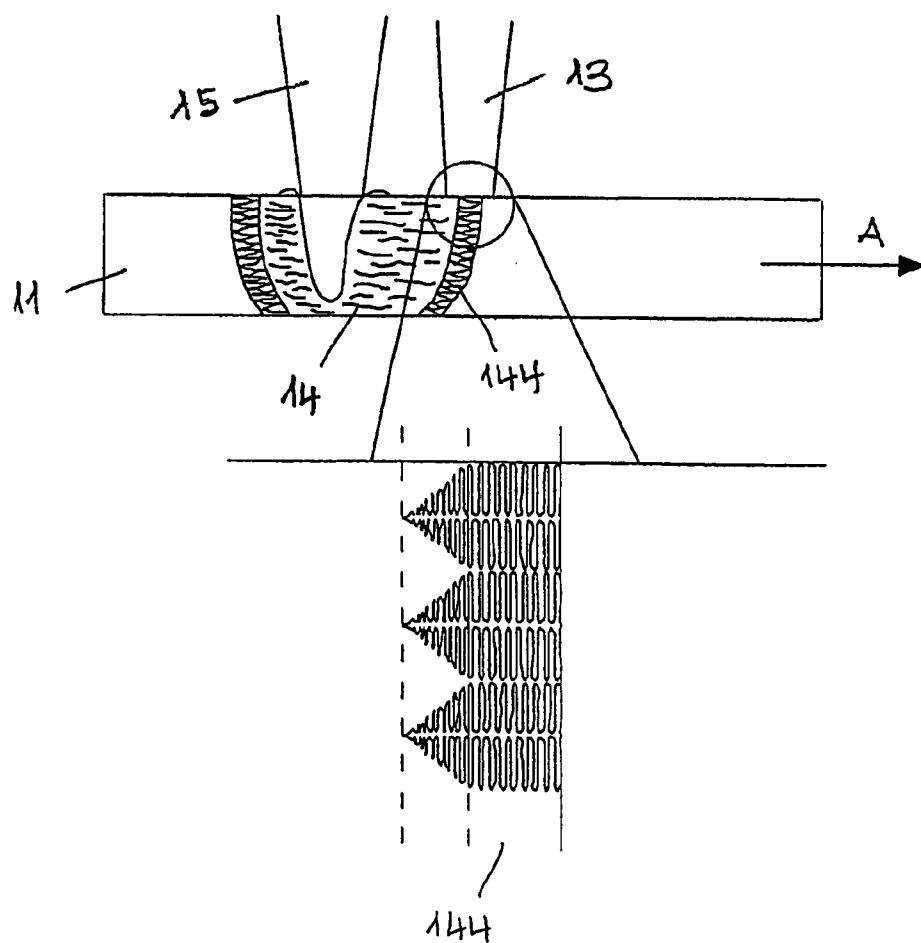
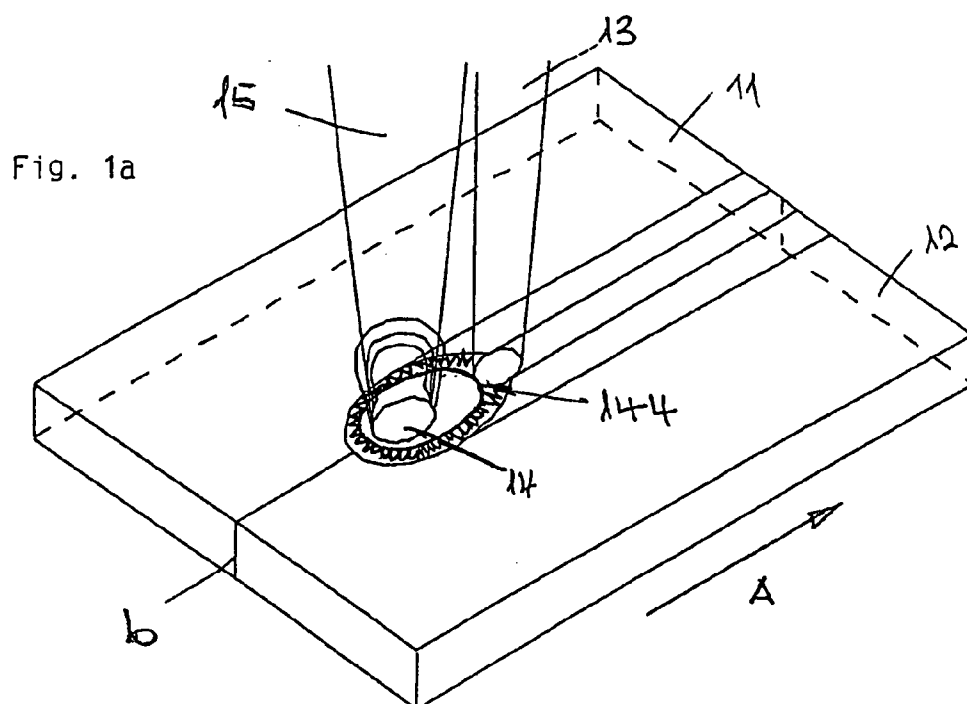
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The new welding process avoids cracking in welding, in repair welding or in cladding of parts of metallic alloys which are sensitive to hot cracking. The process is using a first heat source (15), directed to the parts (11, 12) of the metallic alloy forming a melt pool (14) on the parts (11, 12) of metal or metallic alloy. The heat source (15) and the parts (11, 12) are moved relative to each other. The process is characterized in that there is one (13) or more additional heat sources directed to the parts (11, 12) of metal or metallic alloy and following the first heat source (15) in a distance and with substantially the same speed and in the same direction as the first heat source (15). The additional heat source (13) or heat sources are directed to the solidification region (mushy zone) (144) of the melt pool (14) generated by the first heat source (15). The power of the additional heat source (13) is set such as to reduce the local cooling rate of the solidification region (144) of the melt pool (14), or to even shortly reheat this region without substantial remelting or with no remelting it at all and thereby reducing the tensile stresses or even inducing compressive stresses. During this process a central equiaxed zone might also be enhanced. By this new process the formation of hot cracks is avoided.

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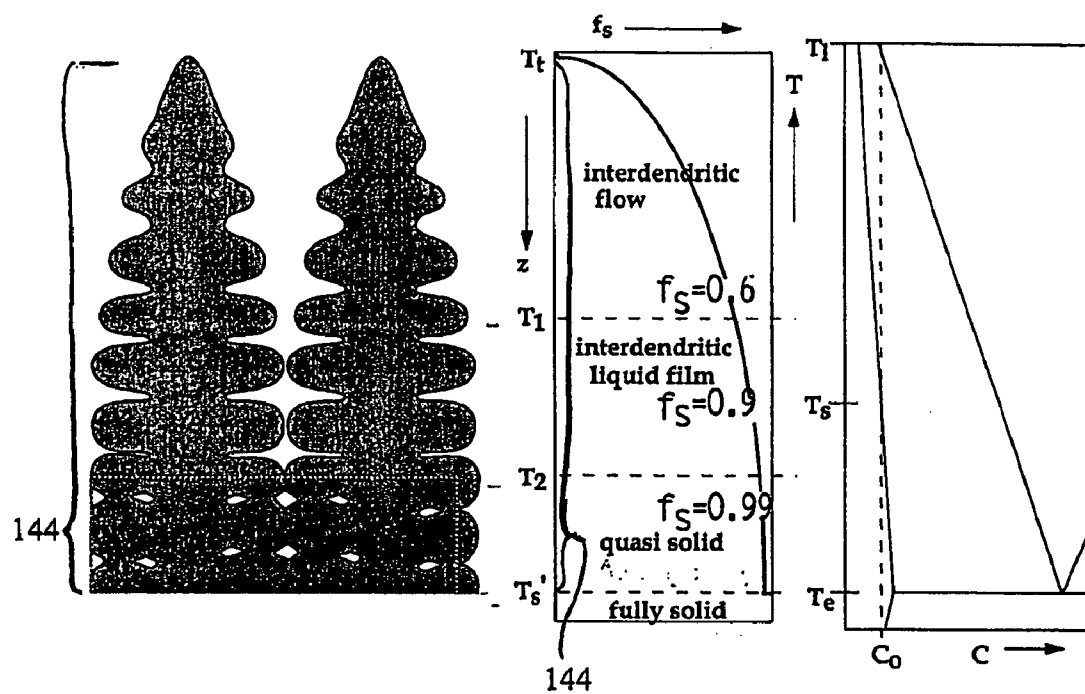


Fig. 1c

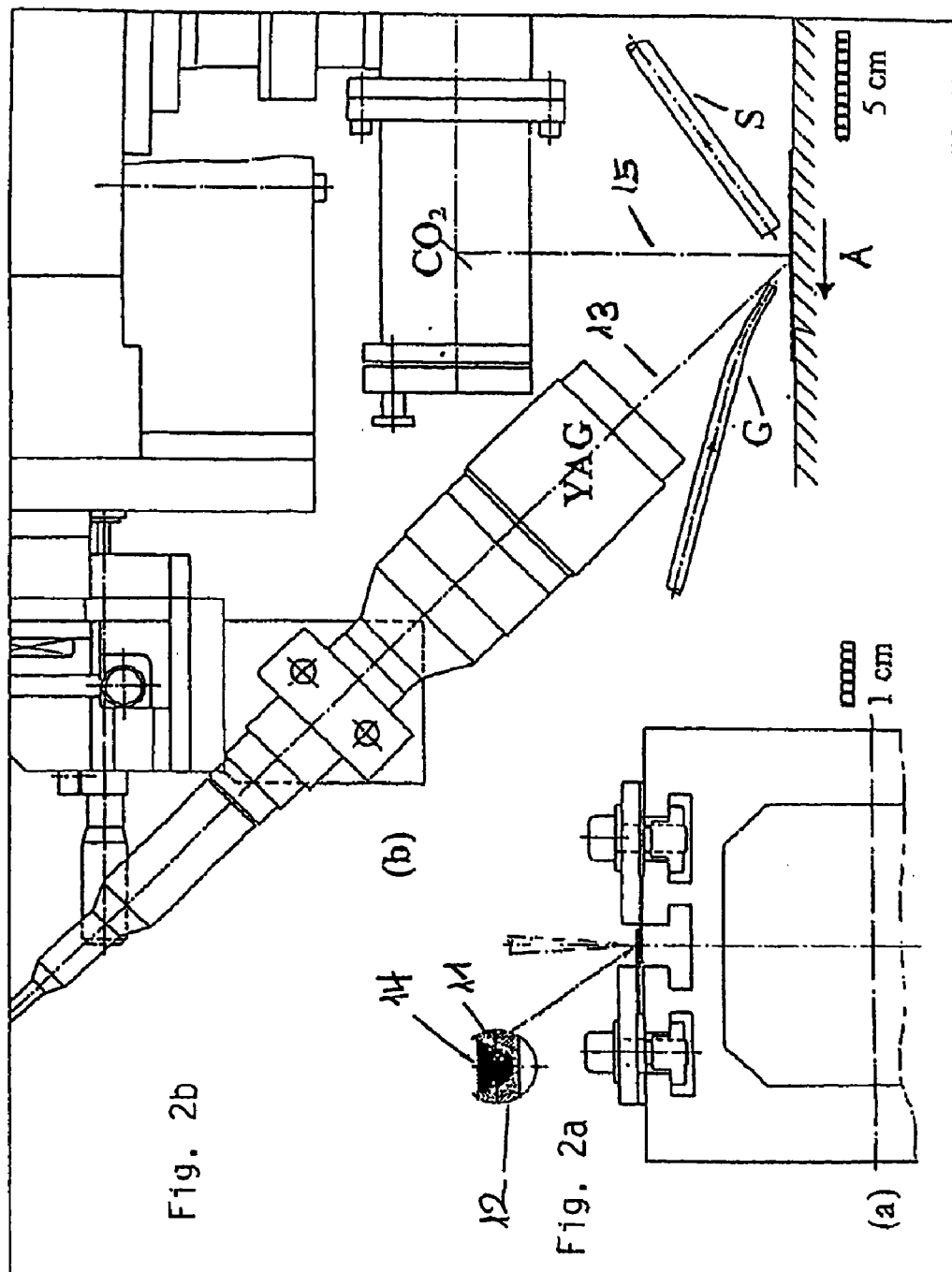


Fig. 3a

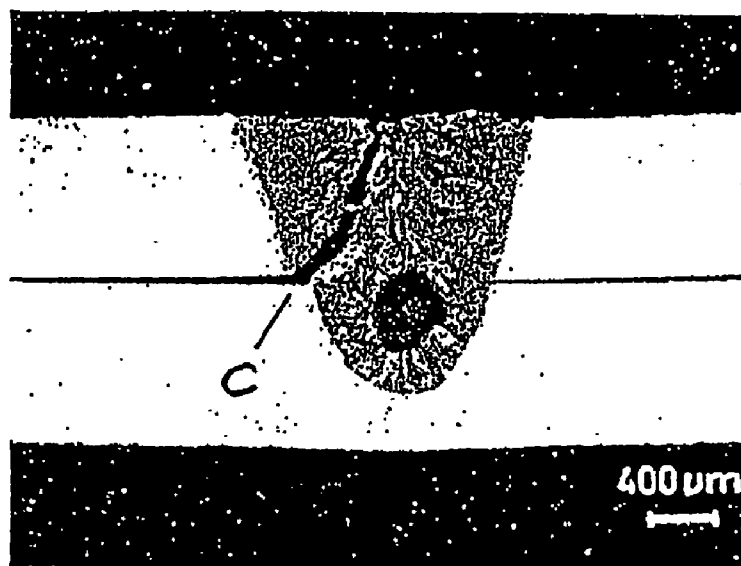


Fig. 3b

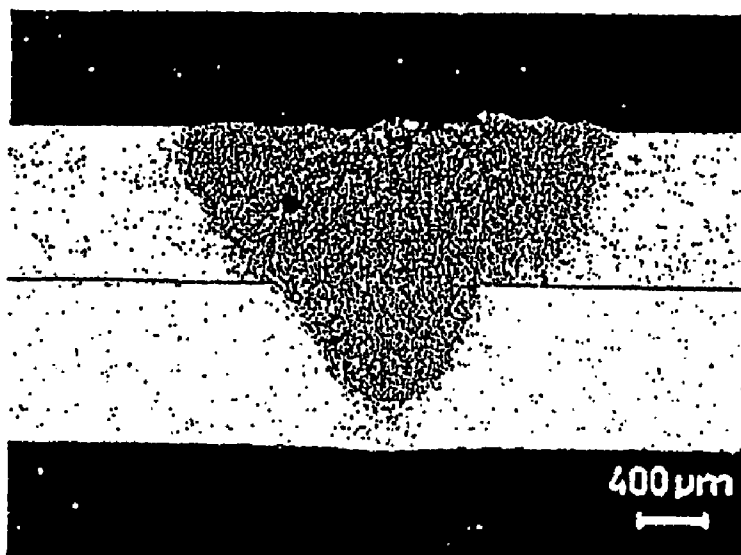
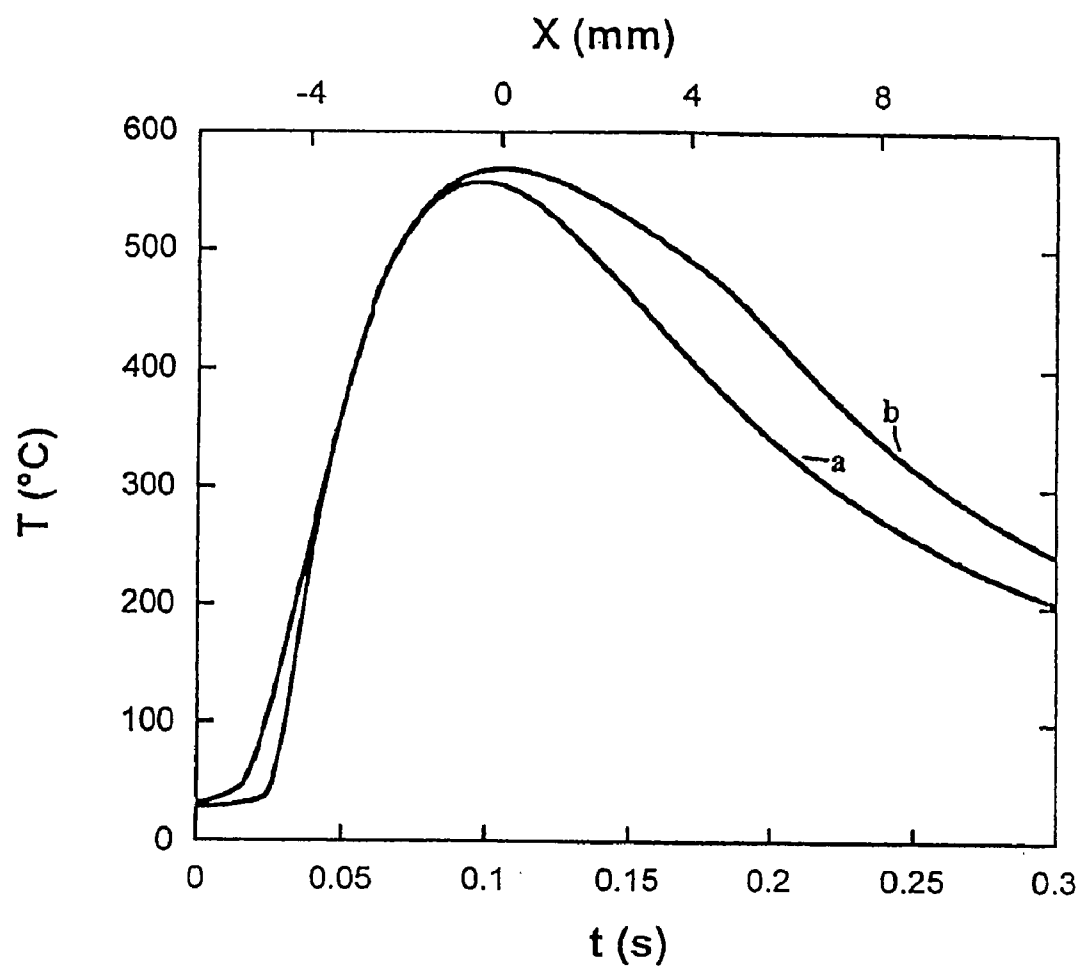


Fig. 4



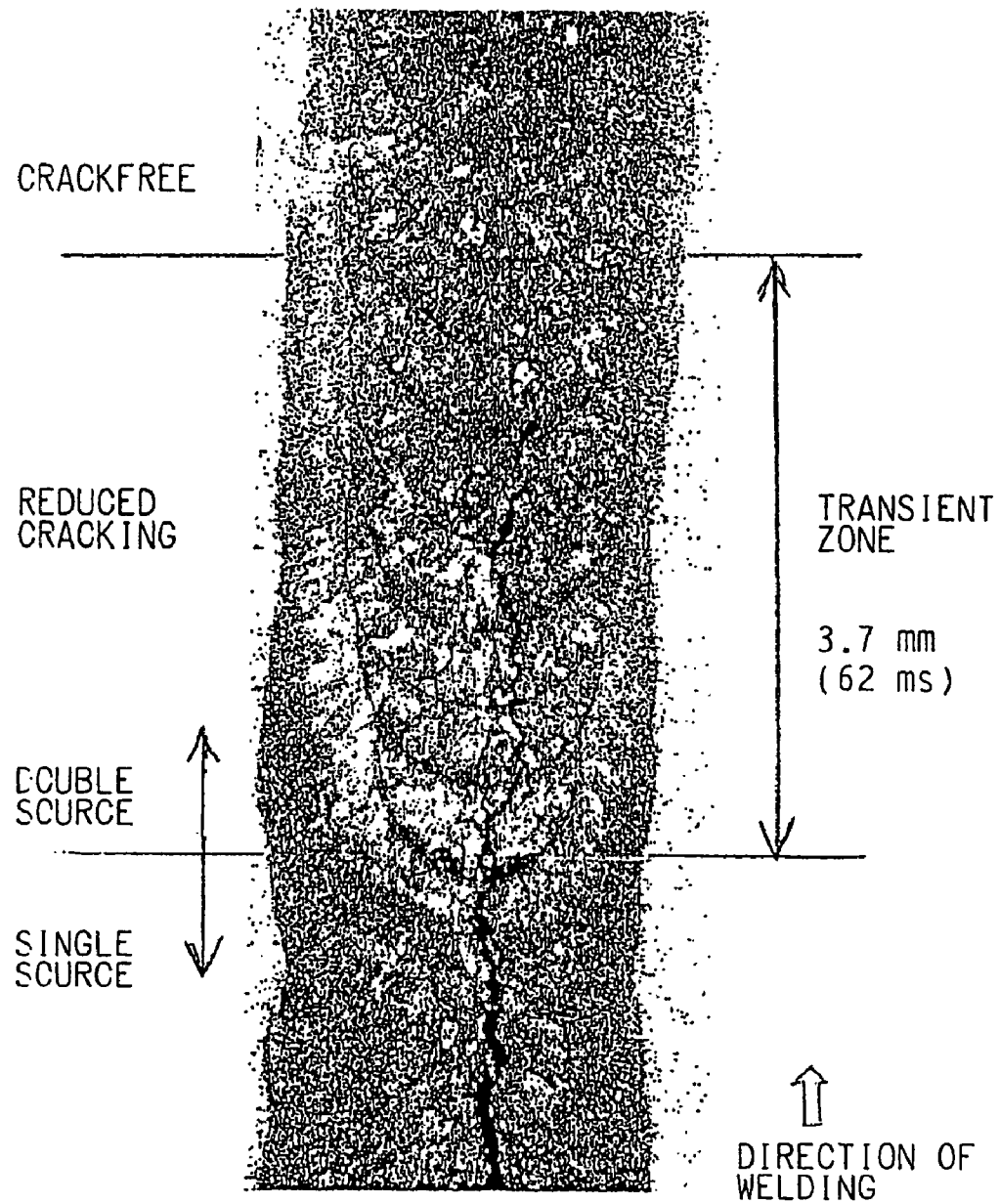


Fig. 5

PROCESS FOR AVOIDING CRACKING IN WELDING

[0001] The invention is related to a welding, repair welding or cladding process of metallic alloys according to the preamble of the independent claim 1. It is further related to the use of the welding, repair welding or cladding process and to work pieces welded or clad with the process. Its main aim is the prevention of hot-crack formation during the process.

[0002] The general behavior of solidification and hot cracking (solidification cracking) is very similar in the three processes mentioned. It is further general to many metallic alloys like steels, super alloys, aluminium alloys. Therefore only the welding process will be explained in more detail, with the aid of hot cracking of prone aluminium alloys. Aluminium alloys are traditional materials in transport technology such as aerospace, automobiles and trains, because of a good combination of mechanical properties and low weight.

[0003] Different joining techniques are used for producing aluminium parts. Riveting, TIG and MIG welding are traditional processes in the manufacturing industry although they present some important weaknesses. Rivets form weak joints and are especially vulnerable to stress corrosion cracking. TIG and MIG produce large heat-affected zones (HAZ), where alloys experience additional solution treatments and averaging, thus leading to a degradation of material properties and a reduction in lifetime. Laser welding is a particularly interesting approach for the construction of metallic structures. New developments in laser technology, such as fiber-optic delivery of YAG beam and high-power diode lasers, have increased and will increase in the future their use in high volume production.

[0004] Many aluminium alloys are weldable provided the solidification interval is relatively small. Some classes of aluminium alloys such as 2xxx (Al—Cu), 5xxx (Al—Mg), 6xxx (Al—Mg—Si) and 7xxx (Al—Zn— . . .) often crack during autogenous welding. Industrial experience has shown that hot cracking can be avoided by the addition of a eutectic-forming alloy, such as a Al—Si wire, to the weld. This methodology is widely applied to the construction of aluminium parts, even if the mechanical properties of the weld are not as good as those of the base material.

[0005] The term “hot cracking” is used to denote brittleness at temperatures above the solidification end (often the eutectic temperature) which is due to the presence of residual liquid films in-between the dendritic grains of the solidifying alloy. Materials in which such cracking occurs invariably possess a large solidification interval, since pure metals and eutectic alloys are not susceptible to hot cracking. During cooling of these alloys from the liquid, the formation of primary dendrites begins close to liquidus temperature, and during subsequent cooling these dendrites grow at the expense of the liquid. When the proportion of liquid is still large, the alloys have essentially the properties of a liquid. Later in the process of solidification, however, the dendrites interlock and form a coherent network with the remaining liquid occupying the interstices. During the formation of this network, there is a progressive increase in strength. However, if the nearly-completely solidified alloy has a high-strength in compression, it is still weak with respect to the transmission of shear/tensile stresses as long

as inter-dendritic and inter-granular liquid films are present. In parallel to this, the interdendritic liquid experiences an increasing difficulty to flow through the high tortuosity paths in order to compensate shrinkage and deformation of the solid skeleton. The combination of shrinkage and shear/tensile stresses will therefore lead to underpressure in the remaining liquid, and thus finally to solidification cracking. The alloy is therefore susceptible to cracking while it is in the brittle temperature range (BTR), i.e. at a temperature corresponding approximately to the last 10% of liquid. The invention is related to an improved welding process that overcomes the problem of cracking and in particular of hot cracking.

[0006] The process according to the invention is characterized by the features of the characterizing part of the independent claim 1. The depending claims are related to favorable improvements of the invention. The process provides for crack free welding of work pieces and in particular metal sheets.

[0007] The invention and the prior art are illustrated and explained in details with reference to the pictures and drawings.

[0008] The figures show the following:

[0009] FIG. 1a show a schematic, perspective view of two work pieces that are welded according to the invention,

[0010] FIG. 1b is a schematic side view of the welding area and a solidification profile of the different solid fractions during the solidification of a dendritic network of the welded area of a work piece.

[0011] FIG. 1c is a schematic representation of dendritic solidification with associated solid fraction as a function of distance and phase diagram.

[0012] FIG. 2a shows a schematic side view of the welding setup;

[0013] FIG. 2b is a schematic side view of the laser setup and one possible configuration of a gas supply and gas suction nozzles of the welding setup.

[0014] FIGS. 3a and 3b show the pictures of two sheets welded with a CO₂ laser according to a prior art method (FIG. 4a) and two sheets welded with the process according to the invention (FIG. 4b);

[0015] FIG. 4 is an example of a temperature-time curve measured by a thermocouple placed close to the weld trace for welding process according to the prior art FIG. 4a and the temperature-time curve of the welding process according to the present invention FIG. 4b;

[0016] FIG. 5 is the picture of a specimen welded in the lower part with a conventional welding process and in the upper part with the process according to the invention, showing crack healing over the transient zone for an overlapped joint.

[0017] On the mesoscale, hot cracks can be distinguished from other cracks formed at distinctly lower temperature by detached grains and crack surfaces decorated by dendrites. The residual liquid remains on both fractured surfaces, which sometimes shows a eutectic layer. A few spikes resulting from the opening of inter-granular grain bound-

aries are also characteristic of hot-cracked surfaces. In most cases, these effects can only be perceived with a scanning electron microscope.

[0018] A possible arrangement for practicing welding process is shown schematically in FIG. 1a and FIG. 1b, as well as in FIG. 2a and FIG. 2b. The two metal sheets 11 and 12 are arranged next to each other, thereby forming a gap 10. The metal sheets 11 and 12 are moved in the direction of arrow A. The laser beam 15 of a CO₂ laser is directed to the surface of the two sheets 11 and 12, and bridging the gap 10. The laser beam 15 is melting the two sheets 11 and 12 and forms a melt pool 14. A second laser beam 13 of a YAG laser is directed to the mushy zone 144 region of the melt pool 14. When the sheets 11 and 12 are moved in the direction of arrow A, the laser beam 13 is following the laser beam 15. It would of course also be possible that the laser beams 15 and 13 are moved in stead of the two sheets 11 and 12. In this case the laser beams 15 and 13 would be moved in the direction opposite to the direction indicated by arrow A. In another arrangement both, the sheets 11 and 12 as well as the laser beams 11 and 12 can be moved relative to one another. As can be seen there is no overlap of the spots of the energy sources 15 and 13 on the sheets.

[0019] FIG. 2 illustrates in more detail and schematically dendritic solidification with associated solid fraction as a function of distance and the phase diagram. In this example the mushy zone 144 is also named the dendritic solidification region or zone, where the f_s the solid fraction is $0 < f_s < 1$. This means that in the mushy zone/dendritic solidification region/zone there is dendritic solid material, but that there is still liquid material in this zone. $0 < x \% < 100\%$ of the material is still in the liquid phase.

[0020] At the temperature T_1 solidification of the material starts and dendrites start building up. At the temperature T_1 lower than T_1 , down to the temperature T_2 there is the zone of the interdendritic film. In the shown example in this area the solidification factor is $0.6 < f_x < 0.9$.

[0021] When in this application it is stated that the wording "or even shortly reheat this region without substantially remelting" is used it is meant, that the temperature of the part of the mushy zone exposed to the second heat source will not go up to T_1 . As a consequence of this, there will always be dendrites. Only the percentage of liquid will be increase by such "non substantial remelting" and there will always be solid dendrite material in the mushy zone 144.

[0022] As can be seen in FIG. 2, the process is performed under gas protection. The gas supply nozzle G supplies the inert gas and the gas suction nozzle S sucks the gas, so that the melt pool 14 is well protected by the gas flowing from nozzle G to nozzle S. In the enlarged part of the sheets 11 and 12 of FIG. 2b can be seen, that the sheets 11 and 12 are arranged overlapping each other in the area that is welded.

[0023] The process may also be performed with lasers beams of the same type. In such an arrangement the laser beams may come from two separate laser sources or the laser beams laser beams.

[0024] Based on present experience of hot cracking phenomena in alloys, the conditions for avoiding cracks can be analyzed. Under normal welding conditions, the transverse stress distribution near the melt pool along the weld centerline consists of three typical regimes. Firstly, compression

forces are observed ahead of the melt pool due to heating and thermal expansion of the solid. Secondly, liquid formation with a free surface accommodates the stresses. Thirdly, tensile forces build up as soon as the mushy zone begins to behave as a continuous solid. These tensile forces, which can result in final deformation of the welded part and/or in residual stresses, are often responsible for hot cracks.

[0025] The control of process conditions, such as the geometry of the weld, the clamping of the parts, and the laser power and speed could reduce stresses behind the melt pool. For example, the clamping distance directly influences stresses. For an edge-mounted sample, a small clamping distance decreases tensile stresses because of the expansion of the sheet. If the thermal conductivity and interaction time are sufficiently large this effect leads to compression of the mushy zone and prevents cracking. However, if the sheets are overlapped this effect leads to sliding, thereby producing cracks in the interface between the sheets. Usually this occurs after complete solidification thus producing cold cracks. Reducing welding heat input and speed also decreases the transverse stresses, increasing the resistance against cracking.

[0026] Rappaz et al. (M. Rappaz, J.-M. Drezet and M. Gremaud, *Met. Trans.* 30A (1999) 449) assessed the influence of strain rate on the HCS (Hot Cracking Susceptibility); their model is based on the maximum tensile/shear strain rate which can be supported by the mushy zone before cracks appear. The strain rate can be decreased if the cooling rate during solidification is reduced, i.e. if the solidification speed and/or the thermal gradient are reduced. Some thermal gradient control is possible with preheating, but this cannot always be applied in industrial manufacturing.

[0027] The addition of a eutectic-forming alloy to the weld is recommended as it increases the permeability of the mushy zone in the regions where shrinkage and stresses occur. For example, the addition of a 4043 Al—Si alloy wire to the 6061 alloy weld reduces the hot cracking susceptibility. However both the yield and ultimate strengths are reduced by 50%. Furthermore, there might be variable heat input resulting from the occasional feeding of filler wire directly into the beam, causing inconsistent penetration and weld-pool instability.

[0028] The weld microstructure also plays a role in hot cracking. It is essentially controlled by the growth speed V and the thermal gradient G at the solidification front, but also by the inoculation conditions. For columnar structures growing from the edge of the weld microsegregation usually produces a centreline channel which is the last part to solidify, and which is especially sensitive to cracking. Two mechanisms can decrease the HCS of this centreline boundary: formation of equiaxed grains and a variation in grain orientation.

[0029] It has been observed that fine equiaxed grains are less susceptible to hot cracking than columnar grains because the strains are more evenly distributed among numerous grain boundaries. Another possible technique for avoiding crack formation consists of changing the directionality of grain growth towards the weld centreline by producing a tortuous path.

[0030] The laser welding process according to the invention in principle includes a precisely controlled cooling

cycle and associated stress build-up evolution. This is achieved by the combination of two or more heat sources such as laser beams (**FIG. 1**). Positioning the laser source over the sensitive region of the melt pool which is the mushy zone, this results in

- [0031] a reduced contraction or even in a compression of this zone;
- [0032] a decreased strain rate. The strain rate can be decreased by a decrease of the cooling rate during solidification, especially at high volume fraction of solid;
- [0033] an increased intergranular and interdendritic feeding time;
- [0034] an enhancement of equiaxed grains. An equiaxed structure can be produced by decreasing the thermal gradient and by producing mechanical stirring due to a pulsed laser, which may lead to an additional fragmentation of dendrites.

[0035] In the following the invention is explained in detail with the aid of an example. A 6016 aluminium alloy (Table 1) which is used in automobiles was chosen for the experiments since it is susceptible to hot cracking. **FIG. 2** shows a schematic representation of the welding setup, showing in **FIG. 2a** the fixture system and the sheets and in **FIG. 2b** the setup with the CO₂ laser beam and the YAG laser beam, together with the gas supply nozzle G and the gas suction nozzle S. The alloy was delivered in a T6 condition, after solution heat-treatment at 540° C. for a short time, air cooling, and a precipitation (aging) treatment at 205° C. for several hours. The sample dimensions were 100×50×1 mm sheets which were welded with an overlap of 8 mm **FIG. 2a**. This geometry is usually used in transportation industry because mounting of butt plates easily leads to uncontrolled gaps.

TABLE 1

6016 alloy composition in wt. %									
Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
1.11	0.24	0.07	0.06	0.41	0.013	0.0052	0.015	0.012	bal.

[0036] The laser workstation consisted of two lasers, one CO₂ and one YAG laser, a CNC controlled table (with linear scanning velocities up to 0.5 m/s) and a gas protection system, **FIG. 2b**. The 1.7 kW CW—CO₂ laser produced a minimum focal spot of about 0.26 mm diameter with an off-axis parabolic mirror with 152 mm focal length. The 1.2 kW pulsed mode YAG laser produced a 0.6 mm focal spot given by the diameter of the optical fibre. For the present application, the mean spot size of the second laser was defocused giving an elliptical 1.2×1.5 mm spot with the longer axis aligned in the direction of the laser movement

[0037] Inert gas was applied through a nozzle and evacuated through a suction system to direct the gas stream and protect the optics. This suction system also moved the plasma plume away from the second laser spot allowing a free interaction of the second laser beam with the sample surface without plasma formation. Pure helium was found to be better than argon, or a mixture of Ar/He, since the plasma

was smoother and less metal particles were ejected. The gas flux was set at an intermediate value of 5 l/min (too high fluxes disturbed the liquid bath and too low fluxes did not protect against oxidation). The best gas injection angle was found to be about 30° from the sample surface plane (**FIG. 2b**).

[0038] The surface cleanliness is important for a high quality weld. Dirty and oxidized surfaces produce bubbles in the welds. Washing with water and ethanol followed by ultrasonic cleaning gave sufficient surface cleanliness to produce good welds. Laser-cleaning prior to welding was also tried. A Q-Switched YAG laser was used to clean some samples as an alternative to traditional cleaning with excellent results.

[0039] Various process parameters have been considered in order to obtain sound weldings by the dual beam method. The welding speed was fixed at 60 mm/s with 1700 W CO₂ power. In other arrangements welding speeds of 100 mm/s and more are possible. The average YAG laser power was fixed at 1200 W, and the following range of process parameters were investigated:

- [0040] YAG energy and frequency: 4/300, 6/200, 8/150, 10/120, and 12/100 (J/Hz)
- [0041] YAG pulse length: 0.2, 1, and 2 ms.
- [0042] Distance between sources: 0, 1, 2, 3, 4, 5, and 6 mm.

[0043] Among the above process variables, the best conditions for crack-free welds at 60 mm/s weld speed were obtained when the YAG beam was placed 3 mm behind the CO₂ beam. Eight joules and 2 ms were the best compromise between an insufficient thermal transfer (4-6 J and/or 0.2-1 ms) and burning (12 J), but satisfactory results were also obtained using 10 J. Using 8 J pulse energy, and a frequency of 150 Hz, the intensity per pulse was about 30 W/cm². In comparison with single beam CO₂ welding see **FIG. 3a**, where there is a crack C.

[0044] The dual beam method produces an enlarged liquid bath. The result of the dual beam method is shown in **FIG. 3b**, where there is no crack at all. Bubbles in the weld disappeared when the dual laser method was applied as length of the liquid bath (L) was increased, thus increasing the time for bubbles to rise to the surface.

[0045] **FIG. 4** shows the temperature-time curve for a welding process with a single laser beam (curve a) and the temperature-time curve for a welding process with a dual laser beam (curve b) with a welding process according to the invention. In other words **FIG. 4** shows the thermal history (a) and the cooling rate (b) during welding for single laser beam (curve a) and dual laser beam (curve b) experiments. The peak temperature was unaffected by the use of the second source, but the cooling rate in the critical location was substantially reduced, from 2600° C./s to 1500° C./s (curve b).

[0046] The results also showed an increase in the pool length at 8 J, which corresponds to the best welding condition. At low power levels of the second beam, the liquid pool length (L) and width (W) was only slightly changed since the heat input was low. At high energy levels (above 10 J) the YAG laser interacted directly with the plasma over the weld, formed by the first laser, both laser beams acting as a single heat source.

[0047] As proposed by Clyne and Davies (T. W. Clyne and G. J. Davies, *J. British Foundry* 74 (1981) 65), two different solidification periods can be considered: a free feeding time (FT), where the interdendritic spacing permits an unimpeded flux of liquid, and a constrained feeding time (CT) where the dendritic bridging leads to an increasing underpressure in the residual liquid. Here these two periods of time were considered as the interval between 60 and 10% and 10 and 1% liquid, for FT and CT respectively. These characteristic times can be calculated from the extension of the solidification interval giving at centerline divided by the scanning velocity, giving:

Single source:	FT = 0.01 s and CT = 0.005 s
Process according to the invention:	FT = 0.043 s and CT = 0.005 s

[0048] The feeding time is four times greater in the welding process according to the invention than in the single source case, and the HCS according to Clyne is now 0.12 in comparison with 0.5 for the single source process. Therefore, the welding process according to the invention reduces cracking by extending the time where the liquid can feed the growing solid.

[0049] The thermal gradient can be estimated with a semi-empirical thermal model. The results at the centerline show that the thermal gradient at the beginning of mushy zone was reduced from 400 K/mm to 175 K/mm. This decrease has consequences on the microstructure, leading to equiaxed dendrites near the centerline.

[0050] To prove the interest of the proposed laser welding process according to the invention, a specimen was welded first with the single source producing a longitudinal crack, and then the secondary laser was switched on during the experiment. Two steady regimes were observed: a cracked weld when a single source was used and a crack-free weld when the second laser source was turned on. Few millimeters of YAG interaction were required in the transient regime to close the crack (FIG. 5). The crack disappears after about 60 milliseconds of YAG interaction in a sample where the YAG beam was turned on at the middle of the experiment (speed of the laser beams 60 mm/s, YAG energy 8J). A series of ten consecutive experiments confirmed the trend without a single exception.

[0051] The difference between the laser welding process according to the present invention, and conventional welding processes is the use of two or more locally and intensity wise well-controlled heat sources. Although this can be performed by any combination of available heat sources, as far as they are localized enough, it appears that laser technology has a major advantage over others methods because of the very precise control of spot size, position and heat input, essential to the effectiveness of the present technique.

[0052] The effect of the dual laser system on strain rate can be discussed in the following way: under the assumption of a fully constrained weld, the mechanical strain rate is equal to the opposite of the thermally induced strain rate. This latter value is proportional to the cooling rate, which can be controlled by the present welding method. Taking the values shown in FIG. 4, the strain rate at the critical location is

decreased to nearly half of the value for conventional CO₂ welding by the use of the second laser source. The important point is that this second laser acts directly on the final part of the mushy zone, thus reducing the cooling rate most effectively, where it is needed.

[0053] It is possible that a dynamic correlation of the inter-source distance and the other process parameters can also produce sound weldments. Moreover, any combination of heat sources, laser or otherwise, which reproduce this process window could be used to avoid, cracks.

[0054] The new welding process avoids cracking in welding, in repair welding or in cladding of parts of metallic alloys which are sensitive to hot cracking. The process is using a first heat source 15, directed to the parts 11, 12 of the metallic alloy forming a melt pool 14 on the parts 11, 12 of metal or metallic alloy. The heat source 15 and the parts 11, 12 are moved relative to each other. The process is characterized in that there is one 13 or more additional heat sources directed to the parts 11, 12 of metal or metallic alloy and following the first heat source 15 in a distance and with substantially the same speed and in the same direction as the first heat source 15. The additional heat source 13 or heat sources are directed to the solidification region (mushy zone) 144 of the melt pool 14 generated by the first heat source 15. The power of the additional heat source 13 is set such as to reduce the local cooling rate of the solidification region 144 of the melt pool 14, or to even shortly reheat this region without substantial remelting or with no remelting it at all and thereby reducing the tensile stresses or even inducing compressive stresses. During this process a central equiaxed zone might also be enhanced. By this new process the formation of hot cracks is avoided.

1. Process for avoiding cracking in welding, in repair welding or in cladding of parts of metallic alloys (11, 12) which are sensitive to hot cracking, the process using a first heat source, directed to the parts of the metallic alloy and forming a melt pool (14) on the parts of metallic alloy, the heat source (15) and the parts being moved relative to each other, the process being characterized in that there is

one or more second additional heat sources (13) directed to the parts (11, 12) of metallic alloy and following the first heat source (15) in a distance and with substantially the same speed and in the same direction as the first heat source,

the second heat source(s) (13) being directed to the solidification region of the melt pool (14) generated by the first heat source (15),

the power of the additional heat source being set such as to reduce the local cooling rate of the solidification region (144) of the melt pool (14) or to even shortly reheat this region (144) without substantial remelting, thereby reducing the tensile stresses or even inducing compressive stresses, thus avoiding formation of hot cracks.

2. Process as claimed in claim 1, one or more additional heat source (13) directed to the solidification region/the mushy zone (144) of the melt pool (14), the power of the

additional heat source (13) being set such as to reduce the local cooling rate or to even shortly reheat this region of the melt pool (14), without remelting at all or without substantial remelting, thereby reducing the tensile stresses or even inducing compressive stresses, thus avoiding formation of hot cracks.

3. Process as claimed in claim 1, the first (15) and/or the additional heat source(s) (13) being beams of high energy sources such as, laser sources, electron beam sources, electric arc sources, plasma sources, or a combination of those.

4. Process as claimed in claim 1, the first (15) and/or the second (13) heat source being beams of one single or of multiple heat sources.

5. Process as claimed in claim 1, using wire, powder or ribbons powder of an alloy of the same or of different composition as the parts to be welded, for filling and cladding purposes.

6. Process as claimed in claim 1, using wire, powder, ribbons or preapplied powder material of an alloy of the same or of different composition as the parts to be cladded.

7. Use of a process as claimed in claim 1, for avoiding cracking in welding, repair welding or cladding of parts of super alloys and/or steels.

8. Use of a process as claimed in claim 1, for avoiding cracking in welding, repair welding or cladding of parts of aluminum alloys.

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