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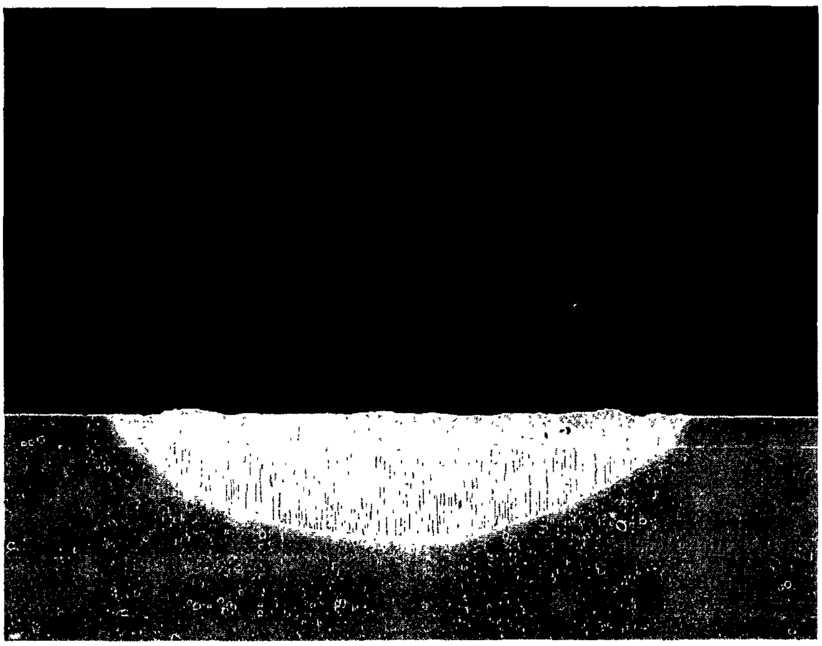
(54) **Title:** METHOD OF REMOVING CASTING DEFECTS



(57) **Abstract:** A method is disclosed for removing casting defects (5) from an article (1) with an oriented microstructure. The method comprises the steps of locating at least one casting defect (5) and melting the casting defect (5) locally by a heat source (7) to a depth at least as great as the casting defect (5) itself. Subsequently the molten material is solidified epitaxially with respect to the surrounding oriented microstructure of the article (1) in a way that the resulting solidified area is substantially free of any defect.

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Method of removing casting defects

FIELD OF THE INVENTION

The invention relates to a method of removing casting defects in articles with oriented microstructure.

BACKGROUND OF THE INVENTION

Single crystal and directionally solidified castings, such as turbine blades, are manufactured using a directional solidification process in which a ceramic shell mould filled with an alloy in the liquid state is withdrawn from a heating zone (temperature above the melting point of the alloy) into a cooling zone (well below the melting point of the alloy in temperature). This is known for example from the documents US-A-4,96,501, US-A-3,690,367 or EP-A1-0 749 790. As the shell mould is withdrawn, the liquid alloy solidifies directionally – beginning with that portion of the mould that enters the cooling zone first, and ending with the last portion of the mould to enter the cooling zone. During the solidification of the alloy, the solid/liquid interface is found substantially at a level between the heating and cooling zones. Those skilled in the art of investment casting and directional solidification are aware of the critical importance of maintaining the proper conditions at the solid/liquid interface. For example, too low of a thermal gradient across the solid/liquid interface, and/or too much of an incline of the interface compared to the horizontal, can result in the formation of freckles. Freckles are formed due to interdendritic fluid flow, resulting in chains of equiaxed grains surrounded by material rich in eutectic phases (overly rich in the elements which segregate to the liquid phase during segregation). The chains can be anywhere from 2 mm to 20 cm long, and constitute zones of unacceptable weakness (fatigue strength) in single crystal alloys due to the lack of grain boundary strengtheners. Freckles are also considered critical defects in columnar grain alloys, despite their higher content of grain boundary strengtheners. In other cases, new grains can nucleate and grow for a limited distance in the direction of growth of the solid/liquid interface, provided that the primary orientation (crystallographic orientation relative to the growth direction) is close to that of the rest of the casting. This defect is known as a sliver, and can reach lengths of 5 cm or more. Since it may comprise a high angle boundary which is almost always impossible to measure using Laue methods due to the limited width of the grain, slivers are also considered critical defects. Other grain related linear defects include low angle grain boundaries which are above the allowed limit of misorientation. Non grain related linear defects include linear chains of pores, surface micro-cracks and dross or inclusions which are normally only detectable using Flourescent Penetrant Inspection (FPI). Another well known potential defect in single crystal and columnar-grained castings is recrystallized grains. Although these develop only during the solution heat treatment and/or reconditioning, repair, rejuvenation treatments, they can be considered casting defects since they are caused by excessive local deformation of the cast article due to the differential thermal contraction of the casting alloy, ceramic core and ceramic shell mold as the casting assembly cools. Recrystallized grains typically occur in the regions of highest deformation which are usually fillets, corners and design features which constrain the core or shell against the cast article.

Those skilled in the art of casting single crystal and columnar grained articles are aware of the economic significance of such linear defects. Part cost decreases substantially when more parts can be cast at the same time in one cluster. However, due to the increased mass of liquid alloy that must be cooled, and the decreased thermal radiation allowed per unit area of shell mould from a denser, heavier cluster to the cooling zone, clusters with more pieces naturally tend to exhibit lower thermal gradients and high inclinations of the solid/liquid interface than clusters with fewer pieces on them. Larger cluster sizes therefore are more freckle prone than clusters with fewer pieces. Even in small sized clusters of castings, freckles are a well known problem as it is desirable to pull castings as quickly as possible into the cold zone, but more rapid withdrawal also results in lower thermal gradients across the solid-liquid interface. Typically, it is industry standard for buyers of single crystal castings to reject some articles based on specifications limiting the acceptable sizes and locations of freckle defects on each casting. The rate of rejection can be anywhere from under 5% to over 50% depending on the alloy used and size of the article. The casting process parameters (including cluster size) are always developed in order to achieve a balance between production rate and the rate of rejection from casting defects to optimize overall process economics. Depending on the alloy chemistry (for example, alloys rich in Ti, Al, W and poor in Ta are more prone to freckles) the optimum process may still produce significant scrap from linear defects. So far no method has been disclosed to repair these defects, but such a method would significantly impact the economics of the columnar grained or single crystal casting process. Parts that are normally thrown away (only value is that of the alloy – about 10% or less of the part value) could be restored to full value for a fraction of the manufacturing cost.

What is required is a method to repair defects in single crystal or columnar grained articles to restore the full strength of the defect-free material without compromising the quality of the material. Until now, no method has been available to carry out such a repair operation. However, newly invented single crystal welding processes offer possibilities.

One such welding process is disclosed in US-A-6,024,792 in which a powder or wire is fed into a laser beam (or other heat source) as it melts an existing single crystal structure. Another welding method is disclosed in US-A-6,084,196 using plasma-transfer arc to deposit material into a damaged section of a single crystal article.

EP-A1-0 558 870 describes free form welding of metallic articles with a laser where already built-up material acts as a substrate for newly deposited metal. However, the authors either use powder or wire feed and pulsed laser irradiation. EP-A1-0 740 977 furthermore describes a containerless method of producing crack free metallic articles using a laser beam operating at moderate power density. A large diameter beam produces a shallow melt pool from which single crystal articles are generated by addition of powder. The relatively long interaction time is claimed to be advantageous to reduce the cracks resulting from hot tearing defects during solidification. The method, however, focusses on the generation of new parts. Also the process parameters are chosen in order to reduce thermal gradients and thus stress, which is not favourable for single crystal solidification.

A similar technique is described in US-A-5,914,059 as a suitable method of repairing metallic articles by energy beam deposition with reduced power density. Again, the focus is on remelting filler material into defective regions of a single-crystal parts and on maintaining process conditions that reduce the cracking risk. The same intention is mentioned in US-A-6,054,672 which describes laser welding of super alloy articles. Here the strategy is to reduce stress by preheating the entire weld area and the region adjacent to it to a ductile temperature above the ageing temperature but well below the melting temperature of the melting temperature of the super alloy.

US-A-5,837,960 describes a computer aided laser manufacturing process which is used to generate articles by laser/powder techniques. Again, the addition of powder is an essential part of that invention. US-A-5,312,584 describes a moldless/coreless method of producing single crystal castings of nickel-aluminides. In this case a laser is used to melt a Ni-Al target which melts, forms a drip and solidifies on an underlying single crystal substrate.

DE-C1-199 49 972 uses a laser method to generate 3D objects using a digitizer/optical vision system and layer by layer material build-up. The method requires additional material supply which is not necessary for the local repair of casting defects.

A method for remedying material defects is suggested in US-A-4,960,611. Here, however, the laser is used to irradiate small coating defects which are caused by adhesion of dust particles, oil droplets or similar. The laser vaporizes the defects and creates a small cavity which is repaired by addition of filler material and subsequent curing with IR laser radiation.

SUMMARY OF THE INVENTION

The object of the present invention is to provide a method for removing casting defects from an article with oriented microstructure in an easy and cost-effective manner while restoring a defect-free grain structure and microstructure to the article.

According to the invention a method was found of removing casting defects from an article with an oriented microstructure, the method comprising the steps of

(a) locating at least one casting defect,

(b) melting the casting defect locally by a heat source to a depth at least as great as the casting defect itself,

(c) solidifying the molten material epitaxially with respect to the surrounding oriented microstructure of the article substantially free of a casting defect.

The advantage and new feature of this method compared to prior art is that it utilizes the material of the defect itself as the welding material. The defect comprises essentially identical material compared to the rest of the article, so melting and re-solidifying epitaxially into the oriented microstructure of the article results in a structure substantially identical to that of a cast article that never had defects in the first place. Where it is difficult to avoid the formation of a small surface layer of equiaxed grains during epitaxial solidification, it is still possible to re-melt the re-solidified portion of material again using a reduced energy density of the heat source compared to what was employed during the first melting operation, and again allowed to solidified epitaxially with the surrounding defect free microstructure.

During the step of melting the casting defect locally the heat source can be moved along the length of the casting defect. In addition, the molten material solidifies epitaxially with respect to the surrounding oriented microstructure of the article in a way that the solidified area is restored substantially to a volume as it was with the casting defect.

In some cases it is advantageous to prepare the cast article for the repair operation by stress relief heat treatments to temperatures close to the incipient melting point or first removing at least a portion of at least one defect according to the object of the invention.

As an example a casting defect of one of the following can be re-melted: a freckle, a sliver, an equiaxed or recrystallized grain, a linear crack, a surface micro-crack, a chain of pores, a linear dross inclusion or a linear cluster of inclusions.

In one advantageous embodiment, additional material is added to the locally melted area during the welding operation, in order to compensate for the missing volume of the defect. In another embodiment, material is added before the melting operation in the form of a preform solid, powder compress, paste or slurry and used to fill at least a portion of the defect that was remelted. Additional material can also be added when no portion of any defect has been removed. This material can have substantially the same composition as the underlying article. In still one other embodiment the defect is melted and re-solidified, and then a second melting operation is carried out while this time adding additional material. After the solidification of the alloy, excess material is machined away e.g. by grinding. One embodiment of the invention is to remove a portion of the casting defect by machining before remelting begins.

For a more precise determination of the locations of existing casting defects, a vision system can be used to record locations on a specific article when it is in the grain etched condition to reveal grain related defects such as freckles, slivers or small equiaxed grains or in Flourescent Penetrant Inspection (FPI) to reveal linear cracks, chains of pores or linear dross/inclusions and then, again, later used to guide the heat source to these areas for melting the casting defect.

As heat source, the casting defect is locally melted by at least one laser or at least one of Plasma Transfer Arc Welding, Micro Plasma Welding, Tungsten Inert Gas Welding, Electron Beam Welding. This can be done under an inert gas atmosphere, with inert gas shielding, or under vacuum. Larger penetration depths can be achieved by further reducing the processing speed or by preheating the article prior to the melting of the casting defect to a desired temperature in the range of 500 – 1000°C.

This method is preferably applied to the article such as gas turbine components made from a nickel or cobalt base super alloy. These article will be a single crystal (SX) or directionally solidified (DS) microstructure.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention are illustrated in the accompanying drawings, in which

Fig. 1 shows a gas turbine blade having a casting defect,

Fig. 2 - 4 show different steps in the repair operation according to the present invention.

Fig. 5 shows an example of an article with a re-melted surface layer.

The drawings show only the parts important for the invention. Same elements will be numbered in the same way in different drawings.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 shows a single crystal (SX) or directionally solidified (DS) article 1 such as blades or vanes of gas turbine engines, the gas turbine blade comprising a root portion 2, a platform 3 and a blade 4 and having a surface 6. The article can as an example be made from a nickel or cobalt based super alloy. Investment casting methods for producing such SX or DS articles are known e.g. from the prior art US-A-4,96,501, US-A-3,690,367 or EP-A1-0 749 790. As seen as well in Figure 2, the article 1 exhibits a linear casting defect 5 such as a freckle, a sliver or any equiaxed or recrystallized grains of limited size somewhere after the production process. Non grain related linear defects include linear chains of pores, surface micro-cracks and dross or inclusions. Figures 3 and 4 show the different steps of removing the casting defect 5 according to the present invention.

In a first step according to the invention at least one casting defect 5 is detected. Casting defects 5 are easily detected by using grain etching methods commonly known to those skilled in the art. Non grain related linear defects including linear chains of pores, surface micro-cracks and dross, inclusions or a linear cluster of inclusions are normally only detectable using Flourescent Penetrant Inspection (FPI). After locating the casting defects 5, the extremities may be demarcated with scribe marks or other such visible means such that after polishing or abrasive cleaning the site of the casting defect 5 is still apparent. It is also possible to leave a light grain etch on the surface and use that to weld in the correct areas. In either case, a vision system may be used to assist in the welding process. The system may be used to first record the position of the casting defect 5 (no marks are required) in the grain etched state and then used to guide the source of heat later for the repair operation.

As seen in Figure 3 the article 1 is melted from the surface 6 in the region of the casting defect 5 by the use of a locally acting heat source 7, e.g. a laser, to a depth at least as great as the casting defect 5 itself. The heat source 7 reheats the affected zone above the melting point. If during this operation the ratio G^n/V_s (where G is the temperature gradient in the melt pool, n is a material constant and V_s is the solidification speed) is kept above a material dependent threshold value, the subsequent solidification (as indicated in Figure 4 with repaired zone 10) will occur epitaxially, i.e. without creating new grain boundaries. The surrounding single crystal bulk material will act as a crystal seed for the remolten material. After solidification the remolten material will have the same microstructure as the bulk material without any defect so that the oriented microstructure is substantially restored to a volume as it used to be with the casting defect 5. The casting defect 5 will be thus remedied.

It can be seen from the previous paragraph that high thermal gradients are crucial for single crystal solidification. For this reason lasers offer a particularly attractive choice for the heat source 7. Laser radiation can be focussed to small spots and generate thermal gradients in excess of 10^6 K/m. It is beneficial if the laser intensity is uniform over the heated area, which can be achieved by fiberoptic beam delivery. As laser power is very easily controlled, it is ensured that the criterion for single crystal solidification is maintained during the whole repair operation. As an additional consequence the boundaries that have been set by the vision system do not have to be rigorously kept. If the heat source 7 acts on zones without casting defects 5 the material will be also remolten and it will subsequently resolidify with its original orientation. The melting of whole areas of limited size can as well be achieved by parallel, partially overlapping laser remelting tracks, for example when repairing clusters of freckles in close proximity, wide slivers, and shallow equiaxed grains. The overlap is typically 30%-50%.

In a typical application the laser will be focussed to a spot size of 1-2mm diameter. Preferably the laser would be either of the Nd-YAG or high power diode laser type. These lasers operate in the near infrared and about 30-40% of the incident radiation is absorbed by typical super alloys. The laser beam will move at relatively slow speeds (approx. 1-10 mm/s) over the affected zones and operate in the conduction welding mode. Laser intensities of $1*10^3$ W/cm^2 to $5*10^4$ W/cm^2 will remelt a zone reaching up to 500µm below the surface. Larger penetration depths can be achieved by further reducing the processing speed or by preheating the article 1 prior to the melting of the casting defect 5 to a desired temperature in the range of 500 – 1000°C, e.g. with a high frequency generator. On preheated articles, however, thermal gradients are smaller and it is more difficult to meet the G^n/V_s criterion. On the other hand the risk of hot tearing defects during the repair operation is reduced.

It is known to those skilled in the art that under certain conditions it is difficult to avoid the formation of a small surface layer of equiaxed grains during the epitaxial solidification of such a weldment, due to failing to meet the G^n/V_s criteria locally at the upper extremeties of the weld pool. This is particularly true when the desired depth of welding is large, requiring a high local heat input. In these cases, it is very helpful to make a second pass after solidification with the heat source producing a lower energy density of heat input into the melt pool, yielding a shallower melting profile which further reduces the fraction of material that solidifies equiaxed. If a second pass is undesirable, the equiaxed grains can be ground or machined off. In this case, it is helpful to add material to the melt pool either before or during melting, so that the portion of the equiaxed solidification falls in the upper regions of excess material in the weld zone, and will be machined off during the removal of excess material to restore the originally intended dimensional profile to the cast article.

As heat source 7 at least one of Plasma Transfer Arc Welding, Micro Plasma Welding, Tungsten Inert Gas Welding, Electron Beam Welding are any other suitable tool can be used. The welding can be carried out under an inert gas atmosphere, with inert gas shielding, or under vacuum to prevent excessive oxidation of the liquid alloy. Furthermore, the article can be prepared before the melting of the casting defects by stress relief heat treatments to temperatures close to the incipient melting point.

After the repair, the normal heat treatments of solutioning and gamma prime coarsening may be carried out, but there may be an additional stress relief heat treatment prior to this to reduce the chances of recrystallization.

Optionally, as seen in Fig. 3, additional material 8 can be added to the already molten area by means of a feeder 9 to ensure the monocrystalline structure of the underlying material. In Fig. 3 coaxial injection is shown, which favourable due its inherent axial symmetry. In another embodiment, material is added before the melting operation in the form of a preform solid, powder compress, paste or slurry and used to fill at least a portion of the defect that was remelted. Additional material can also be added when no portion of any defect has been removed. With advantage, additional material 8 with substantially the same composition as the article itself is fed to the locally melted area. The defect comprises essentially identical material compared to the rest of the article, so melting and re-solidifying epitaxially into the oriented microstructure of the article results in a structure substantially identical to that of a cast article that never had defects in the first place. In another embodiment of the method according to the invention, the casting defect 5 is melted and re-solidified. Subsequently a second melting operation is carried out while this time additional material is injected to the melt pool. In case when excess material remains on the surface 6 after the solidification, this material will be machined away e.g. by machining or grinding. Still it is possible to remove by machining a portion of the casting defect before the method begins with the step of remelting.

<u>Example of the invention</u>

As an example of the invention as shown in Fig. 5 a re-melting track on a SX-substrate (CMSX-4) having a remelting depth of 0.40 mm. The matched orientation of the (fine) dendrites in the remolten area can be seen. Laser parameters were: P=320 W, v=8 mm/s, spot diameter: 2.0 mm.

NUMBERING

1	Article, e.g. blades or vanes for gas turbines
2	Root portion
3	Platform
4	Blade
5	Casting defect
6	Surface of article 1
7	Heat source
8	Additional material
9	Feeder
10	Repaired zone

CLAIMS

1. A method of removing casting defects (5) from an article (1) with an oriented microstructure comprising the steps of
   (a) locating at least one casting defect (5),
   (b) melting the casting defect (5) locally by a heat source (7) to a depth at least as great as the casting defect (5) itself and
   (c) solidifying the molten material epitaxially with respect to the surrounding oriented microstructure of the article (1) substantially free of a casting defect.

2. The method of claim 1, wherein during step (b) of claim 1 the casting defect (5) is locally melted along the length of the casting defect (5) by moving the heat source (7).

3. The method of claim 1, wherein the re-solidified portion of material is remelted again using a reduced energy density of the heat source (7) compared to what was employed during the first melting operation, and again allowed to solidified epitaxially with the surrounding defect free microstructure.

4. The method of claim 1, wherein the molten material solidifies epitaxially with respect to the surrounding oriented microstructure of the article (1) in a way that the solidified area is restored substantially to a volume as it was with the casting defect (5).

5. The method of claim 1, wherein after step (a) of claim 1 the article (1) is prepared for the repair operation.

6. The method of claim 1, wherein as at least one casting defect (5) comprising at least one of the following: a freckle, a sliver, an equiaxed or recrystallized grain, a linear crack, a surface micro-crack, a chain of pores, a linear dross inclusion or a linear cluster of inclusions is remelted.

7. The method of claim 1, wherein a portion of the casting defect (5) is removed by machining before re-melting begins.

8. The method of claim 1, wherein additional material (8) is added before the melting operation or to the locally melted area.

9. The method of claim 1, wherein the defect (5) is melted and re-solidified, and then a second melting operation is carried out while this time adding additional material.

10. The method of claim 8, wherein material is added in the form of a preform solid, powder compress, paste or slurry before the melting operation begins.

11. The method of claim 8, wherein the additional material (8) is added to the locally melted area with substantially the same composition as the article (1).

12. The method of any of the claims 8 to 11, wherein excess material is machined away after solidification of the molten material.

13. The method of claim 1, wherein a vision system is used to locate the at least one casting defect (5) and then used to guide the heat source (7) for melting the at least one casting defect (5).

14. The method of claim 1, wherein prior to the melting of the casting defect (5), the article (1) is pre-heated to a temperature in the range of 500 – 1000°C.

15. The method of claim 1, wherein the casting defect (5) is locally melted by at least one laser as the heat source (7).

16. The method of claim 1, wherein the casting defect (5) is locally melted by at least one of Plasma Transfer Arc Welding, Micro Plasma Welding, Tungsten Inert Gas Welding, Electron Beam Welding as the heat source (7).

17. The method of claim 15 or 16, wherein the melting of the casting defect (5) is carried out under an inert gas atmosphere, with inert gas shielding, or under vacuum.

18. The method according to any of the claims 1 to 17, wherein at least one casting defect (5) in a single crystal or directionally solidified article (1) is re-melted.

19. The method according to any of the claims 1 to 17, wherein the article (1) is a gas turbine component made from a nickel or cobalt base super alloy.

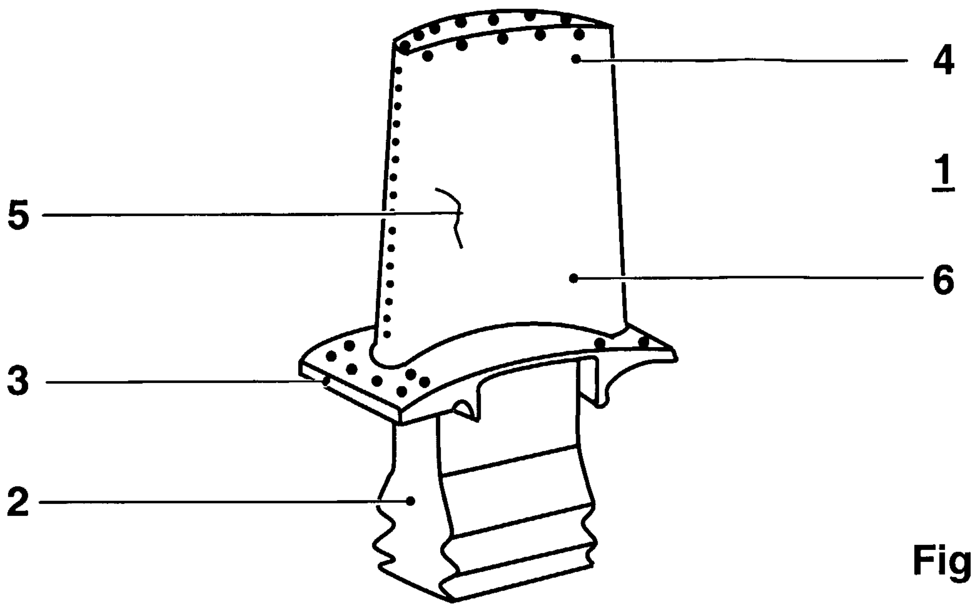

Fig. 1

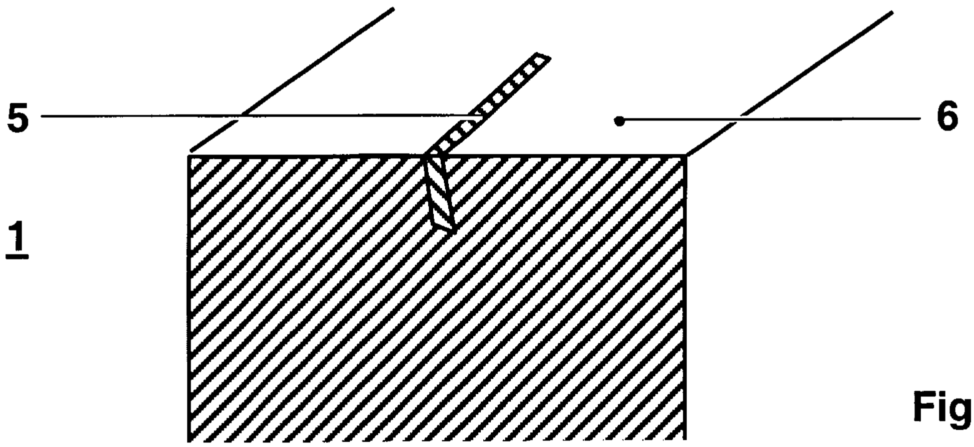

Fig. 2

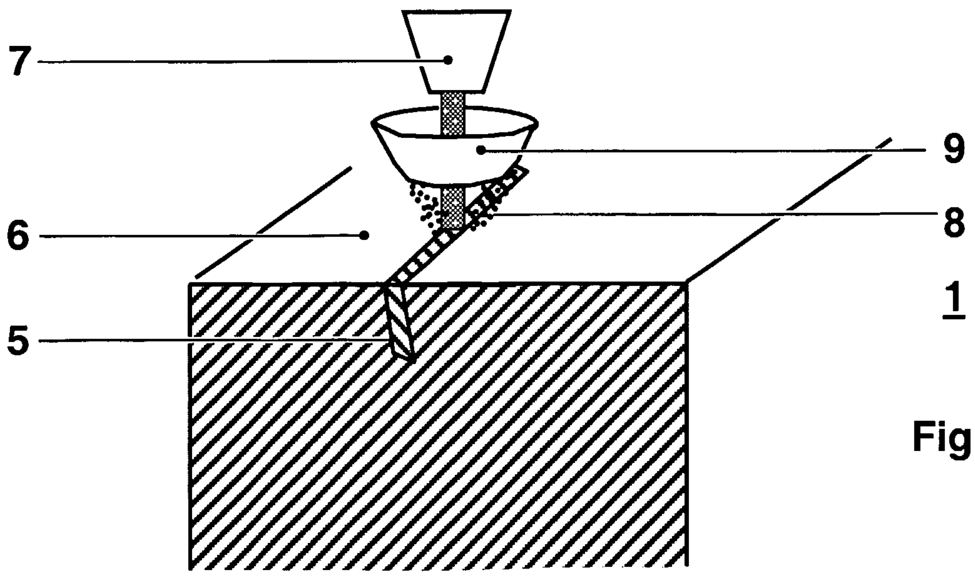

Fig. 3

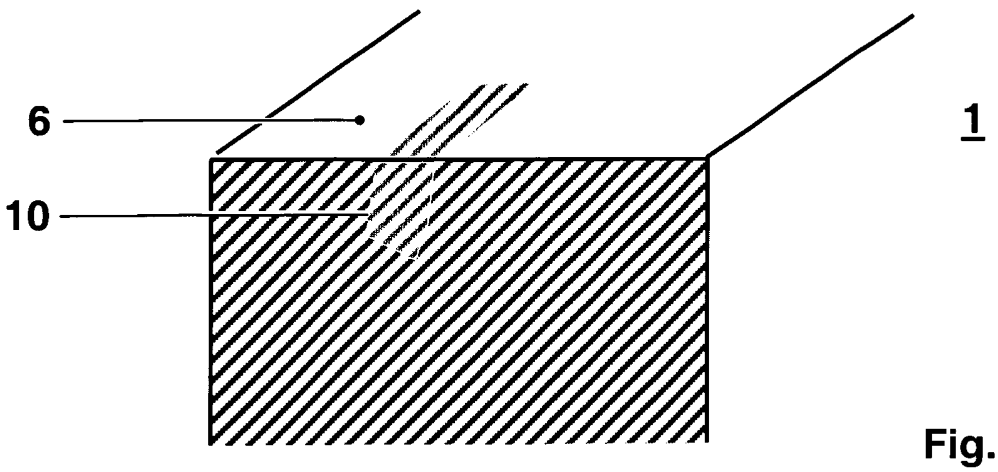

Fig. 4

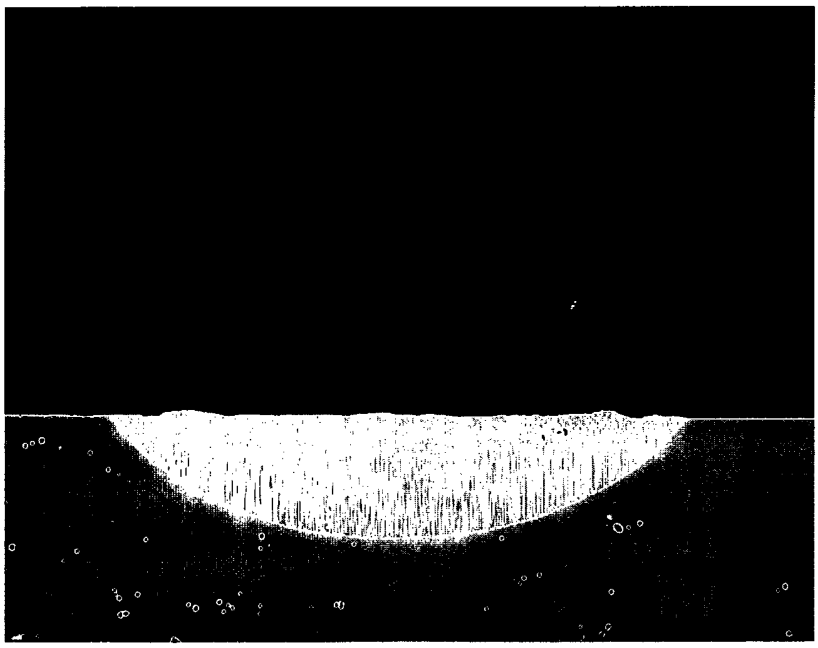

Fig. 5