RAPID PROTOTYPING USING 3-D WELDING

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Introduction

Rapid prototyping systems are based, almost exclusively on polymer, or paper materials. The dimensions of the parts produced are limited by the volume of the processing area within the machine, and parts tend to warp or distort due to shrinkage and lack of support. Also the mechanical properties of the part are restricted to those of the processable materials and thus, in many cases, required 'engineering properties' cannot be obtained.

Various European organisations are undertaking research to produce metal prototypes directly, for example, one project is concerned with a version of Laminated Object Manufacturing where sheets of steel are laser welded together. There are also a number of organisations using laser sintering to produce parts in Mild Steel and Stainless Steel.

At Nottingham, work on Rapid Prototyping systems, based on a 3-D welding system, has been undertaken to try to combat some of the weaknesses of the other processes. There is some history of the use of welding as a means of building up components and parts for salvage and reclamation; thicknesses up to 50mm being typical (1). The use of welding for creating free standing shapes was established in Germany in the 1960's (2). This led to companies such as Krupp, Thyssen and Sulzer developing welding techniques for the fabrication of large components of simple geometry, such as pressure vessels which could weigh up to 500 tonnes (3). The technique was to become known as 'shape welding'.

Other work in this area has been undertaken by Babcock and Wilcox (4) who have been working mainly on large components produced in austenitic material. Also, work by Rolls-Royce (5) has centred on investigating the technique as a means of reducing the wastage levels of expensive high performance alloys which can occur in conventional processing. They have successfully produced various aircraft engine parts in Nickel based and titanium based alloys.

As a production technique, 3-D welding offers significant advantages over conventional processing, these include:

- The potential for robot control of the welding torch allowing large variation in part dimensions and geometry.
- A highly automated system.
- Parts with consistent properties.
- Rapid processing times, hence vastly reduced development times.
- Efficient use of materials.
- Direct production of a metal part - unique amongst current Rapid Prototyping.

3-D Welding Trials

Initial work on 3-D welding, verified the potential of welding as a Rapid Prototyping system. The first parts produced by robot welding were simple unsupported vertical walls in a square box formation (figure 1). The successful completion of these parts led to trials involving the production of sloping walls in the form of a truncated pyramid (figure 2).

Once it was established that more complicated structures were possible, a thermostat housing for a Ford automobile was obtained and the robot programmed to manufacture this shape. Firstly the base and body of the housing was produced and then rotated through 90° to weld the outlet (see figure 3), this required 22 minutes of welding. This proved the ability to manufacture parts that would normally be produced by casting. A sheet metal part was chosen next and figure 4 illustrates the original part with the welded version alongside. As there was more material in this part, the welding time was longer, at approximately 3 hours.

Effect of Welding Parameters on Weld Bead Characteristics

The shape and dimensions of the weld bead are very important in the use of 3-D welding as a Rapid Prototyping system, since these will determine the limits to the wall thickness which may be produced and will also influence the quality of the surface finish.

Numerous trials were undertaken to produce single weld beads for a range of welding conditions. The parameters which were varied included voltage, wire feed rate, wire stickout, wire diameter and welding velocity. The arc voltage and welding current under each condition was monitored and the dimensions of the bead produced (height and width) were subsequently measured using a shadowgraph technique. A vast amount of data was generated in this way, but the general trends are presented in Table 1.

Increasing Variable	Effect on Measured Variable			
	Arc Voltage	Current	Bead Width	Bead Height
Voltage	↑	=/↑	↑	↓
Wire Feed	↓	↑	↑	↑
Stickout	↑	↓	↓	↑
Wire Diameter	↓	↑	↑	↑
Velocity	=	=	↓	↓

Table 1 - Effect on Measured Variables

The shape of the weld bead can be controlled to change it from a wide-flat bead to a more narrow bead with vertical walls (see figure 5). When thin walls are to be produced then the best results are achieved by using a narrow bead, however, there are many situations where beads will need to be placed along side each other and so a variety of bead shapes could be used, depending on the slope of the wall surface (see figure 6).

This work has produced information to start constructing a welding database but further work is required, areas such as the effect of multiple layers on weld bead dimensions, require further investigation, even though wall smoothness has improved (see figure 7).

Materials

As one of the main advantages of this technique is the direct production of a metal part, it is very important to confirm the mechanical and structural properties of parts produced in this way. To do this, a programme of mechanical and microstructural examination was undertaken. Using typical operating parameters and mild steel welding wire based on Fe-C (0.08%) - Si:(0.9%) Mn(1.5%), square box section walls were produced and test-pieces were cut at different positions and orientations within the walls.

Vickers hardness measurements (10kg load) made in a range of positions over the wall surface, showed little variation along the wall length, but a definite increase in hardness from 146.3 VHN at the base to 172.6 VHN at the top of the wall was noted (the height of the wall being approximately 100mm and corresponding to around 70 welding passes).

Tensile tests were carried out on test-pieces cut from various orientations in the wall, with samples being taken:-

(i) With the tensile axis corresponding to the vertical direction and

(ii) With the tensile axis corresponding to the horizontal direction, both from the upper and lower part of the wall.

Results were consistant, regardless of orientation, with typical values of 490 MPa measured.

Values obtained from vertical specimens indicated few areas of weakness between adjacent weld layers. Elongation to failure values however, showed a marked difference between horizontal test-pieces cut from the bottom and top of the wall. Typical values for the base of the wall are in excess of 30%, whilst those at the top average 22.5%. The measured mechanical properties are summarised in Table 2.

Specimen Orientation	Ultimate Tensile Strength MPa	Elongation to Failure %
Vertical	489	35.0
Horizontal (Top)	484	22.5
Horizontal (Bottom)	499	33.1

Table 2 - Average Tensile Test Data

Optical microscopy revealed a microstructure in the wall of largely equiaxed ferrite (α) and pearlite ($\alpha + Fe_3C$) with a grain size of approximately 60μm, see figure 8. There are local regions where the structure is much less equiaxed and more columnar in nature (grain size approximately 600μm x 100μm) as would be expected in an as-cast material, seen in figure 9, These regions, however, are restricted to the very top layers of the wall where the layers have not been subjected to reheating, from the deposition of subsequent weld layers. This accounts for the lower levels of ductility measured in specimens cut from the top of the wall in the horizontal direction. A simple heat treatment procedure could be used to produce a more uniform microstructure throughout the wall.

Microscopy revealed no voids or cavities and the measured density was approximately 99.5% of equivalent wrought material. No indication was found of oxidation between adjacent layers, this is supported by the strength measurements for the vertical test pieces

Results indicate that parts produced by the 3-D welding process have good structural integrity and property levels which would allow them to be exploited in service conditions.

Off-Line Robot Programming

The parts which have been produced and described so far have been produced using a cumbersome and highly time consuming on-line robot programming technique. It is evident that to be a viable process for producing prototype parts in the desired timescale, an efficient off-line programming system is required.

To test the robot welding system for more complex and representative shapes, a CAD system was used to generate welding trajectories. The following procedure was adopted:-

1) A CAD image of the part to be manufactured was created using the PEPS2 CAD machining package (6). This package does not have a robot post processor but the instructions are similar to those used for milling. The milling process could be considered to be the negative of the welding process.

2) Once the part has been designed and a simulation of the process has been successfully presented, the post processor generates the spatial positions required for the welding torch along with commands to signify the tool status (torch/gas on/off).

3) The file of positions is not fully understandable to the robot. A further post processing (written on a PC in the C programming language) is required to include robot command words. This file is then concatenated with an initialisation programme which provides start positions, velocity profiles and signal levels. This concatenated file is then capable of being directly down-loaded to the robot for part fabrication.

A number of limitations to the system can be identified and some modifications need to be made.

As has already been mentioned, there is no feedback loop between the robot controller and the welding system. It is not possible, therefore, to dynamically control the welding quality through the robot system. Sensory feedback would be a requirement for improvement of the system quality through process monitoring and for post inspection purposes. Some of this information could be used to direct any further machining of the part that may be required. Attention must also be given to the use of sensors to prevent possible collapse of the part through temperature build up. The CAD/CAM link and the post processor is only of limited value, allowing only sequential machine operations with no facility for sensory update. The PEPS2 system will only provide code using a cartesian coordinate system for 3 axis machines which is only of limited use for robot systems. The technique used required a substructure that is directly below the current welding path. Part manipulation is therefore required to build up complex shapes (like the thermostat housing in figure 3) by combining simpler ones. The need for extra degrees of freedom and integration of robots with part manipulators (rotary XY tables) requires a software simulation and post processing system beyond the capabilities of PEPS2.

Future Developments

The 3D robot welding system relies as much on CAD/CAM technology as welding and robotic technology. Further development will be linked very strongly with the CAD system used and the manipulator post processor. The fabrication procedure involves the building up of complex geometric shapes from more simple constituent shapes. It has been found that cylinders (for instance) are best built in the form of rings laid on top of each other. It can be seen, therefore, that the layer formation used by conventional rapid prototyping is not wholly appropriate for this technique. Since the constituent shapes can be placed in an infinite number of ways with respect to each other, it is obvious that some form of part manipulation will be required in conjunction with the robot welder. A future system must therefore incorporate both a robot and a 3-axis part manipulator.

The formulation of the geometry will require the adaption of an existing CAD package. This package will be used to design the part and then determine the best geometric procedures required to fabricate it. This information will then be passed onto a robot simulation package (eg GRASP (7)) which will calculate the robot and part manipulator instructions. The post processor within this system will be used to programme the robot once simulation has been shown to adequately construct the part. This whole procedure of design and simulation may require an iterative process with some human intervention.

Initial experiments have already shown that, although complex shapes can be formed, the results are not perfect. There are a number of basic reasons for such imperfections:-

- Heat build up due to the welding process can cause earlier welding passes to remelt and cause part distortion or collapse of the structure.

- Inaccuracies in the welding and robot parameters can cause cumulative errors, resulting in the torch being too close or too far away from the surface.

- Solid layers (ie filling in of outline shapes) cannot be performed sufficiently accurately to form a smooth surface. This means that gaps can occur inside solid objects.

It is evident from these problems that some form of sensing is required to control the process. Real time weld monitoring systems do exist, but it is unlikely that such systems can be used to overcome all of these difficulties. However, it will be necessary to stop welding at intermittent stages to leave the part to cool down and avoid collapse due to heat build up, or to implement forced cooling. Sensors can be used at this time to determine how much cooling is required and to perform post inspection of the welding process. This inspection information can be used to update the robot position to avoid cumulative errors, plot new robot trajectories to avoid gaps and generally control the weld parameters.

Conclusions

The object of this work has been to expand the use of 3-Dimensional Welding from large simple pressure vessels to a wide range of part sizes having much greater geometrical complexity.

There are several targets to aim for in the future:-

- Part Complexity: Parts will be produced such as engine castings, cylinder heads and inlet and exhaust manifolds, in order to demonstrate the capability of the system.
- Part accuracy: At present the part accuracy is about ± 0.5mm, but it is expected that eventually this will be reduced to ± 0.2mm.
- Surface Roughness: The present poor surface roughness is unacceptable for many situations, but better weld control and appropriate cooling techniques will improve this considerably.

The applications for this technique can be characterised by two main groups:-

- Parts: Prototype parts or small batches can be rapidly produced without any specific tooling. In addition, small modifications could be made to existing components, such as different brackets or lugs on a car chassis.
- Tooling: If it is possible to build a part without tooling then it should also be possible to produce prototype tools, such as press or forge tools, plastic molds and dies.

Further investigation of the welding technology will also be required. As yet, other welding techniques that may result in smoother, more predictable finishes have not been tried. Investigation into this branch of technology may result in the development of new welding based processes. In the past it has usually been more important to develop new welding systems that can lay down as much weld as possible in a short time. The 3-D welding system relies on precision methods and may require development of robotic welding system with very small diameter filler wires.

References

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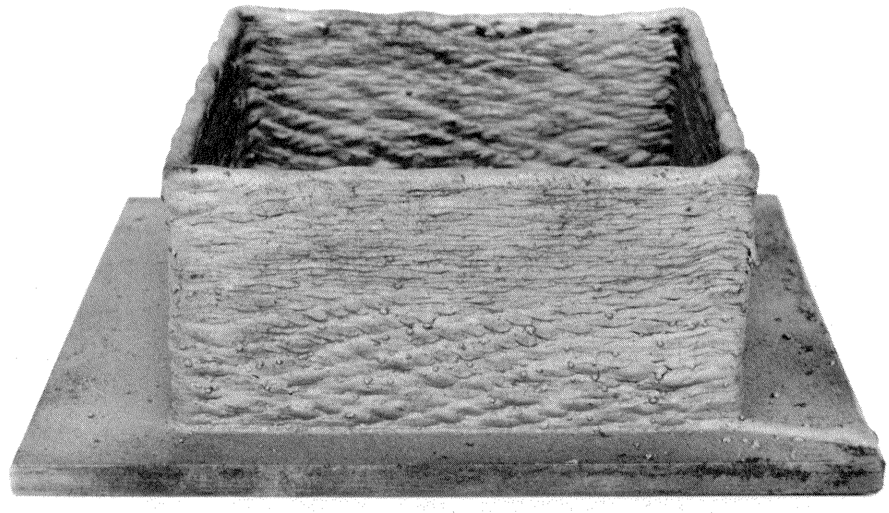

Figure 1 - Square Box Formation

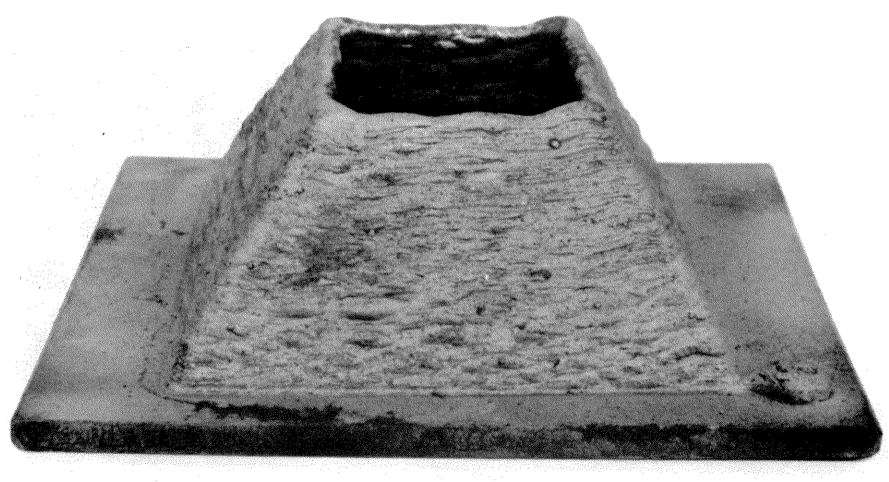

Figure 2 - Truncated Hollow Pyramid

Figure 3 - Welded Thermostat Housing

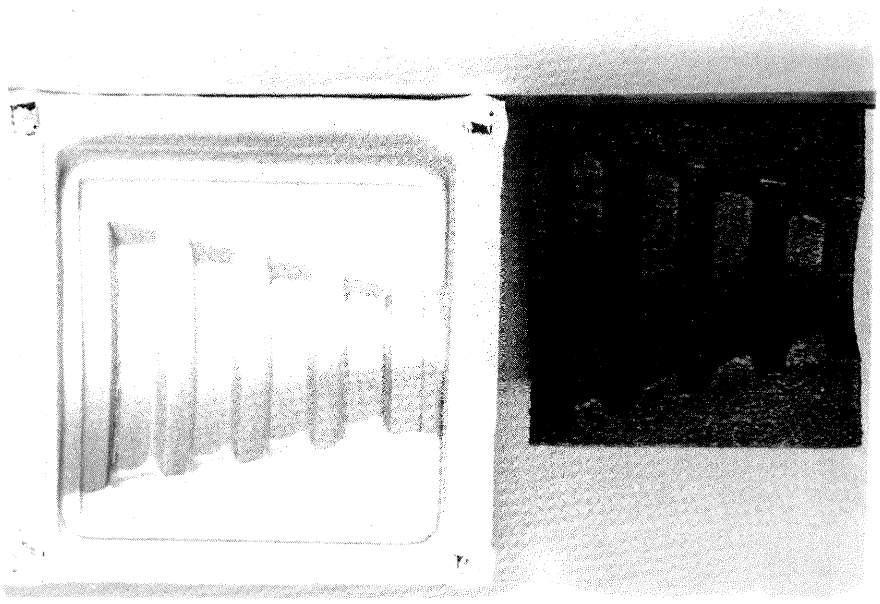

Figure 4 - Sheet Metal Part and Welded Version

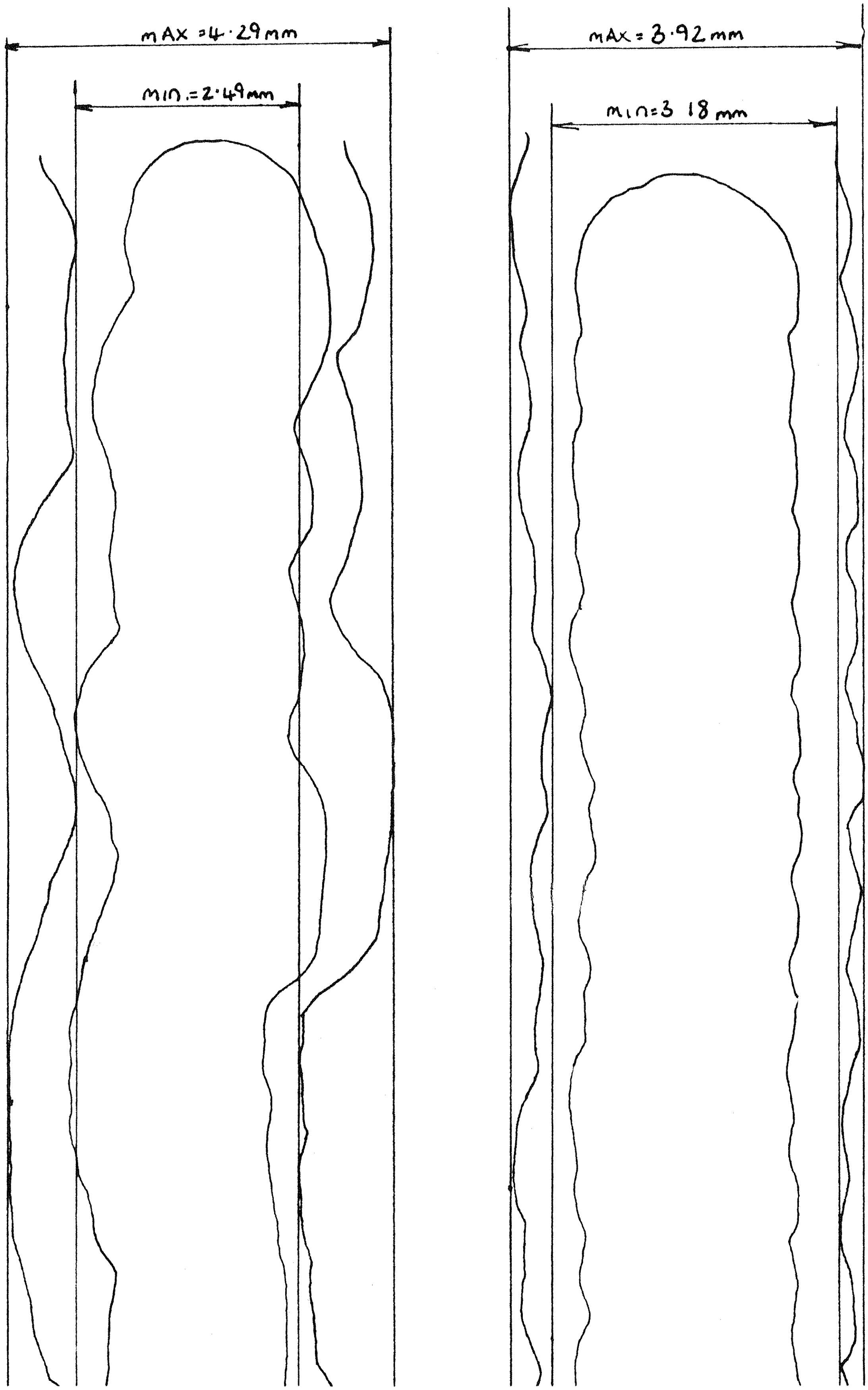

Figure 5 - Cross-section of welded walls before and after investigating the effect of weld bead parameters

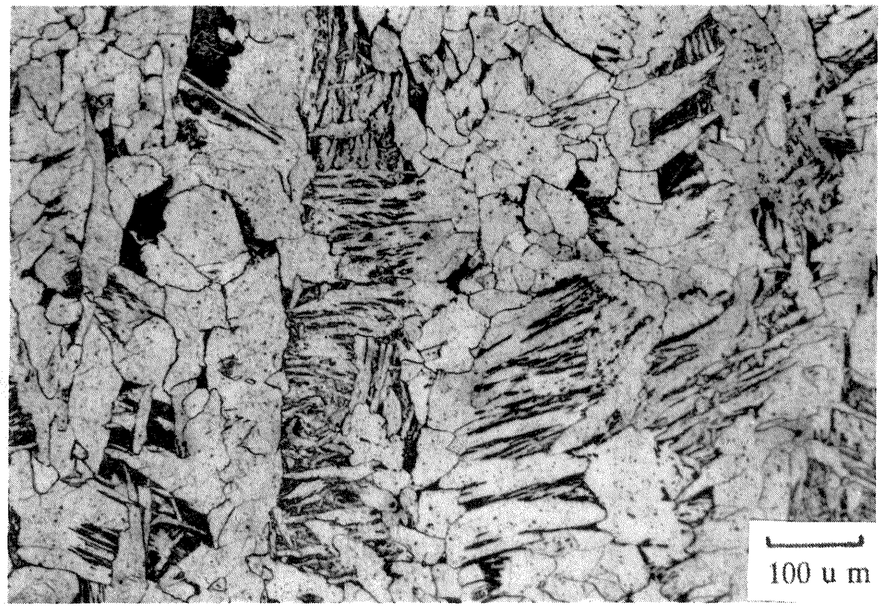

Figure 6 - Large equiaxed Ferrite and Pearlite structure

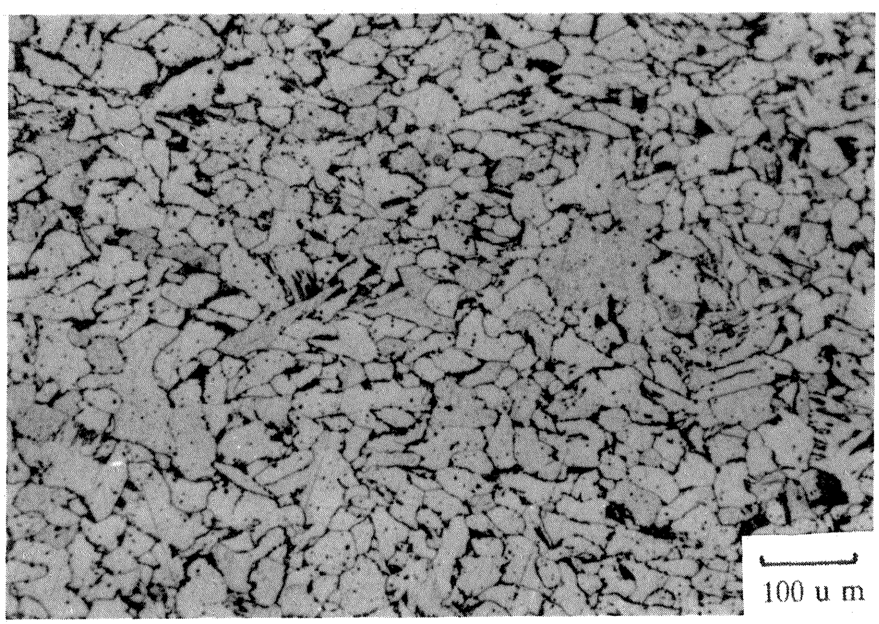

Figure 7 - As-cast type structure