EVALUATION OF THE POTENTIAL OF LOW PRESSURE PLASMA SPRAYING AND SIMULTANEOUS SPRAY PEENING FOR PROCESSING OF SUPERALLOYS

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Abstract

The potential of low pressure plasma spraying with or without simultaneous peening has been assessed as a means of producing superalloy materials. The equipment and techniques utilised are described and some of the limiting features identified. The quality of the deposits obtained has been investigated using a variety of metallurgical techniques and the structural differences attributable to simultaneous peening are described in detail. Mechanical testing, primarily tensile at ambient and elevated temperature, has been carried out to characterise the properties of the deposits obtained. Effort has been devoted primarily to work on conventional sheet materials such as Nimonic alloy 263 and to work on oxide dispersion strengthened alloys. Superior levels of tensile strength were obtained at room temperature on the sprayed and spray peened superalloys relative to ingot processed stock. Spray joining of FeCrAlY_2O_3 - type alloys was achieved with negligible loss in tensile strength providing that post spraying heat treatments were carried out.

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Introduction

Plasma spraying is routinely used as a method of depositing metallic or ceramic materials on component surfaces to restore worn or damaged areas and to provide a variety of coatings for engineering purposes. Work has also been performed on the direct forming of components by the plasma spray route. A further extension of spray forming of materials proposed and patented by Singer ([1]) is that of simultaneous spray deposition and peening of metals (SSP). This process consists of the spray deposition of metal by various means on the surface of a substrate whilst concurrently bombarding the deposit with a stream of high velocity, hard, rounded particles (e.g. shot-peening balls). The peening process plastically deforms the deposit as it is being built up thereby enhancing the physical and mechanical properties. Further details are given in the literature ([1]).

A programme of work has been undertaken at Lucas Aerospace Limited utilising an experimental facility designed to carry out plasma spraying or spray-peening processes in a low pressure, controlled atmosphere chamber. The choice of the reduced pressure processing offers significant benefits such as:-

(i) The increased length of the plasma flame, typically 250 mm to 350 mm, provides a more homogeneous distribution of particles in the flame and a higher mean particle velocity and temperature.

(ii) The low pressure environment reduces the level of oxide contamination in the deposit.

The potential of the SSP route was assessed by comparing the structure and properties of low pressure plasma sprayed (LPPS) material produced with or without simultaneous peening.

Equipment and Processing

The facility required considerable design and procurement effort as SSP techniques are entirely experimental. It was designed to fulfil the requirements of low pressure plasma spraying, with or without concurrent peening, and to have sufficient flexibility to enable equipment modifications to be carried out easily. The equipment is shown schematically in Fig. 1 and comprises a water cooled vacuum chamber in which a plasma gun, workpiece holder and mechanical peening unit are mounted. Associated power supplies, motors for linear and rotational manipulation of the workpiece and for the shot slinger, and the powder feed system were located outside the chamber. The shot peening facility is capable of delivering high carbon steel shot at velocities up to 30 metres per second. The shot is directed onto the workpiece by a tapered chute, enabling 100% coverage to be achieved over a 100 mm square target on each traverse.

For commissioning purposes a number of powders readily available within Lucas were utilised. A series of parametric surveys were carried out to identify the more critical factors controlling deposit efficiency and integrity. As the work progressed, areas of potential interest became more clearly identified and a wider range of materials was produced for metallographic characterisation and for mechanical tests where appropriate. Powder materials have included Stellite ([2]) 31 and Nimonic ([3]) APl. More recently work has been done on the powder processed sheet superalloys Nimonic ([3]) 86 and 263, and also on powder having a similar composition to the iron-based oxide dispersion strengthened Incoloy ([3]) MA 956 alloy.

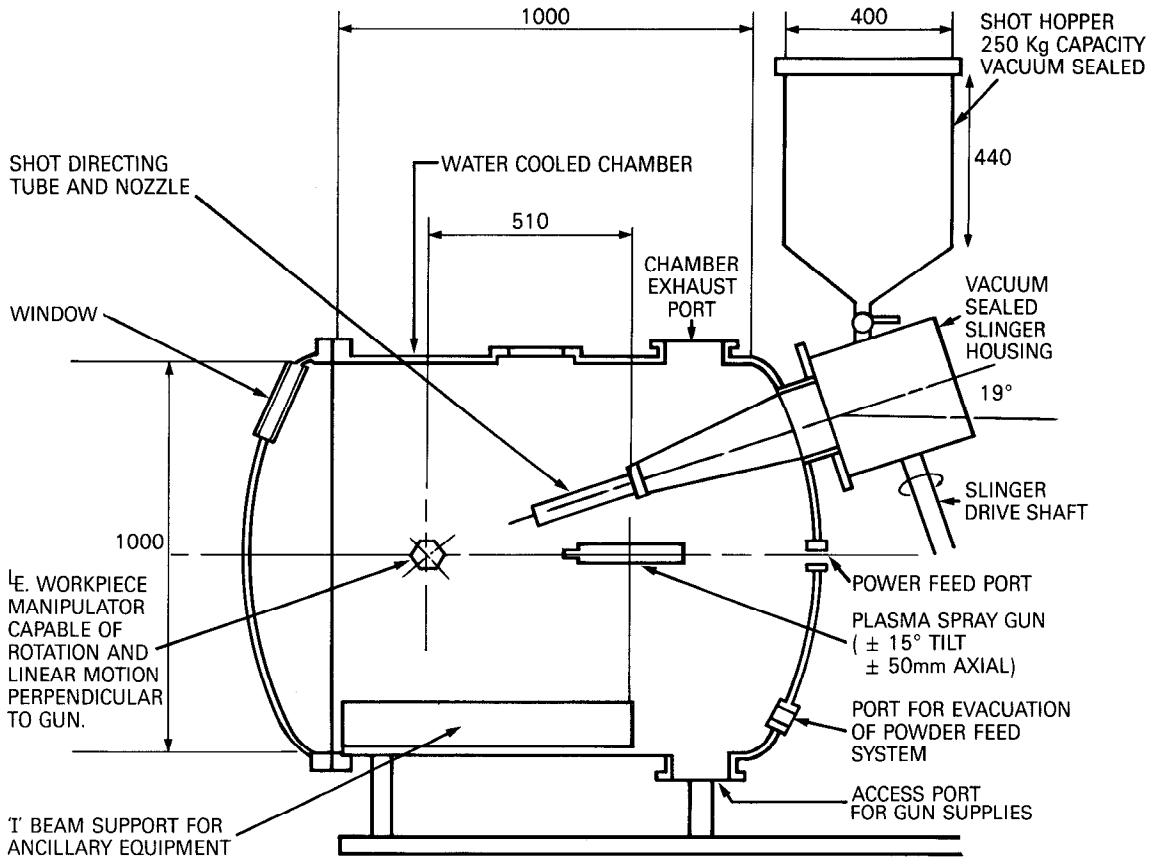


Figure 1 - Low pressure simultaneous spray peening chamber (Dimensions in mm)

The sequence of operations for low pressure plasma spraying is well established ([4]) and will not be described further. Simultaneous peening was usually introduced after a brief period (< 30s) of LPPS deposition to permit the build up of a well bonded initial deposit on a shaped mandrel or other type of former. On completion of the spraying or spray peening operation the deposit was stripped from the mandrel by machining or chemical dissolution.

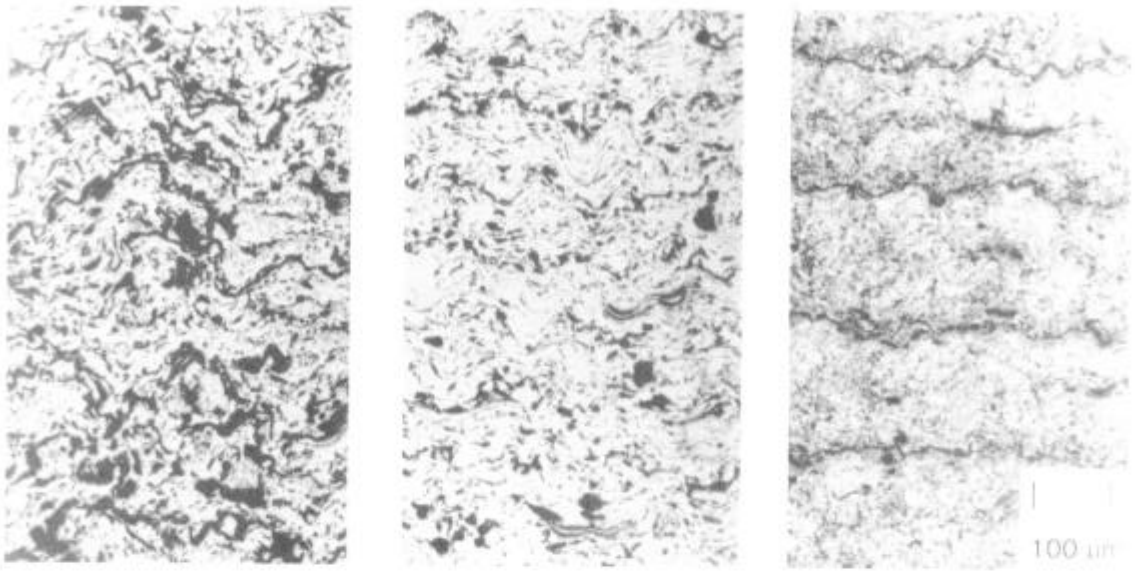
Experimental Assessment

Initial Trials

Plasma spraying trials were carried out initially using readily available spray powders to identify and optimise the critical parameters involved in LPPS. The critical factors in achieving acceptable deposit efficiencies were found to be carrier gas flow rate and particle size. The gas flow in conjunction with the gun nozzle geometry regulates the injection of powder into the mainstream of the plasma gas jet. The influence of powder particle size on deposit quality is illustrated in Fig. 2 for MAR M002 alloy powder deposited under LPPS conditions. Spraying was carried out at a chamber pressure of 45 mbar.

Prior to SSP trials an assessment of the peening intensity was made using Almen 'A' test strips. The total arc height of the strips was measured after peening to provide comparative data for various operating conditions of the slinger. The shot, made from 1.0% carbon steel was supplied in the clean

and dry condition and was heat treated in hydrogen prior to use. A high energy sifter was used to separate the overspray powders from the shot so that shot could be re-used in subsequent SSP trials.



a) Particle Size 0 - 150 µm

b) Particle Size 53 - 90 µm

c) Particle Size 53 µm

Figure 2 - Effect of particle size on structure in LPPS MAR M002 deposits

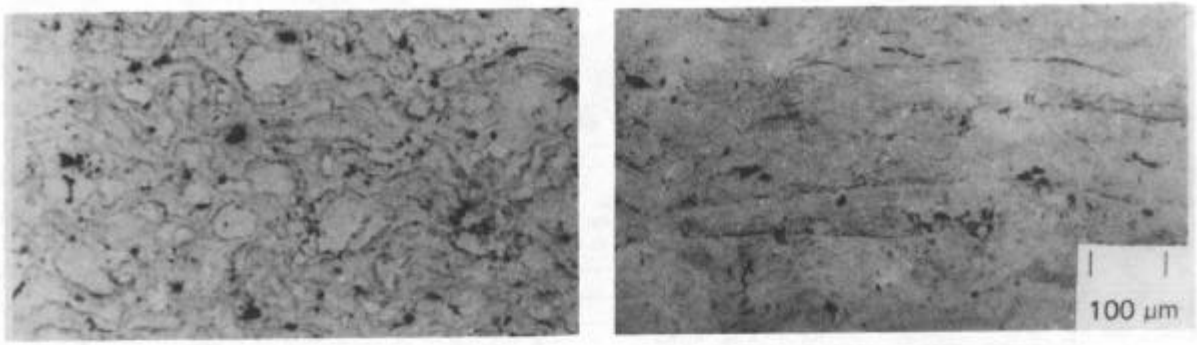
Materials produced by SSP had a comparable microstructure to that seen in LPPS samples but contained lower levels of porosity. Using the image analyser (quantimet-type) technique, the inclusion count (i.e. total porosity plus inclusions) was measured at 1.8% for SSP material compared with 4.8% for the LPPS material. In both LPPS and SSP samples the major element concentrations were in accordance with the analysis of the powder. The etched microstructure revealed particles which had passed through the plasma flame without melting and became embedded in the plasma spray deposit. In SSP deposits the larger particles had been severely deformed by impact with the peening shot. Typical microstructures obtained for LPPS and SSP Stellite 31 alloy deposits are shown in Fig. 3 (a) and (b) respectively. The powder size range used for the spraying of these deposits was -150 + 75 µm. In Fig. 3 (b) the larger unmelted artefacts have effectively been eliminated and the structure is more homogenous.

Residual stress levels in spray peened deposits can be controlled by varying the peening intensity and temperature. The effect was demonstrated by slitting longitudinally tubes which had been spray deposited on a cylindrical mandrel. The change in diameter was a measure of the residual stress in the tube wall and showed that the tensile stresses in an LPPS deposit 1mm thick were typically three times those in the corresponding SSP deposit.

LPPS/SSP of Nickel-Base Superalloys

Interest in plasma spraying materials such as Nimonic alloys 263 or 86 lies in the potential for spraying thin section (sheet) components as one piece constructions, thus obviating the need for complex and expensive forming and welding operations. The work formed part of a collaborative programme with Rolls-Royce Limited. In the first instance it was necessary to establish the practicability of producing high integrity material by the

plasma spray route and then to explore any benefits arising from spray peening.

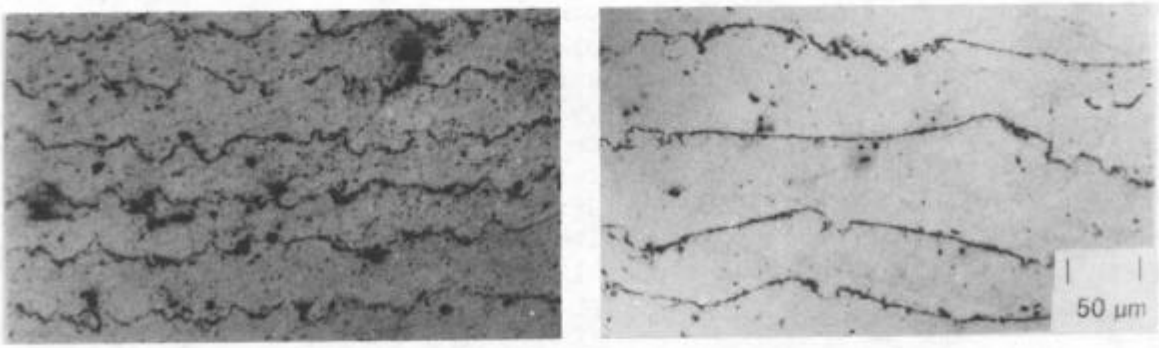


a) Deposit produced by LPPS b) SSP deposit using same size of powder

Figure 3 - Microstructure of LPPS and SSP Stellite 31 alloy

Extensive parametric surveys were carried out on Nimonic 263 powder to determine optimal plasma spray conditions. The conditions identified as producing a sound deposit were used as baseline conditions for the spraying of all subsequent superalloy powders. The powder was supplied in two size ranges, 12 - 35 µm and 35 - 70 µm, the finer powder being used for LPPS deposition whereas a mixture of the two particle sizes was used for the manufacture of SSP deposits.

Metallographic examination of the Nimonic 263 deposits showed that both the SSP and the LPPS material had a relatively low level of porosity Figure 4. The layered structure is typical of plasma spray deposited material and, as expected the layer thickness was greater with the coarser powder. The influence of simultaneous peening on the layer profile can clearly be seen, producing a series of linked smooth facets rather than the more familiar 'splat' structure of LPPS deposits. Deposits up to 9 mm thick were produced to enable a number of miniature bar tensile test pieces to be manufactured. Data for material processed by LPPS or SSP routes are compared in Table I with corresponding data on ingot processed material. Following heat treatment at 1100° or 1150°C, the LPPS or SSP material showed improved levels of ductility and excellent proof and ultimate strengths. The strength advantage of the LPPS/SSP material was maintained at 600°C, but at 800°C there was a significant reduction in strength relative to wrought bar. In order to optimise the properties of alloy 263 deposits further work is required to evaluate the interplay between LPPS/SSP and heat treatment.



LPPS Nimonic Alloy 263 12 - 35 µm SSP Nimonic Alloy 263 12 - 70 µm

Figure 4 - Influence of simultaneous peening on layer profile

For the limited amount of work carried out on Nimonic alloy 86 powder trends similar to those for Nimonic 263 were observed.

Table I. Tensile Test Data Determined on Low Pressure Plasma Sprayed and Simultaneously Spray Peened Nimonic Alloys 263 and 86

Material	Processing Route	Heat Treatment	0.2% P.S. MPa	UTS MPa	Elong. %	Reduction in Area %	Hv	Data Ref.
Nimonic Alloy C263 at Room Temperature	Wrought Bar	Solu. Treat & Age[1]	600	985	27	24	265	
	SSP	1100°C 1h AC	690	907	9	7	280	
		1150°C 1h AC	678	975	16	11	285	
		Solu. Treat & Age[1]	883	1048	9	7	353	
	LPPS	Solu. Treat & Age[1]	877	1180	16	16	348	
Nimonic Alloy C263 at 600°C	Wrought Bar	Solu. Treat & Age[1]	490	820	43	50	-	3
	SSP	Solu. Treat & Age[1]	905	937	7	6		
	LPPS	Solu. Treat & Age[1]	906	975	5	5		
Nimonic Alloy C263 at 800°C	Wrought Bar	Solu. Treat & Age[1]	460	587	15	26		3
	SSP	Solu. Treat & Age[1]	-	449	5	5		
	LPPS	Solu. Treat & Age[1]	-	357	11	15		
Nimonic Alloy 86 at Room Temperature	Wrought Sheet	1150°C 15m AC	438	873	45	-	200	3
	SSP	1100°C 1h AC	665	902	15	13	269	
		1150°C 1h AC	645	925	20	16	272	
	LPPS	1150°C 1h AC	-	-	-	-	271	
Nimonic Alloy 86 at 800°C	Wrought Bar	1150°C 2/4h AC	210	400	60	-		3
	SSP	1150°C 1h AC		298	7	5		

Note: [1] - 15-90 min. (depending on section) at 1150°C, W.Q. + 8h 800°C, AC

LPPS/SSP of Oxide Dispersion Strengthened Material

Incoloy alloy MA 956 develops its high temperature strength by combining an elongated lamellar grain structure with a uniform dispersion of yttria. However, the strength and structural stability of MA 956 are degraded by fusion welding processes. Both LPPS and SSP processing of powder FeCrAlY$_2$O$_3$ materials offer the possibility of manufacturing components directly and may circumvent the problems associated with joining.

For proprietary reasons the powder made available by the supplier had slightly different chemistry to alloy MA 956 and is designated FeCrAlY$_2$O$_3$. The FeCrAlY$_2$O$_3$ particles processed by mechanical attrition were more irregular than the gas atomised Nimonic 263/86 powders. To compensate for the reduced flow characteristics of the FeCrAlY$_2$O$_3$ it was necessary to reduce the powder feed rate or increase the carrier gas flow rate to the plasma gun.

Tensile tests were again carried out at room and elevated temperature to compare the properties of spray deposited FeCrAlY$_2$O$_3$ bar with corresponding data on Incoloy MA 956 and FeCrAlY$_2$O$_3$ material processed by powder consolidation and manufactured into plate. Tests were also carried out on deposits heat treated at temperatures in the range 1100°C - 1300°C, Table II.

High levels of proof and ultimate strengths were obtained at room temperature. However, the most consistent results were obtained when spraying the finer cuts of powder. Spray deposits processed from < 35 µm FeCrAlY$_2$O$_3$ powder also performed well after heat treatment in miniature Charpy impact tests absorbing almost 13 Nm without fracture.

Table II. Tensile Test Data Determined on Low Pressure Plasma Sprayed and on Simultaneously Peened ($FeCrAlY_2O_3$) Material

Material and Condition		Heat Treatment	Test Temp. °C	0.2% P.S. MPa	UTS MPa	Elong. %
Incoloy MA 956 - Wrought Plate		As Supplied	20	550	680	16
$FeCrAlY_2O_3$ - Wrought Plate		As Supplied	20	525	620	15
$FeCrAlY_2O_3$	LPPS	As Deposited	20	-	765	-
		1100°C 1h AC	20	797	875	3.0
		1150°C 1h AC	20	785	900	4.0
		1300°C 1h AC	20	-	840	20
$FeCrAlY_2O_3$	SSP	As Deposited [1]	20		761	3
		1100°C 1h AC	20	810	860	2
		1150°C 1h AC	20	825	900	4.5
		As Deposited [1]	600	-	323	15
		As Deposited [1]	800	-	105	19

[1] Data determined at RAE, Pyestock on spray deposit material provided by Lucas

Spray Joining of Incoloy MA 956 Sheet

The joining of two sheets of MA 956 sheet (0.9 mm) with a spray deposit of $FeCrAlY_2O_3$ material was investigated. Problems to be overcome included joint design, bonding of MA 956 with plasma spray deposit, application of preheat and optimisation of spray deposition without developing oxide debris or porosity in substrate or deposit material. It was important that all traces of surface oxide be removed from the joint area immediately prior to mounting of the MA 956 alloy in the plasma spray chamber. Also, the duration of preheat to a surface temperature of approximately 800°C should be kept to a minimum. A typical joint profile, and microstructure after heat treatment are shown in Fig. 5.

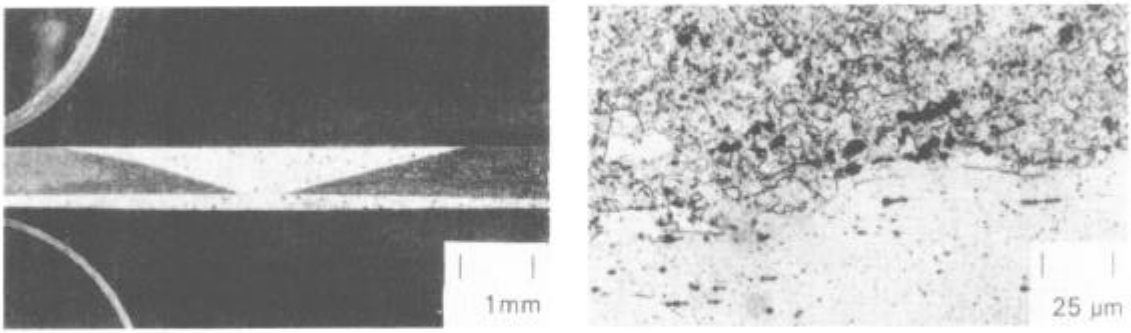


Figure 5 Joint profile and interfacial structure of MA 956 spray joined with LPPS $FeCrAlY_2O_3$

The tensile properties of flat strip joints are compared in Table III for MA 956 alloy measured by the supplier and by Lucas Aerospace.

Table III Tensile Test Data Determined on Incoloy MA 956 Sheet Unwelded and Low Pressure Plasma Spray Joined with $FeCrAlY_2O_3$

Material and Condition	Heat Treatment	Test Temp. °C	0.2% P.S. MPa	UTS MPa	Elong. %	Failure Locn.	Number of Tests
Unwelded MA 956	As recd. (Inco)	20	550	650	10		-
	As recd. (Lucas[1])	20	-	629 ± 25	10 ± 2.5		10
	1300°C 4h AC	20	-	577 ± 12	14 ± 3.0		10
	1200°C 17h in vac.	20	470	595	8		2
Spray [2] Joined with $FeCrAlY_2O_3$	1200°C 17h in vac.	20	457	636	5	Parent Sheet	3
Unwelded MA 956	1200°C 17h in vac.	800	-	136	8		2
Spray [2] Joined with $FeCrAlY_2O_3$	1200°C 17h in vac.	800	-	114	1	Joint	3

[1] Determined on batch of MA 956 used for joining trials.
[2] Specimens machined back to original thickness taking care to remove any excess $FeCrAlY_2O_3$

Good levels of tensile strength were obtained in the joined test pieces and although the ductilities appear low in comparison with those of alloy MA 956 it should be borne in mind that the joints were very small in relation to the overall size of the test piece gauge length. Further study of heat treatment is required to optimise the strength and ductility of such joints.

Discussion

A conventional plasma spray facility has been modified for use at low pressure in a chamber incorporating facilities for simultaneous peening workpiece during plasma spraying. Preliminary trials showed that high density deposits were achieved when plasma spraying was carried out without peening at low pressure, particularly when fine ($<53\ \mu m$) particle size powders were employed. Peening conditions were identified that enabled 100% coverage to be achieved over an area 100 mm square on each pass of the workpiece.

Metallographic examination of plasma spray deposits showed that some improvement in density was achieved using SSP processing. With SSP there was marked evidence of mechanical working of both individual particles and of the successive layers of deposit. Also powder particles which were coarse and unmelted following LPPS became severely deformed and aligned by the peening shot and were difficult to distinguish from the overall plasma spray structure. Both types of deposit showed a pronounced layering effect after etching which was related to the number of plasma spray passes across the workpiece. In SSP material the inter-laminar layers had clearly been deformed by the shot so that the interface had the appearance of a series of flat facets in contrast with the more usual plasma sprayed 'splat' surface.

The boundaries between the layers were less than 1 m thick and showed no evidence, when examined by EPMA, of oxygen or nitrogen enrichment. The structure had no significant influence on the recrystallation and grain growth in heat treated deposits.

The use of SSP processing to reduce the levels of residual stress in plasma spray deposits was clearly demonstrated in the split tube experiments. It is recognised that residual tensile stresses in LPPS deposits are already low in comparison with deposits sprayed at atmospheric pressure enabling thick deposits to be achieved in selected materials. However, the ability to control the level of residual stress by SSP will be of particular benefit in achieving thick deposits in materials of limited ductility.

Conventional sheet alloys Nimonics 263 and 86 were both successfully processed by LPPS/SSP routes. Both SSP and LPPS materials had previously been shown to have low ductility in the as processed condition. However, subsequent heat treatments effected considerable improvements. Although the data showed some scatter, clear trends were evident. There was no marked difference between the tensile properties of LPPS and SSP processed material. However, plasma-deposited material did show remarkably good proof and ultimate strengths at room temperature and 600°C. At 800°C, better properties were obtained with conventional ingot processed materials. The amount of testing carried out to date has been severely restricted by the limited availability of good quality spray powders and it felt that conclusions drawn from this preliminary exercise may be premature.

Similar problems were encountered when evaluating the properties of the mechanically alloyed $FeCrAlY_2O_3$ powder. The test specimens were also in the form of small round bar machined from a thick plate of spray deposit. In general the tensile test data reflected the trends obtained for the more conventional superalloys. Significant improvements in proof and ultimate tensile strength were obtained at room temperature following plasma spray processing but at the expense of some ductility. It is evident that further work is required to optimise heat treatments for the structures produced via plasma spray processing. The fine grain size obtained as a result of spray deposition was usually retained after heat treatment even when simultaneous peening had been employed. The effects of the shot although significant were not sufficient to promote recrystallisation and grain growth, at least for the range of materials and heat treatments investigated.

The investigation into the spray joining of the oxide dispersion strengthened alloy MA 956 was particularly encouraging. In general a number of specimens were prepared for each condition in an attempt to reduce the effects attributable to scatter in material or specimen preparation for these relatively brittle materials. Particular care was taken when preparing joint specimens to ensure that the test section was truly representative of joined MA 956. The room temperature tensile data show that an excellent joint has been achieved with properties which compare favourably with those of the parent sheet. Failure in every case was in the MA 956 material. At 800°C although the properties of the composite specimen were disappointing the bond between the MA 956 and the $FeCrAlY_2O_3$ remained intact. The measured properties thus reflect the relatively low strength of the joint material itself. Further work to modify the grain structure by thermo-mechanical processing possibly including SSP may well enable properties equivalent to the MA 956 being achieved throughout the working temperature range of the alloy.

Conclusions

Conventional superalloys can be processed by LPPS/SSP techniques and provide an interesting combination of mechanical properties at 20°C, 600°C and 800°C.

Simultaneous Spray Peened material generally showed marginally better strength than LPPS material in the as deposited condition. However, post deposition heat treatment had a significant beneficial influence on the strength and ductility relationships.

Mechanically alloyed ODS FeCrAlY$_2$O$_3$ powder was processed via the LPPS/SSP route yielding significant improvements in proof strength at room temperature relative to MA 956 alloy.

Spray depositing FeCrAlY$_2$O$_3$ powder into profiled gaps between MA 956 strips produced joints which had strengths comparable with the MA 956 sheet at 20°C and 800°C.

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