Mathematical Modelling of Osprey Process

by

Guisong Zhong

Department of Mining, Metals and Materials Engineering McGill University Montreal, QC, Canada

April 2006

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of **Master of Engineering**

©Guisong Zhong 2006



Library and Archives Canada

Published Heritage Branch

395 Wellington Street Ottawa ON K1A 0N4 Canada Bibliothèque et Archives Canada

Direction du Patrimoine de l'édition

395, rue Wellington Ottawa ON K1A 0N4 Canada

> Your file Votre référence ISBN: 978-0-494-28638-8 Our file Notre référence ISBN: 978-0-494-28638-8

NOTICE:

The author has granted a nonexclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or noncommercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.



Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

ABSTRACT

Osprey process is a new kind of metal forming technology. In this process, a stream of liquid metal is atomized into a spray of molten droplets by a high velocity inert gas jet. The atomized droplets are accelerated towards a substrate of suitable shape and size. At the same time, they are rapidly cooled by the surrounding relatively cold gas and thereby partly solidified. After a certain flight distance, the droplets impinge on the cold substrate, and solidification continuous on the substrate. Near-net shaped products can be manufactured by this process.

In this study, a simple mathematical model is established to describe the atomizing gas velocity profile and the velocity, thermal and solidification profiles of rapidly cooled metal droplets of different sizes during the in flight droplet-gas interaction. Given the relevant spray parameters, the model allows to predict quickly the transient droplet velocity, temperature, and solid fraction contents of individual droplets at various spray distances from the substrate. This model can be used to ascertain the suitability of the nozzle-substrate distance in Osprey process. The developed mathematical model has been used to predict thermal history and solidification behavior of atomized droplets of γ -TiAl alloy. The model predicts undercooling, nucleation temperature, nucleation position and the extent of solidification of the in flight droplets of sizes ranging from 20 µm to 500 µm.

RÉSUMÉ

Le procédé Osprey est une nouvelle technologie de mise en forme pour le métal. Dans ce procédé, un flux de métal liquide est atomisé en une pulvérisation de gouttelettes en fusion par un jet de gaz inerte à haute vélocité. Les gouttelettes atomisées sont accélérées vers un substrat de forme et de taille convenables. En même temps, elles sont rapidement refroidies par un gaz environnant relativement froid et par conséquence partiellement solidifiées. Après une certaine distance de vol, les gouttelettes atterrissent sur le substrat froid, et la solidification continue sur ce dernier. Des pièces proches de leur forme finale peuvent être fabriquées par ce procédé.

Dans cette étude, un modèle mathématique simple a été établi pour décrire le profil de vélocité du gaz atomisant ainsi que la vélocité, les profils thermique et de solidification des gouttelettes métalliques de tailles différentes rapidement refroidies lors de leur interaction avec le gaz. A partir des paramètres pertinents de pulvérisation, le modèle permet de prédire rapidement la vélocité de gouttelettes individuelles pour plusieurs distances de pulvérisation par rapport au substrat. Ce modèle peut être utilisé pour vérifier l'aptitude de la distance buse-substrat dans le procédé Osprey. Le modèle mathématique développé a été utilisé pour prédire l'histoire thermique et le comportement de solidification de gouttelettes atomisées d'alliage de γ -TiAI. Le modèle prédit la surfusion, la température de germination, la position de germination et l'étendue de la solidification de la solidification des gouttelettes en vol avec des tailles variant de 20 µm jusqu'à 500 µm.

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere gratitude to my thesis supervisor Professor Mainul Hasan, for giving me the opportunity to join his group, for his guidance, supervision, understanding and patience throughout the project. His graduate Transport Phenomena course has immensely helped me to model the Osprey process and complete this research work.

Many thanks go to the technicians and former and present staffs in the department, namely, Carol, Norma, Barbara, and Genny for their kind help in one way or another.

I want to extend my appreciation to all the friends in our group and other groups in our department for the encouragement, help and fun time. I especially want to acknowledge Shiliang, Gang, Hujun for their helpful hands in computer programming, and their invaluable time we spent discussing the project.

Thanks to all my friends who in many ways help me carry through this thesis. Sorry I could not list you all here.

Finally, my sincerest thanks to my family, especially my parents and my wife for the confidence and support they place in me. I would like to dedicate this work to show my endless love to my lovely sons, Zhong Wenxuan, who was born when I was doing this project, and Zhong Ziyi, who was born not long before I submit this thesis.

TABLE OF CONTENTS

ABSTRACT	1
RESUME	11
ACKNOWLEDGEMENTS	
TABLE OF CONTENTS	IV
LIST OF FIGURES	VIII
LIST OF TABLES	Х
CHAPTER 1: INTRODUCTION	1
§1-1. Advantages of Osprey process	2
§1-2. Typical Osprey equipment	5
§1-3. Mechanism of Osprey process	7
§1-4. Mathematical modelling of Osprey process	10
CHAPTER 2: LITERATURE REVIEW	13
§2.1. The history of the development of Osprey process	14
§2.2. Technological improvements of the Osprey process	18
§2.2.1. Research works on different materials	19
§2.2.2. Research works on process improvement	20
§2.3. Mathematical Modelling of Osprey Process	23
§2.3.1. Assumptions for the atomizing/spray stage	23
§2.3.2. Assumptions for the deposition/solidification stage	25
§2.3.3. Heat transfer approaches	26

	§2.3.3.1.Continuum approach	26
	§2.3.3.2.Discrete event approach	26
	§2.3.4. Prediction of important parameters	27
	§2.3.4.1. Droplet size distribution	28
	§2.3.4.2. Droplet velocities	28
	§2.3.4.3. Droplet thermal histories during flight	31
	§2.3.4.4. Deposition rate	32
	§2.3.4.5. Thermal profile within the consolidated material	33
	§2.3.4.6. Spray enthalpy	33
	§2.3.4.7. Fraction of solidification	34
	CHAPTER 3: OBJECTIVES	36
	CHAPTER 4: NUMERICAL SIMULATION PROCEDURE	38
	§4.1. Basic assumptions	39
	§4.1.1. The liquid metal stream is atomized into molten metal droplets	
	spray of a particular droplet size distribution immediately after the	
	atomizing gas impinges on it.	39
	§4.1.2. The droplets size distribution formed at the atomization point will	
	not change during the whole spray process	40
	§4.1.3. The droplets travel in a linear trajectory towards the deposition	
	surface. The motion of a spray droplet is mainly governed by the gravity	
	force, buoyancy force, and the drag force exerted on the droplet by the	
	high velocity atomizing gas	40
\sim	§4.1.4. A lumped droplet is considered in the whole spray process.	41

§4.1.5. In the atomizing velocity profile, the momentum influence from the	
droplets to the atomizing gas is ignored	41
§4.1.6. The thermal effect from droplets to atomizing gas is described	
with a fixed relationship	42
§4.1.7. The cooling operation of the droplets during the spray process is	
caused by the effect of the convection heat transfer from atomizing gas to	
droplets and the radiation heat transfer from droplets to the surroundings.	42
§4.2. One-dimensional velocity profile of atomizing gas	43
§4.3. One-dimensional velocity profile of metal droplets	43
§4.4. Thermal and solidification profile of metal droplets	45
§4.4.1. Undercooling of molten droplets	46
§4.4.2. Cooling in the liquid state stage	47
§4.4.3. Recalescence stage	49
§4.4.4. Segregated solidification stage	50
§4.4.5. Peritectic solidification stage	51
§4.4.6. Cooling in the solid state stage	52
§4.5. The physical properties and conditions used in the simulation	52
§4.5.1. Material used for the simulation and its properties	52
§4.5.2. Atomizing gas used for the simulation and its properties	53
§4.5.3. Other conditions and parameters used for the simulation	54
CHAPTER 5: RESULTS AND DISCUSSION	56
§5.1. One-dimensional velocity profile of atomizing gas and metal droplets	57
§5.1.1. One-dimensional velocity profile of atomizing gas	57

§5.1.2. One-dimensional velocity profile of metal droplets	58
§5.2. One-dimensional Thermal and solidification profile of metal droplets.	60
§5.2.1. One-dimensional Thermal and solidification profile of metal	
droplets of 20 μm	60
§5.2.2. One-dimensional thermal and solidification profiles of metal	
droplets of 80 μm	63
§5.2.3. One-dimensional Thermal and solidification profile of metal	
droplets of 180 µm	64
§5.2.4. One-dimensional thermal and solidification profile of metal	
	66
§5.2.5. One-dimensional thermal and solidification profile of metal droplets of 500 µm diameter	
	67
of metal droplets with different droplet sizes	60
	73
CHAPTER 7: SUCCESSIONS FOR EUTURE WORK	75
CHAPTER 7. SUGGESTIONS FOR FUTURE WORK	70
KEFEKENUES	79

LIST OF FIGURES

Fig. 1-1. Microstructure comparison of centrifugally cast roll alloy	3
Fig. 1-2. Osprey process is conducted under protective atmosphere	4
Fig. 1-3. The operation scheme for the production of performs with different	
shapes	5
Fig. 1-4. Equipment for Osprey process	6
Fig. 1-5. Atomizer and Atomizing Process	8
Fig. 1-6. Mechanism of Osprey Process	9
Fig. 2-1. The equipment and principle of the production of Aluminum strip	
by double roller system	15
Fig. 2-2. Preform produced by Osprey process and the coal-cutting pick	
formed by following manufacturing process	16
Fig. 2-3. High alloy steel preforms weighing about 100 kg each which was	
produced with their pilot plant	17
Fig. 2-4. A rolled preform weighing of 450 kg which was produced by one	
of Osprey's licenses	17
Fig. 2-5. An aluminum alloy billet preform produced by Osprey process	18
Fig. 2-6. Droplet size distribution for spray casting of molten Tin in	
percentage	21
Fig. 2-7. Microstructure of spray deposited Cu-10Sn bronze	22

Fig. 2-8. Microstructure of as-deposited Nimonic 115	23
Fig. 2-9. The modeling results of droplet flight velocity as a function of the	
flight distance for Ni-20 wt% Cr alloy	30
Fig. 2-10. The modeling result of the droplets temperature as a function of	
the flight distance	32
Fig. 2-11. The modeling result of the fraction solidified f_s for the droplets of	
three different sizes as a function of the flight distance z _{subs}	34
Fig. 5-1. Axial atomizing gas velocity vs. spray distance	57
Fig. 5-2. Axial velocity of metal droplets with different droplet size vs. spray	
distance (droplet size unit: μ m)	58
Fig. 5-3. Axial velocity of atomizing gas and metal droplets with different	
droplet size vs. spray distance (droplet size unit: μ m)	60
Fig. 5-4. The temperature of droplet with droplet size of 20 μm vs. spray	
distance	61
Fig. 5-5. The temperature of droplet with droplet size of 80 μ m vs. spray	
distance	63
Fig. 5-6. The temperature of droplet with droplet size of 180 μm vs. spray	
distance	65
Fig. 5-7. The temperature of droplet with droplet size of 300 μm vs. spray	
distance	67
Fig. 5-8. The temperature of droplet with droplet size of 500 μm vs. spray	
distance	68
Fig. 5-9. The state of droplets in different position for different droplet size	70

LIST OF TABLES

Table 4-1. Physical properties of the γ -TiAl alloy	53
Table 4-2. Physical properties of Argon	54
Table 4-3. Other conditions and parameters used for the simulation	55
Table 5-1. Maximum velocity for different droplet size	59
Table 5-2. Droplets temperature after undercooling for different droplet size	69
Table 5-3. The nucleation starts point and fully solidified point for different	
size droplets in the spray trajectory	70
Table 5-4. Droplet temperature at different flying distance for different	
droplet size	71

CHAPTER 1

INTRODUCTION

Osprey process is a relatively new kind of metal forming technology. It is also known as consolidated spray deposition (CSD) or liquid dynamic composition (LDC). It essentially consists of three processes in tandem, namely, atomization, deposition, and solidification. In this process, a stream of molten metal having a proper temperature range is atomized by high velocity atomizing gas (nitrogen or argon) into a large quantity of small metal droplets in proper size distribution. These small metal droplets are then deposited onto a collecting substrate having a proper shape and size. Due to the cooling by the atomizing gas and heat loss through the substrate; the deposited material solidifies rapidly and thereby big grain size and macro-segregation are significantly reduced ^{[2], [4], [8], [17]}.

§1-1. Advantages of Osprey process

Compared to the traditional casting-metal forming processes and powder metallurgy processes, Osprey process has many advantages ^{[1]-[15]}.

First, preform produced by Osprey process has a very uniform microstructure with fine grain size, along with uniform alloy components distribution, and without macro-segregation. As a consequence, the products which are made by Osprey process have a comparable good mechanical properties and workability. The density of the preform produced by Osprey process can also reach near to the density of casting preform. Figure1-1 shows the microstructure compared to the centrifugally cast roll alloy and spray-deposited/forged roll alloy^[4]. Fine microstructure produced by Osprey process is clearly evident in this figure.

Second, Osprey process provides a means of metal forming with simple equipment and investment saving. Dense preforms can be produced in a single equipment directly from liquid metal to the near net shape products by an integrated atomization and deposition process. But with the traditional casting-

metal forming processes, casting equipment and many other down-stream forming equipment are needed which lead to a huge equipment investment.





Third, the production cost of Osprey process is low, and it is an energy saving and cost saving process. Osprey process provides a means of metal production in one step directly from liquid metal to near net shape products. One can also perform small forming process with the help of the heat from the spray operation to further improve the properties and surface quality. Consequently, a lot of preheating and annealing processes can be eliminated which result in a large energy and cost saving.

Fourth, the operation of Osprey process is simple. It is easy to control the whole operation. One can save production time, manpower and investment for equipment and workshop. The whole operation can also be performed under the protective atmosphere and hence oxidation of material can be minimized or

prevented. The latter arrangement can eliminate the major disadvantages resulting from multi-step processes (e.g., casting-metal forming process and powder metallurgy process) which often leads to oxide contamination in the material. Figure1-2^[1] shows how the oxide formation can be prevented in a Osprey process.



Fig.1-2. Osprey process is conducted under protection atmosphere^[1]

Fifth, metal matrix composite materials can be easily produced by this process with uniform distribution of the reinforce materials components within the metal matrix.

Sixth, the products with different shapes, such as tube, cylindrical ingot, sheet, plate, etc, can be easily produced by Osprey process by changing the collecting substrate and controlling its movement. Figure.1-3 shows the operation scheme for the production of preforms having different shapes^[24].



Fig.1-3. The operation scheme for the production of performs with different shapes ^[24].

§1-2. Typical Osprey equipment

The typical Osprey process equipment is shown in Fig. 1-4^[3]. Initially metal or alloy is melted in a crucible placed in a heating furnace. The heating temperature is usually about 100° - 200°C above the melting point of the metal alloy. Molten metal flows out from a nozzle placed under the crucible. When the molten metal flow pass an atomizer placed around the outlet of the nozzle, the high speed gas from the atomizer strikes on the molten metal flow and atomize the continual liquid metal flow into a stream of very small liquid metal droplets.

With the help of high speed room temperature gas, the small liquid metal droplets, which are of different sizes, are cooled down and they deposit rapidly onto a collection substrate placed beneath the atomizer. The collecting substrate is controlled by a transfer mechanism and can be revolved, moved vertically or



Fig. 1-4. Equipment for Osprey process^[3]

Furnace. 2. Crucible. 3. Nozzle. 4. Atomizer.
5. Atomizing Chamber. 6. Collecting Substrate.
7. Transfer System. 8. Transfer controlling System.
9. Gas Exhausting System. 10. Gas Pressure control System.

11. Gas Supply

horizontally. The atomization and deposition operation are performed in a spray chamber. Atomization gas is exhausted through a gas-exhausting channel. The metal particles, which are not deposited on to the collecting substrate, are

collected by a powder-collecting device placed at the bottom of the spray chamber^{[2], [3]}.

The equipment for Osprey process can be different for the production of different shape products, such as, strip, plate, bar, disc, etc, or for different production procedures, such as, for the production under protective environment, or for the production of metal matrix composite material.

§1-3. Mechanism of Osprey process

The mechanism of spray process and deposition process have been discussed in many different literatures ^{[]-[19]}. The spray process and deposition process are shown by Fig.1-5^[1] and Fig.1-6^[4], respectively. Liquid metal flow is atomized into small liquid metal droplets by high velocity gas from the atomizer placed around the molten metal flow nozzle. The small liquid droplets also are cooled by the high velocity room temperature gas during the spray process. Since the sizes of the liquid metal droplets are different, the cooling speeds of different droplets are different. As a consequence, if one places the collecting substrate at a proper distance from the atomizer, the metal droplets will reach to the collecting substrate in different states, as shown in Figure 1-6. When the speed and temperature of the atomizing gas are fixed, the cooling speeds of the flying liquid metal droplets will mainly depend on the size of the droplets. The metal droplets can reach the collecting substrate in three different states. For small size metal droplets, they will be fully solidified after they fly a certain distance and reach to the deposition surface. Since the loss of heat is faster in small size droplets, so they deposit in fully solid state. For very large size droplets, they will be still in liquid state when they reach to the deposition surface. Because of a greater thermal resistance, the loss of heat is slower in very large size droplets. Hence they will deposit in fully liquid state. But for most of the droplets between these two extreme situations, they are only partially solidified when they reach to the



Fig.1-5. Atomizer and Atomizing Process^[1]

deposition surface, and therefore these droplets will deposit in a partially solid and partially liquid state^{[2], [3], [4]}.

By properly controlling the parameters of the Osprey process, the temperature of the droplets can be controlled, and consequently the state of the droplets can be controlled when they arrive to the deposition surface. The proper expected state of the droplets is that when the droplets reach to the deposition surface, only a small part of them should deposit in fully liquid state or in fully solid state, and most of them should deposit in a semi-liquid and semi-solid state. So there is always a thin layer of liquid metal on the deposition surface. This is schematically shown in Fig.6. Because of the heat losses caused by the convection of the high velocity gas and the conduction of the as-solidified deposited metal through collecting substrate, this thin layer of liquid metal solidifies rapidly. But many newly arrived, big size, fully liquid droplets come to the deposition surface

continuously and build up a new, thin liquid layer. The solidification of the old thin liquid layer and the build up of the new thin liquid layer are completed in a very



Fig.1-6. Mechanism of Osprey Process^[4]

short time. Finally, they reach a balance and the thin liquid metal layer keeps in a certain thickness continuously^{[2], [3], [4]}.

If the deposition temperature is too low, it will cause most of the droplets to be solidified or nearly solidified when they reach the deposition surface. Then these solidified particles will keep their own identity and characteristic microstructure after deposition. This will in effect lead to a loose and porous microstructure. On the contrary, if the deposition temperature is too high, most of the droplets will be

still in a liquid state when they arrive at the surface, and this will result in a thick layer of liquid metal on the deposition surface. This situation will lead to splashing of molten metal by the high velocity gas and transverse flow of liquid metal on the deposition surface. The solidification process will be similar to a casting process ^[3].

It is regarded that the thickness of the semi-solid/semi-liquid layer is about several times or dozens of times the size of the droplets. The droplets in which dendritic solidification had already occurred during flight when they impact at high speed onto the deposition surface, this leads to dendritic fragmentation. Fine pre-solidified particles, dendrite fragments and liquid metal mixed together to form the semi-solid/semi-liquid layer. Some of the fine pre-solidified particles and dendrite fragments may re-melt in the liquid metal, aided partly by the release of latent heat^{[3], [4], [9]}.

Solidification of sprayed metals takes place rapidly by convective cooling of the relatively cold atomizing gas which flows over the deposition surface and by conductive cooling through the as-deposited metal and collecting substrate. The fine pre-solidified particles and the dendrite fragments behave as the nucleation sites and the cores of solidification. It is difficult to form dendritic arms during the solidification process because of the violent turbulence in the semi-solid/semi-liquid layer cause by the impact of the high velocity droplets and gas stream. This results in a very rapid solidification with fine grains but without dendrites and leads to homogeneous macrostructure^{[3], [4]}.

§1-4. Mathematical modelling of Osprey process

Mathematical modelling of this process is a useful undertaking and has been proved to be an important and useful part of technology which helps one to fully understand the principle and detail behavour of the process, and which can guide to improved experiments and industrial practice. The importance of mathematical

modelling of this process is more and more recognized in scientific and industrial communities. In order to develop a good mathematical model of a process, one has to fully understand all the physical aspect of processes one is going to simulate. In addition, one must also collect enough necessary information and data (initial and boundary conditions etc.) from industry and through experimental campaign to validate the model ^{[20], [23], [24], [36]}.

Osprey process is a metallurgical process. For the mathematical modelling of the Osprey process, a high velocity gas jet flow behavour, a high velocity liquid metal jet flow behavour, the momentum and thermal interactions behaviour between high velocity gas jet and high velocity liquid and solid, the undercooling, recalescence, and solidification behavour of liquid metal, the heat transfer behavour of liquid and solid metal after deposition, etc. have to be modelled and fully understood. The mathematical modelling of Osprey process essentially involves the application of momentum conservation equations, energy conservation equations, and mass conservation equations in different forms and at different stages of the process.

If one considers Osprey process as a whole, it is a complex process to be correctly described through mathematical modelling techniques. But a complex process can be subdivided into several simple individual stages for the convenience of analysis. In each individual stage, different materials and different phases can be analysed separately. For Osprey process, the following main sub-processes can be divided and analyzed separately for the convenience of study^{[20], [23], [24], [36]}.

 Atomization process: Is the process of atomizing liquid metal stream into liquid metal particles jet flow by atomizing gas (argon or nitrogen). This stage starts with the supply of continuous melt stream, continues with the disintegration and fragmentation of the melt stream, and ends with the

forming of the jet flow of liquid metal droplets with a proper droplet size distribution.

- Spray process: Is: the part of the process in which the jet of the melt droplets travels with high velocity from the atomization zone to the deposition area. This stage can be considered to be a multi-phase flow process in which momentum, energy, and mass transfer takes place among various phases, through interaction between those phases. In this stage, solidification of droplets is the key marker to study.
- Deposition process: During this process the deposition of multi-phase metal droplets occur onto a deposition surface. This stage involves a multiple of steps including the multi-phase metal spray impaction onto a solid, or liquid, or mush deposition surface, the phases change after the spray deposited onto the deposition surface, the build up and growth of the deposited melt and solid metal, and the heat transfer inside the asdeposited preform.

CHAPTER 2

LITERATURE REVIEW

§2.1. The history of the development of Osprey process

The principles of Osprey process were first explored by Singer at the University College of Swansea, U. K. during the end of 1960s^{[1], [2]}. The general principle of Osprey in Singer's research is to atomize a stream of molten metal (aluminum) with a high velocity gas jet (nitrogen). And then the atomized molten metal droplets jet impact directly onto shaped collecting substrate (a mould, a plate, or the surface of a turning roller). The high velocity molten metal droplets upon impact onto the collecting surface, they either flatten, or brake, and quickly weld and solidity to form a dense shaped preform. Further deposition of metal can be carried on to improve the properties and surface quality of the deposited layer. Singer's research work on Osprey process mainly focused on aluminum alloys. During 1970s, Singer first proposed rolled aluminum strips by spraying molten aluminum onto a flat steel substrate traversing beneath a single atomizing nozzle designed to over spray the substrate. His spray system produced a strip of preform which subsequently had to be reheated and hot rolled to make a dense aluminum strip^[1]. Figure 2-1 shows schematically the equipment and the arrangement of various components of the spray process used in the production of aluminum strip by double roller system. The surface of one of the rollers was the collecting substrate for the deposition of the spray. In another experiment, Singer managed to produce a continuous strip of 0.127 m width of as-deposited metal onto a single wheel of 0.914 m in diameter and 0.127 m width, which was allowed to rotate slowly beneath an atomizing nozzle^[1].

During 1970s, Osprey Metals Ltd. was founded by Brooks, Leatham, Coombs and others in Neath, South Wales, U. K. These researchers successfully applied the early ideas of Singer to produce discrete shaped preforms which were subsequently forged to take final desired shapes. From then on, many

researchers have experimented with many metals and alloys, especially ironbased alloys ^{[2],[4], [6], [8], [12]}.



Fig. 2-1. The equipment and principle of the production of aluminum strip by double roller system^[1]

The earlier aims of Osprey Metals Ltd., were to reduce the production cost, improve material utilisation factor and increase production efficiency of metal forming industry, especially in forging industry, compared to the traditional forging of casting/pre-rolled bars, or preform produced by powder metallurgical methods. In 1977, Osprey Metals Ltd. reported to have produced sectioned preforms up to 2 kg^[6] in weight. Figure 2-2 shows a sample of their shaped spray deposited perform. The steps required to manufacture the final product, and the manufacturing system, which was called a coal-cutting pick^[6], are also shown in Fig. 2-2. The preform was reported to have a homogeneous, fine-grained microstructure, with low oxide content, and without segregation. Its average density was shown to have reached to over 98% of its theoretical value^[6].



Fig 2-2. Preform produced by Osprey process and the coal-cutting pick formed by following manufacturing process

By the end of 1970s, the ability to produce preforms of various thick sections and of various shapes had been achieved. During that time, various metal alloys had been experimented by Osprey process. From then on the research work on Osprey process progressed rapidly and great advancements have been made until now^{[2] –[19]}.

In 1980's, Osprey process and technology went through a very significant progress. More and more Osprey facilities with larger production abilities have come into production.. And the production ability of Osprey process reached to an industry scale In 1985, Evans form the Metallurgy Department, University College of Swansea, along with Leatham, and Brooks from Osprey Metals Ltd. reported that they were successful in producing tubular and billet preforms weighing up to 120 kg from many kinds of ferrous and non-ferrous metal alloys in



Fig. 2-3. High alloy steel preforms weighing about 100 kg each which was produced with their pilot plant^[12]



Fig 2-4. A roll preform weighing of 450 kg which was produced by one of Osprey's licenses^[12].

their pilot plant facility. Their pilot plant was equipped with a 150 kg tilting furnace^[12].which allowed them to spray cast bigger size performs. Figure 2-3 shows a picture of high alloy steel performs, weighing about 100 kg each, which was produced from their pilot plant^[12], and Fig. 2-4 shows a roll preform weighing about 450 kg which was produced utilizing one of the patented processes licensed under Osprey Metals Ltd.^[12]. Figure 2-5 shows an aluminium alloy billet preform produced by Osprey process^[8].



Fig. 2-5. An aluminium alloy billet preform produced by Osprey process^[8].

§2.2. Technological improvements of the Osprey process

Along with the progress in research and technological developments of Osprey process in terms of production facilities and production capability, the study of the process, the properties and microstructure of as-deposited material made by Osprey process had been carried out worldwide and successful achievements were made in these areas by researchers around the world^{[1]-[19], [25]-[32]}.

§2.2.1. Research works on different materials

The research work on Osprey technology covered a wide range of metals and materials in order to find suitable practical applications.

Aluminium alloys: Professor Singer's early research works on Osprey process were on aluminum alloys^{[1].} One of the advantages for using aluminium alloy as the experimental material is that aluminium alloys have a relatively lower melting temperature which leads to a simpler experimental facilities and thus allows easy control of the process. Subsequently, many researchers selected aluminum alloys as the materials for study for the Osprey process. Another reason why aluminum alloys were used by many researchers in the Osprey process is the fact that aluminum and its alloys are widely used in aerospace industry which require critical performance of the material in it's applications. Usually 2000 (Al-Cu) and 7000 (Al-Zn-Mg) series aluminum alloys were preferably investigated by researchers using the Osprey process^[2].

Iron-based alloys: Iron and steel are the most widely used and the most important metals used in industry. In traditional multi steps costing/metal forming process, iron-based alloys get easily oxidized in the atmosphere during metal forming and downstream heat treatment processes. Production of iron-based alloys with Osprey process can effectively eliminate the above disadvantages. Many researchers carried out deposition of iron-based alloys with Osprey process and investigated their structure and property improvements. Brooks et al^[6] []studied in 1977 on a wide range of low alloy steels including En.3A, En.8, En.16, En.19, En.24, En.31 and En.33, and reported that the microstructure of as-deposited preform is uniformly fine and have competitively good properties¹.

Superalloys: Production of superalloys by Osprey process can effectively eliminate oxidation during powder metallurgy process, and reduce the production

cost. Many cases of the experimental work with superalloys have been reported in the literature^[2].

Metal matrix composite materials (MMC): Metal matrix composite material can be produced by Osprey process. The reinforce materials components within the metal matrix have a uniform distribution inside the metal matrix. Bedford et al. carried out their investigation on low alloy steel, tool steel, and austenitic and martensitic stainless steel based steel matrix composite with the reinforce material of Al₂O₃ to provide friction resistance surface^[7]. Friction surface rods can be produced by hot work of metal matrix composite preforms containing up to 12 vol. %Al₂O₃ reinforcement. The investigation on microstructure and wear resistance performance of the metal matrix composite preforms manufactured by Osprey process has shown encouraging results.

Other materials: Many other materials have also been investigated by researchers all around the world, including copper-based alloys, lithium-based alloys, magnesium-based alloys, nickel-based alloys, and magnetic alloys^{[2], [4], [8]}. The results from all of these studies demonstrated that Osprey process is applicable for the production of preform from a wide range of metals and their alloys including composite materials.

§2.2.2. Research works on process improvement

Since the early exploitation of Osprey process, a great progress and many scientific and practical achievements have been made in the studies of this process and its principles.

Gas atomization: Gas atomization is realized by impinging high velocity inert gas onto a molten metal stream, and the high velocity gas breaks the molten metal stream into a large quantity of liquid metal droplets with a wide range of

droplet size distribution. The principle of atomization is that the velocity difference between high velocity gas and the low velocity molten metal stream causes that the gas tears off liquid ligaments from the surface of molten metal stream, and then those liquid ligaments break down to short sections and then to spherical droplets under the surface tension forces^{[10], [19]}.

Droplet size distribution: Droplet size distribution is determined by many factors, such as the velocity difference between the atomizing gas and the molten metal stream; the flow of the molten metal or the size of nozzle; the temperature of the molten metal, etc. Some researchers estimated the droplet size distribution by calculating the mass mean droplet diameter $d_{50}^{[23]}$. Some reported the droplet size distribution from experiments. Mathur et al. obtained the droplet size distribution by sampling the droplets in flight at different radial distances from the axis of the spray chamber by placing concentrically copper tubes filled with water^[24]. Figure. 2-6 shows the experimental results of droplet



Droplet size (µm)



size distribution reported by Guisong at al. in their study for spray casting of molten Sn^[3]. The conditions used were^[3]: temperature: 388 °C, atomizing gas pressure: 0.4 MPa, deposition distance: 530 mm. The average droplet size measured was approximately 111 mm.

Microstructure: In general, the preform produced by Osprey process has a very uniform microstructure with fine grain size, uniformed alloy components distribution, and without macro-segregation. In recent years, a wide range of materials have been produced by Osprey process and the microstructural characteristics and alloy components distribution of the products have been studied. Figure 2-7 and 2-8 illustrate the microstructure of spray deposited Cu-10Sn bronze and as-deposited Nimonic 115 respectively^[12]. Both of these micrographs illustrate the uniform microstructure of spray deposited preform.



Fig. 2-7. Microstructure of spray deposited Cu-10Sn bronze^[12]



Fig 2-8. Microstructure of as-deposited Nimonic 115^[12]

§2.3. Mathematical Modelling of Osprey Process

The Osprey process essentially consists of atomizing/spray process and deposition/solidification process. So the modelling process can be divided into these two sequential processes: (1). Molten metal is atomized by high velocity gas into droplets and the droplets spray towards a collecting substrate. The droplets in flight are cooled by convective gas cooling and some of them start or complete their solidification process before reaching the substrate; (2). When the droplets deposit onto the collecting substrate, solidification occurs due to the convective cooling caused by the atomizing gas which flows over the deposition surface and also due to the conductive cooling through the previously solidified metal and the substrate^{[20] - [25], [33] - [36]}.

§2.3.1. Assumptions for the atomizing/spray stage

The following assumptions are generally adopted by different researchers for modeling the atomizing/spray process:

i) When the atomizing gas impacts on the molten metal stream, the droplet size distribution is established instantaneously, and during the whole spray process, the established droplet size distribution does not change until the moment the droplets impinge onto the deposition surface. This means that there is no droplets separation and mergence, or droplet size change during the whole spray process. It is assumed that the droplet size distribution is formed instantaneously and the time for establishing the size distribution is negligible compared to the time of flight of the droplets ^{[21], [23], [24]}.

ii) The molten metal droplets take spherical shapes immediately when the atomizing gas impacts on the molten stream and the droplet size distribution is established. Because of the fact all metallic melts have a very high surface tension, and the high surface energy makes the droplets stable and promotes to take on spherical shapes. This assumption has been experimentally proved to be very reasonable ^{[21], [24]}.

iii) The sprayed droplets travel in a linear trajectory towards the deposition surface immediately after the droplets are formed by the atomization process. The driving forces for the spray droplet consist of the gravity force and the drag force. The latter force is exerted on the droplet by the high velocity atomizing gas. Collisions between droplets are disregarded. A lumped droplet can be considered and the relative motion between the liquid metal on surface layer of the droplet and the liquid metal, or partially solidified metal, inside the droplet is disregarded ^{[21], [23], [24]}.

iv) The cooling operation of the droplets during the spray process is accounted for through the pre-assigned heat transfer coefficient between the droplets and the atomizing gas. The heat transfer coefficient changes for different droplets according to the size of the droplet and the relative velocity between the droplet and the atomizing gas. The heat exchange between droplets (for example,
between large size droplets and small size droplets, between liquid droplets and solidified droplets) is disregarded ^{[21], [23], [24]}.

v). A lumped capacity droplet model is applicable, The temperature across the whole section of the droplet can be considered to be the same and the temperature gradient within the droplet can be neglected. This assumption is reasonable because the droplets in the spray process are very small. The calculations made by Gutierrez-Miravete et al.^[23] show that the calculated results from two different models, a) a lumped droplet model, and b) a model which considers the temperature gradient across the droplet radius, have a very close agreement. Their results clearly indicate that the temperature gradient within the droplet can be neglected for the modeling of Osprey process. This assumption makes the modeling effort much more simple ^{[21], [23], [24]}.

vi) Each droplet is accelerated by the atomizing gas to a certain velocity at a certain point from the atomizing nozzle where the velocity equals to the instantaneous velocity of the atomizing gas at that position. After that distance the droplet travels faster than the gas and consequently it is decelerated ^{[21], [23], [24]}

§2.3.2. Assumptions for the deposition/solidification stage

The following assumptions are generally adopted for the modeling of the deposition/solidification stage.

i). In a stable spray deposition process, the deposition rate will not change dimensionally, and it is only a function of time ^[23].

ii). The heat transfer takes place through the as-deposited preform and the collecting substrate, and only conducting cooling takes place during the deposition/solidification process^[23].

iii). The thermal energy transfer rate from the atomization/spray stage into deposition/solidification stage is in accordance with the average heat content of the spray droplets when they deposit onto the deposition surface^[23].

iv). The thermal energy transfer rate from the atomization/deposition process to the collecting substrate is related to a heat transfer coefficient ^[23].

§2.3.3. Heat transfer approaches

§2.3.3.1. Continuum approach

In this approach, heat transfer is conducted in one-dimension from the spray to the deposition substrate direction. The boundary of the deposition surface is moving upward when the deposition process continues. The enthalpy exchange between the deposition surface and the spray process is a continuous function. The enthalpy is taken as a function of time along the thickness of the deposited layer ^[20].

§2.3.3.2. Discrete event approach

In this approach, one considers a layer of metal in the deposit surface region as a control volume. The enthalpy exchange between the control volume and the exterior region consists of three heat transfer events ^[20]:

(a) The enthalpy input from the spray onto the top boundary of the control volume is a discrete event during a time interval δt .

26

(b) The enthalpy loss due to the convective cooling by the atomizing gas at the top boundary of the control volume during that time interval.

(c) The enthalpy loss due to the conductive cooling through the as-solidified preform and the collecting substrate during that time interval.

§2.3.4. Prediction of important parameters

The droplets are cooled through the thermal interaction between the droplets and the atomizing gas. By modelling the thermal interaction between droplets and gas, the solidification paths, the thermal history and the droplets' temperatures can be predicted as a function of flight distance.

In the second stage, in stable spray deposition process, the droplets deposit onto previously consolidated metal layer. According to the rate of heat and mass influx to the deposition surface from the spray of droplets, and heat exchange with the gas flow, the deposition surface and pre-consolidated metals, the temperature history in the deposition layer can be predicted. Consequently, the rate of advancement of the solid-liquid interface, the local solidification time and the variation in microstructure features across the deposition thickness can be predicted. Both the rate of deposition and the rate of solidification will determine the solidification process inside the semi-solid/semi-liquid layer on the deposition surface. The latter factors will hence determine the microstructure of the preform. If the solidification rate is greater then the deposition rate, successive droplets will impinge onto a pre-solidified surface. A rapid solidification takes place on the surface under this condition. On the deposition surface, there is no liquid layer which can help to form a dense and less porous microstructure for this condition. If the rate of deposition is greater than the rate of solidification, a liquid layer will

27

form and grow on the deposition surface. If the liquid layer is too thick, a microstructure with coarse, dendritic grains will form.

In order to model the atomizing/spray process and deposition/solidification processes, some important parameters have to be determined first. Some of these parameters are determined by experiments, and some of them are calculated from empirical mathematical formulations.

§2.3.4.1. Droplet size distribution

It is necessary to know the droplet size distribution for the determination of the average enthalpy of the spray at impact. There are different ways to determine the droplet size distribution. Lavernia et al^[21], and Gutierrez-Miravete et al^[23]:. have used the following empirical equation for the calculation of mean droplet size in a spray process::

$$d_{50} = K_D [(\mu_m d_0 \sigma_m / \mu_g V_{ge}^2 \rho_m)(1 + J_{melt} / J_{gas})]^{1/2}$$

where,

$$J_{melt} = A_0 \rho_m C_D (2 g h_c)^{1/2}$$

and,

$$J_{gas} = A_t \{\gamma \rho_g p_0 [2/(\gamma + 1)]^{(\gamma + 1)/(\gamma - 1)} \}^{1/2}$$

 $\rho_{g} = 2.7 \ (1.6317 * 10^{-5} p_{0} + 1.0585)$

§2.3.4.2. Droplet velocities

The droplet velocity is used to assess the prediction of the modeling process. The metal spray can be examined by means of short exposure still photography

over different flight distances. The velocity of the droplets in the metal spray can be determined by the recorded streak lengths on the film ^[24].

According to Mathur's consideration, the velocity profile is determined from the momentum equation. The acceleration of droplet is related to the relationship between the velocity of gas and the velocity of droplet. The total force acting on a spherical droplet is given by ^[24]

$$F = m(dV_d/dt) = (C_D \rho_g V_r^2 A/2) + mg$$

Droplet acceleration:

$$(dV_d/dt) = \{3C_D\rho_g(V_g - V_d) | V_g - V_d | / 4d\rho_d\} + g$$

Lavernia et al. and Gutierrez-Miravete et al. have calculated the droplet velocities from the force balance on a given volume $V_d^{[21], [23]}$: The force balance equation simplifies to:

$$\rho_d V_d dV_d / dt = V_d (\rho_d - \rho_g) g - (A_d / 8) C_{drag} \rho_g (v_g - v_d) I (v_g - v_d) I$$

Figure2-9 shows Mather's prediction of droplet flight velocity as a function of the flight distance for Ni-20 wt% Cr alloy.. Well in accordance with the actual Osprey operation, small droplets accelerated to very high velocities very rapidly. For example, the droplets with a diameter of 20 μ mis accelerated to a velocity of about 120 m/sec within the flight distance of about 100 mm. For the bigger size droplets, the acceleration is much slower. The velocity of the droplet witha diameter of 130 μ m is only about 40 m/sec when their flight distance is about 100 mm. Small size droplets reach to their maximum velocity rapidly, and the velocity then decreases slowly. The maximum velocity for a 20 μ m droplet is about 120



Fig. 2-9. The modeling results of droplet flight velocity as a function of the flight distance for Ni-20 wt% Cr alloy^[24]

m/sec, and it is reached at the flight distance of about 150 mm. For the droplet with a diameter of 80 mm, the maximum velocity is only about 60 m/sec, and this velocity is attained at a flight distance of about 350 mm. During the spray operation, the velocity of the spray gas decreases rapidly due to the impact with the metal droplets and causing in turn the droplets to accelerate. When the spray gas and the flying droplets attain the same velocity, the droplets reach to their maximum velocity, and then on their velocity decreases slowly. In Fig.2-9, the droplets whose flight trajectory curves intersect the velocity curve of gas, those droplets reach to their maximum velocity.

§2.3.4.3. Droplet thermal histories during flight

Mathur considered that the change of a droplet temperature ΔT over a time increment is related to the rate of heat loss during flight. So the temperature can be calculated from the heat balance between the droplet and the surrounding gas [24].

Similar to the work of Lavernia et al. and Gutierrez-Miravete et al., lumped parameter models are usually adopted to calculate the heat exchange between droplets and gas. Under-cooling of liquid droplets and recalescence due to the release of latent heat caused by nucleation inside the droplets are also been considered^{[21], [23]}.

Figure 2-10 shows a typical profile of the prediction of the droplets temperature as a function of the flight distance^[23]. From the figure, one can clearly see that the thermal history curve is divided into four regions. The first region shows that, in a very short distance, the temperature of the droplets decrease rapidly. This is due to the fact that, at the beginning of the atomizing process, the temperature difference between the atomizing gas and the metal droplets is large. The cold atomizing gas gives an intensive cooling to the high temperature molten metal droplets. This intensive cooling may cause a liquid metal droplet to go in an undercooled state. In the second region, temperature of the droplets increase sharply in a very small distance. This is due to the nucleation inside the droplets, and this event leads to the release of the latent heat and promote recalescence. The droplets undergo this process more rapidly than the cooling action of the spray gas, so the temperature of the droplets increases a little. The third region is a stable thermal section. In this region, solidification takes place in some of the droplets, more so for the small size droplets than intermediate size droplets, or bigger size droplets. Since there are still the release of the latent heat from the

31



Fig. 2-10. The modeling result of the droplets temperature as a function of the flight distance^[23].

larger size droplets, as a result the solidification process is slower and, the temperature decrease slowly in this section. But in the fourth and final region, the solidification process is complete in almost all the droplets, so the temperature of the droplets decreases rapidly.

§2.3.4.4. Deposition rate

The usual experimental method for the determination of the deposition rate is by measuring the build up of deposits on a collecting substrate by recording the deposition with a video camera. The thickness profiles recorded by Mathur for the build-up of Fe-20 wt% Mn deposits can be expressed by the equation^[24]:

32

$$D = B \exp(-b R^2)$$

where B is the maximum deposition rate (determined as 5.25 mm/s) and b is the radial distribution coefficient (determined as 0.0018 mm⁻²), and R is the radial distance from the spray axis.

§2.3.4.5. Thermal profile within the consolidated material:

The thermal profile within the consolidated material can be determined experimentally by placing thermocouples initially at different places above the stationary substrate surface ^[24].

§2.3.4.6. Spray enthalpy

Annavarapu ^[18] assumed that the spray region of the droplets is conical in shape and the spray enthalpy, H_{spray} does not change with time within this region, but changes along the radial direction from the spray axis. The spray enthalpy was determined from ^[20]:

 $H_{spray} = \left[\Sigma H_{(di)} d_i^3 f_{(di)}\right] / \left[\Sigma d_i^3 f_{(di)}\right]$

where:

 $H_{(di)} = \int C_p dT + \Delta H_f df_s$

and $f_{(di)}$ is the fraction of droplet in the size range of d_i to d_{i+1} .

§2.3.4.7. Fraction of solidification

Figure 11 shows the modeling result of the fraction solidified (f_s) for droplets of three different sizes as a function of the flight distance z_{subs} ^[14]. For a small size droplet with a diameter of 22 µm, the solidified fraction reached to about 0.35 at the flight distance of 100 mm. But the solidified fraction for the droplets with the diameter of 78 µm and 274 µm are still around zero at that flight distance. It means that they are still in fully liquid state. At the flight distance of 300 mm, 22 µm droplets are fully solidified, but the solidified fraction for the droplets of 78 µm and 274 µm are still around one the droplets of 78 µm and 274 µm are still around 0.5 and 0.15, respectively. From the modeling results, one can estimate the average rate of formation of solidified fraction for the whole array of droplets when they impact on the deposition surface. One can also



Fig. 2-11. The modeling results of the fraction solidified f_s for the droplets of three different sizes as a function of the flight distance $z_{subs}^{[24]}$.

adjust the spray distance appropriately so as to control the average rate of solid fraction metal arriving at the deposition surface. This figure can also guide one to design an optimal deposition process and control solidification condition at the deposition surface for the purpose of getting a homogenous microstructure with a very fine grain size.

CHAPTER 3: OBJECTIVES

CHAPTER 3

OBJECTIVES

CHAPTER 3: OBJECTIVES

The advantages of Osprey process have been realized by industry and researchers around the world. Over the years, a significant progress has been made concerning the operation, materials production and process improvements of Osprey technology. Mathematical modeling studies have also been undertaken by many researchers on different aspects of the Osprey process and for different materials.

In this work, Osprey process is simulated through mathematical modeling in order to predict the momentum, thermal and solidification behavior of spray metal droplets and momentum behavior of the atomizing gas.

The objectives of this study are as follows:

- 1. Establish a simple model for the atomizing gas velocity vs. spray distance.
- 2. Establish a simple model for spray droplets velocity vs. spray distance.
- 3. Establish a user friendly and practical model to predict the spray droplets temperature and solidification state vs. spray distance.

CHAPTER 4

NUMERICAL SIMULATION PROCEDURE

In the atomization process, a high velocity, inert gas at room temperature spray out from the atomizer, and then impinges onto the surface of a liquid metal stream, and atomize it into a molten metal droplets spray. In this case, first, there is an atomizing gas spray velocity field from the atomizer to the collecting substrate. Second, the molten metal droplets spray is accelerated in the high velocity gas spray field towards the collecting substrate, and form metal droplets spray field. Third, because of the cooling of the droplets from the low temperature atomizing gas environment surrounding the droplet, the temperature and state of the droplets change in the spray field. Depending on the heat transfer rate from the in-flight metal droplets to the surround high velocity gas stream, the droplets could be in the liquid, partial solid or completely solid state. The prediction of the thermal state of the spray droplets is one of the objectives of the present study.

The numerical simulation process in this study is divided into the following three parts: prediction of one dimensional velocity profile of atomizing gas, prediction of one dimensional velocity profile of metal droplets, and prediction and assessment of one dimensional thermal and solidification profiles within the metal droplets.

§4.1. Basic assumptions

The following basic assumptions were made for the simplification of the numerical simulation procedures.

§4.1.1. The liquid metal stream is atomized into molten metal droplets spray of a particular droplet size distribution immediately after the atomizing gas impinges on it.

In this study the very rapid transient phenomena of droplet formation due to the interaction of the liquid metal stream and injected gas stream is ignored. In the

atomization process, the kinetic energy is transferred from the high velocity atomizing gas to the liquid metal stream. As described in Kelvin and Helmnoltz phenomenon^[45], the liquid metal stream separates into many liquid metal straps as a result of the kinetic energy increase of the stream. Because of the Rayleigh Taylor instabilities, the molten strips are not in a stable state, and tend to break into many short and small sections. And then, as a result of a capillary instability, the small sections get fully separated into a large quantity of small droplets because of the high kinetic energy of the surface of the straps or droplets^{[34], [35], [36]}.

The mechanism of the atomization from molten stream to molten metal droplets is a very complicated process, and a lot of research work is needed to fully understand this phenomenon. Since the process of droplets formation takes place in a very short time and distance compared to the whole spray process, one can safely ignore the process of that changes the molten stream into numerous molten droplets. Invoking the above realistic assumption, one can assume that the droplets size distribution is formed instantaneously when the atomizing gas impinges onto the molten stream.

In the present numerical model, it is assumed that the droplets of a particular size distribution is formed instantaneously at the outlet of the atomizing nozzle. All calculations are therefore started at the nozzle outlet.

§4.1.2. The droplets size distribution formed at the atomization point will not change during the whole spray process.

Due to this assumption, the interactions between droplets during the spray process are not considered. That is, the droplets maintain their size and do not disintegrate or coalesce in the spray region.

§4.1.3. The droplets travel in a linear trajectory towards the deposition surface. The motion of a spray droplet is mainly governed by the gravity

40

force, buoyancy force, and the drag force exerted on the droplet by the high velocity atomizing gas.

Due to this assumption, one can ignore the collisions between droplets, and any other force(s) exerted on the droplets during the spray process.

§4.1.4. A lumped droplet is considered in the whole spray process.

The temperature across the whole section of the droplet is considered to be the same, and the temperature gradient across the droplet radius is neglected. This assumption is reasonable because the droplets in the spray process are very small, and the value of the Biot number is very small, Bi < $0.1^{[34]}$. Specifically, the Biot number for the simulation cases reported in this thesis, was found to be less than 0.012.

§4.1.5. In the atomizing velocity profile, the momentum influence from the droplets to the atomizing gas is ignored.

In an actual spray process, there is an interaction between the atomizing gas and metal droplets. The momentum influence from metal droplets to the atomizing gas is exerted by the whole metal droplets spray. The spray in a real process is usually is comprised of a large number of droplets of different sizes. In this simulation study, the momentum and thermal history of a single droplet is calculated at each time step. It is a difficult undertaking if one wants to calculate the momentum influence of the droplets to the atomizing gas. So in this simulation study, an experimental relationship is used to describe the atomizing velocity profile, and the momentum influence from the droplets to the atomizing gas is disregarded.

§4.1.6. The thermal effect from droplets to atomizing gas is described with a fixed relationship.

The thermal effect from droplets to atomizing gas is very complicated, and it depends on many aspects, such as, the liquid metal flow rate, droplets size distribution, initial molten metal temperature, etc. In this numerical model, the momentum and thermal history of one size droplet have been tracked at a time, and without considering the droplet size distribution. It is very difficult to consider the total thermal effect from all of the droplets to atomizing gas. So it is assumed that the thermal effect from droplets to atomizing gas has a fixed relationship as follows ^[34]:

$$T_0 = T_{0f} - (T_{0f} - T_{0i}) \exp\left(-\frac{Z}{\alpha}\right)$$
(4-1)

where T_0 is the temperature of the atomizing gas. The above gas temperature expression states that its temperature decreases exponentially with the spray distance from the nozzle. In Eqn. (4-1), T_{0i} is the initial temperature of the atomizing gas. T_{0f} is the assumed final temperature of the atomizing gas. α is a constant, and Z is the spray distance from the atomizer.

§4.1.7. The cooling operation of the droplets during the spray process is caused by the effect of the convection heat transfer from atomizing gas to droplets and the radiation heat transfer from droplets to the surroundings.

The heat transfer coefficient changes for different droplets according to the size of the droplet and the relative velocity between the droplet and the atomizing gas. The heat exchange between droplets (for example, between large size droplets and small size droplets, between liquid droplets and solidified droplets) are disregarded.

§4.2. One-dimensional velocity profile of atomizing gas.

At room temperature, inert gas spurts out from atomizer with a very high velocity. The velocity of the gas decreases rapidly after it leaves the atomizer. This process is quite complicated and is beyond the scope of the study of this research. So in the present simulation study, the experimental results provided by Bewlay and Cantor^[37], and Grant and Cantor^[38] have been used. These investigators' studies resemble the spray situation that is present in the atomizing region of Osprey process. The above investigators provided the following expression for one dimensional velocity profile of atomizing gas:

$$v_{gz} = v_{g0} \exp\left(-\frac{Z}{\lambda}\right)$$
(4-2)

where :

$$\lambda = 3.04 \times 10^{-4} v_{o0}^{-1.24} \tag{4-3}$$

In Eqn.(4-2), v_{gz} is the axial gas velocity, v_{g0} is the initial gas velocity, λ is a exponential decay coefficient, and z is the axial position from the atomizer.

§4.3. One-dimensional velocity profile of metal droplets.

After the atomization process, once the droplet size distribution of the molten metal is established, these droplets are accelerated by the high velocity atomizing gas towards the deposition surface. In the spray region, there is a large quantity of small metal droplets. But for the convenience of the simulation, only a single droplet of a fixed size is considered each time in this simulation study. As assumed above, the droplets travel in a linear trajectory towards the deposition surface without changing size. The motion of a spray droplet is mainly governed by the resultant interactions of gravity force, buoyancy force, and the drag force exerted on the droplet by the high velocity atomizing gas. Except for

the above forces, other forces which might play a role on the droplet are disregarded.

The momentum equation for a droplet in the spray region can be simply written as follows:

$$\sum F = F_{gravity} + F_{bouyance} + F_{drag}$$
(4-4)

The total force exerted on the droplet will be balanced by the acceleration of the droplet:

$$\sum F = m_d \frac{dv_{dz}}{dt} = m_d g - m_g g + F_{drag}$$
(4-5)

or

$$\rho_{d}V\frac{dV_{dz}}{dt} = V(\rho_{d} - \rho_{g})g + \frac{AC_{drag}\rho_{g}(v_{gz} - v_{dz})U_{dg}}{8}$$
(4-6)

where

$$C_{drag} = 0.28 + \frac{6}{\sqrt{N_{\rm Re}}} + \frac{21}{N_{\rm Re}}$$
(4-7)

$$U_{dg} = |v_{dz} - v_{gz}| \tag{4-8}$$

$$N_{\rm Re} = \frac{D\rho_g U_{dg}}{\mu_g} \tag{4-9}$$

The symbols ρ_d and ρ_g signify the densities of the droplet and atomizing gas, respectively. V and A are the volume and surface area of the droplet respectively; v_{gz} and v_{dz} are the axial gas velocity and axial droplet velocity respectively; g is the gravity constant. C_{drag} is the drag coefficient; U_{dg} is the relative velocity

between atomizing gas and droplet; N_{Re} is Reynolds number; D is the droplet diameter and μ_g is the gas viscosity.

According to the literature^{[34], [39]}, the equation for the drag force C_{drag} is only applicable within the range of Reynolds number ($0.1 < N_{Re} < 4000$). If the droplet Reynolds number is beyond the above range, a special treatment is needed in the program to accommodate the change in Reynolds number.

§4.4. Thermal and solidification profile of metal droplets

After the atomization process, and once the droplet size distribution of the molten metal is established, these droplets will be cooled by the high velocity, room temperature atomizing gas surrounding the droplets as they travel towards the deposition surface. As assumed above, the heat loss from the droplet is mainly comprised of the convective heat transfer to the atomizing gas and radiation heat transfer to the surroundings.

During the calculations of the thermal history of the metal droplets, the following five stages are considered^{[34], [35]}:

(1), Cooling in liquid stage, which is defined as the time between the initial melting temperature and nucleation temperature;

(2), Recalescence stage, which is defined as the temperature increase as the result of nucleation;

(3), Segregated solidification stage, which is defined as the time period between the start of nucleation and until the peritectic temperature is reached;

(4), Peritectic solidification stage is defined as the time interval between the start of peritectic solidification until the droplet is fully solidified as the time interval.

(5). Cooling in the solid-state stage is defined between the time the solidification process is completed and the time needed for the droplet to reach to the deposition surface.

Depending on the droplet size, some of the droplets will experience the above mentioned five stages, and some others will only undergo a few of the above five stages.

§4.4.1. Undercooling of molten droplets

In Osprey process, we are dealing with very small droplets, and a very fast cooling process. According the some literature^{[34], []}, the cooling rate in the liquid state stage is in the magnitude of 1.37×10^3 K/s to 1.55×10^6 K/s depending on the size of the droplet and its initial condition. Under the high above cooling rate, under-cooling of the droplets has to be considered in the simulation process.

The maximum homogeneous undercooling ΔT_{hom} is calculated based on the following equation presented by Hirth ^[40] and Turnbull^[41]:

$$\Delta T_{\rm hom}^2 = \frac{16\pi\sigma_m^2 \Omega^2 T_L^2}{3k(T_L - \Delta T_{\rm hom})H_f^2 \ln[10^{44}V \Delta T_{\rm hom}/\dot{T}]}$$
(4-10)

where H_f is the latent heat of fusion, σ_m is the solid-liquid interface energy, Ω is the atomic volume of the metal, k is the Boltzmann's constant, T_L is the liquidus temperature, V is the volume of the droplet, and \mathring{T} is the cooling rate of the droplet in liquid state.

It is well accepted in the literature that it is heterogeneous nucleation instead of homogeneous nucleation which is dominated in the rapid cooling process^{[34], [35]}. Homogeneous nucleation may dominate in the situation for the cooling of very small size droplets, for example, when droplets diameter is less than 20 μ m. The reason for this may be: first, the cooling rate for smaller size droplets is much greater than bigger size droplets; second, the nucleation of smaller size droplets takes place at the position nearer to the atomizer, where the relative velocity of the atomizing gas and droplets is larger. This situation results in a higher convective heat transfer loss from droplet to the surrounding gas. But for larger size droplets, heterogeneous nucleation seems to be more closer to reality and hence heterogeneous nucleation is considered in the present simulation process.

So the actual undercooling should be much smaller then the theoretically calculated homogeneous undercooling ΔT_{hom} by the above mentioned equation. In the present simulation process, the experimental relationship of homogeneous undercooling ΔT_{hom} and heterogeneous undercooling ΔT_{actual} presented by Mathur et al.^[24] in the form of the following equation has been considered.

$$\Delta T_{actual} = \Delta T_{hom} \exp(-2.2 \times 10^{12} V)$$
(4-11)

With the above Eqns. (4-10) and (4-11), the actual undercooling for different size droplets can be determined, and consequently, the nucleation temperature for a certain size droplets can be calculated.

§4.4.2. Cooling in the liquid state stage:

When the molten metal flows out from the nozzle, it is in fully liquid state and the temperature of the molten metal is relatively high. High velocity and low temperature atomizing gas cools the molten metal droplets rapidly. From the

atomizing position to the distance when the nucleation will initiate in the droplet, the droplet is cooling in fully liquid state.

In this stage, the heat loss from the droplet to the environment is comprised of the convective heat loss by convection heat transfer to the surrounding atomizing gas, and radiation heat loss by radiation heat transfer to the environment or the inner wall of atomizing chamber. The energy balance for the droplet in this stage can be stated as the intern energy decrease of the droplet is balanced by heat loss by convection heat transfer and radiation heat transfer.

$$E = Q_{conv} + Q_{radi} \tag{4-12}$$

or

$$-\rho_d dV C_{pl} \frac{dT}{dt} = h(T - T_0)A + \varepsilon \sigma (T^4 - T_0^4)A$$
(4-13)

with

$$h = \frac{k_g}{D} \left(2 + 0.6 \sqrt{N_{\text{Re}}} \sqrt[3]{N_{\text{Pr}}} \right)$$
(4-14)

and

$$N_{\rm Pr} = \frac{\mu_g C_{pg}}{k_g} \tag{4-15}$$

where C_{pl} is the specific heat of the molten metal; ε is the emissivity of the droplet surface; σ is the Stephen-Boltzmann constant. h is the convection heat transfer coefficient; k_g is the thermal conductivity of the atomizing gas; N_{Pr} is the Prandtl number; μ_g is the viscosity of atomizing gas; C_{pg} is the specific heat of atomizing gas; T_0 is the temperature of the atomizing gas which is determined by equation [4-1]. Using Eqns. (4-12) to (4-15), one can trace the thermal history of a droplet in liquid state, and calculate the time when nucleation will begin.

§4.4.3. Recalescence stage:

Recalescence is the rapid temperature increase of an undercooled molten metal because of the rapid latent heat release due to the formation of solid nucleus in the liquid phase. A larger under-cooling of the molten metal will result in a greater recalescence. For Osprey process, since it is a rapid cooling process for very small size droplets, it will result in a great magnitude of undercooling in the droplets. So recalescence will play an important role in the development of thermal profile for small droplets in Osprey process.

Recalescence is a complicated metallurgical phenomenon in the solidification process of metal alloys. In this study, the temperature-enthalpy relationship presented by LI et. al. [.] has been used to calculate the temperature, and the solidified fraction inside the droplet after recalescence:

$$T_{r} = \begin{cases} T_{L} & \frac{H_{f}}{C_{ps}} + T_{N} > T_{L} \\ T_{N} + \frac{H_{f}}{C_{ps}} & \frac{H_{f}}{C_{ps}} + T_{N} \le T_{L} \end{cases}$$
(4-16)

$$H_{f}f_{r} = (T_{r} - T_{N}) \left[C_{pl} \left(1 - f_{r} \right) + C_{ps} f_{r} \right]$$
(4-17)

During the solidification of an alloy, recalescence is completed in a very short time interval. Some published scientific literature show that the time interval for the completion of the recalescence is in the order of less than 10^{-6} s^[34]. So in the present simulation program, one can safely consider that the recalescence is completed in one calculation time step Δt .

§4.4.4. Segregated solidification stage:

After recalescence, further solidification process takes place inside the droplet as a result the droplet temperature decreases. With the continuous cooling of the droplets by the atomizing gas the droplet temperature decreases until the peritectic temperature is reached. Segregated solidification process can be presented by the Scheil equation^{[42],[34]}, as follows:

$$(c_1 - c_s)df = (1 - f)dc_1$$
(4-18)

and it integrated form:

$$f = 1 - (1 - f_r) \left(\frac{c_l - 30}{c_0 - 30}\right)^{\frac{1}{k_e - 1}}$$
(4-19)

with:

$$k_e = \frac{c_s - 30}{c_l - 30} \tag{4-20}$$

where, c_0 , c_s and c_l are the initial, solid and liquid composition of the droplet respectively. And k_e is the coefficient of the equilibrium ratio. After transforming the above relationship in terms of temperatures, the following relationship is obtained:

$$f = 1 - (1 - f_r) \left(\frac{T_M - T}{T_M - T_L} \right)^{\frac{1}{k_e - 1}}$$
(4-21)

where f_r is solidified fraction in a droplet after recalescence; T_M is a reference temperature of the molten alloy and T_L is the liquidus temperature of the pure metal which is the base material of the molten alloy.

Using Eqn. (4-20), one can calculate the instant fraction of the solid part inside a droplet when the droplet is flying from the atomizing point to the collecting substrate.

The specific heat for the segregated solidification stage C_{pseg} comes from the composition of the liquid part, solid part, and the contribution of the latent heat released during solidification:

$$C_{pseg} = C_{pl} \left(1 - f \right) + C_{ps} f - H_f \frac{df}{dT}$$
(4-22)

The energy balance equation for the segregated solidification stage can be written as follows:

$$-\rho_d dV C_{pseg} \frac{dT}{dt} = h(T - T_0)A + \varepsilon \sigma (T^4 - T_0^4)A$$
(4-23)

§4.4.5. Peritectic solidification stage:

In segregated solidification stage, the temperature of the droplet degreases as solidification continues. After the temperature of the droplet reaches the peritectic temperature T_p , it remains at that temperature until the solidification of the droplet is completed. In the present simulation program, the solidified fraction increase inside the droplet is traced from the point when peritectic solidification begins (when f = f_P) to the point when the droplet is completely solidified (when f = 1).

In this stage, the temperature of the droplet does not change. The energy balance equation for the droplet takes into account the interval energy increase, caused by the latent heat release resulting from phase change of the liquid to the solid state, which is equal to heat losses by convection heat transfer and radiation heat transfer. The thermal energy balance equation is as follows:

$$\rho_d H_f V \frac{df}{dt} = h(T - T_0)A + \varepsilon \sigma (T^4 - T_0^4)A$$
(4-24)

§4.4.6. Cooling in the solid state stage:

After the solidification inside the droplet is completed, further cooling of the droplet is the cooling in the solid state. And the temperature of the droplet will decrease rapidly by the cooling of the atomizing gas and surroundings. The energy balance equation for this stage is similar to the energy balance equation for the stage, and the only difference is that the C_{pl} in equation (4-13) is replaced by C_{ps} , which is the specific heat of the metal alloy in solid state. So the thermal balance equation is as follows:

$$-\rho_d dV C_{ps} \frac{dT}{dt} = h(T - T_0)A + \varepsilon \sigma (T^4 - T_0^4)A$$
(4-25)

§4.5. The physical properties and conditions used in the simulation

§4.5.1. Material used for the simulation and its properties

The metal alloy used in this simulation process is ordered gamma titanium aluminide (γ -TiAl) intermetallic with the component of Ti-48 at.% Al. Gamma titanium aluminide is a novel metal alloy which is newly introduced into commercial use for the replacement of some superalloys in some critical applications. γ -TiAl alloy possess some unique properties, such as, low density, good creep and stress rupture and fatigue resistance, high strength-to-weight ratio, good high temperature strength, high stiffness and strength, and good oxidation resistance. These unique properties allow it find applications in some

critical place, such as, in aircraft turbine engines, airframes, and automotive parts, etc^[34].

Some physical properties of the γ -TiAl alloy used in the simulation are listed in table 4-1.

Parameter	Value	Source
C _{pl}	829 J/kg K	Ref. ^[34]
C _{ps}	727 J/kg K	Ref. ^[34]
H _f	28.27 kJ/mol	Ref. ^[34]
μ _m	3.6 x 10 ⁻³ kg/m s	Ref. ^[34]
ρd	3636 kg/m ³	Ref. ^[34]
Т	1885 K	Ref. ^[43]
ΤL	1785 K	Ref. ^[43]
Тм	2016 K	Ref. ^[43]
Τ _Ρ	1764 K	Ref. ^[43]
σ _m	203.4 x 10 ⁻⁶ kJ/m ²	Ref. ^[34]
Ω	2.08 x 10 ⁻⁵ m ³ /mol	Ref. ^[34]

Table 4-1. Physical properties of the γ -TiAl alloy

§4.5.2. Atomizing gas used for the simulation and its properties

Atomizing gas has three main functions in Osprey operation: first, it atomizes metal alloy from liquid metal stream into droplet spray in a proper droplet size distribution; second, exhausting heat from high temperature droplets for providing the condition for the solidification of the droplets; third, providing a protecting environment for the droplet for preventing it contacting with harmful environment atmosphere.

During the selection of an atomizing gas, one should consider the following two factors: first, the atomizing gas itself should not react with the molten metal alloy; second, the atomizing gas should provide a protection environment for the droplets spray. Nitrogen and Argon are usually the preferred choices as atomizing gas in Osprey process.

In the present simulation study, Argon is selected as the atomizing gas. Some physical properties of Argon are listed in table 4-2.

C_{pg} 518.8 J/kg K Ref. ^{[44], [34]} μ_g 1.7 x 10 ⁻⁵ kg/m s Ref. ^{[44], [34]} ρ_g 1.654 kg/m ³ Ref. ^{[44], [34]}	Parameter	Value	Source	<u> </u>
$\begin{array}{c} \mu_{g} & 1.7 \ x \ 10^{-5} \ \text{kg/m s} & \text{Ref.} \ ^{[44], \ [34]} \\ \rho_{g} & 1.654 \ \text{kg/m}^{3} & \text{Ref.} \ ^{[44], \ [34]} \end{array}$	C _{pg}	518.8 J/kg K	Ref. ^{[44], [34]}	
ρ _g 1.654 kg/m ³ Ref. ^{[44], [34]}	μ _g	1.7 x 10 ⁻⁵ kg/m s	Ref. ^{[44], [34]}	
	ρ _g	1.654 kg/m ³	Ref. ^{[44], [34]}	
K _g 0.01636 W/m K Ref. ^{[44], [34]}	Kg	0.01636 W/m K	Ref. ^{[44], [34]}	

Table 4-2. Physical properties of Argon

§4.5.3. Other conditions and parameters used for the simulation

Some other conditions and parameters used in the simulation process are listed in table 4-3. T_{0i} is the initial temperature of the atomizing gas; T_{0f} is the assumed final temperature of the atomizing gas; α is a constant for the calculation of the instant temperature of atomizing gas; v_{g0} is the initial velocity of atomizing gas; v_{envir} is the assumed velocity of the environment air; ε is the assumed emissivity of the metal droplets.

54

Parameter	Value	Source
T _{0i}	273 K	Ref. ^{[44], [34]}
Т _{оf}	473 K	Ref. ^{[24], [34]}
α	0.1 m	Ref. ^{[45], [34]}
V _{g0}	150 m/s	Ref. ^[34]
Venvir	0.004 m/s	Ref. ^[34]
З	0.5	Ref. ^{[39], [34]}

Table 4-3. Other conditions and parameters used for the simulation

CHAPTER 5:

RESULTS AND DISCUSSION

§5.1. One-dimensional velocity profile of atomizing gas and metal droplets.

§5.1.1. One-dimensional velocity profile of atomizing gas



Fig. 5-1. Axial atomizing gas velocity vs. spray distance.

Figure. 5-1 shows the axial atomizing gas velocity along the spray distance. From this figure, one can find out that the velocity of atomizing gas decreases rapidly from its initial velocity of 150 m/s after it spurt out of the atomizer. At the spray distance of 0.2 m and 0.4 m, the gas velocity decreased to 40.2 m/s and 10.8 m/s, respectively. At the spray distance of 0.8 m, the gas velocity decreased to almost zero (0.8 m/s). So the kinetic energy influence from the atomizing gas to the metal droplets is mainly in the beginning of the spray process.





Fig. 5-2. Axial velocity of metal droplets with different droplet size vs. spray distance (droplet size unit: μm)

Figure. 5-2 shows the axial velocity of metal droplets for different droplet sizes along the spray distance. From this figure, one can find out that, for all metal droplets, the axial velocity increase rapidly when the atomizing gas impinges onto the metal stream. After a short flying distance, the axial velocity of the droplets reaches to the maximum, and then they start to decrease. The maximum velocity for small size droplets is much higher than bigger size droplets. Table 5-1 shows the maximum velocities of different droplet sizes and the axial positions where the maximum velocities are reached.

Droplet size	Maximum velocity	Flying distance for reaching the
(μm)	(m/s)	maximum velocity (m)
20	90.56	0.077
80	52.86	0.165
180	37.65	0.217
300	30.16	0.258
500	24.10	0.308

Table 5-1 Maximum velocity for different droplet size

For small size droplet, the maximum velocity of the droplet is reached quickly, and then its velocity decreases rapidly. For the droplet with size 20 μ m, at the flying distance of 0.5 m, its velocity decreases to 7.12 m/s. Although for bigger size droplets, the maximum velocity of the droplet is achieved relatively slowly, but its velocity also decreases slowly. For the droplet of 300 μ m size, at the flying distance of 0.8 m, its velocity is still at 24.75 m/s.

Figure 5-3, shows the axial velocity of atomizing gas and velocity of metal droplets of different droplet sizes, along the spray distance. One can find out from this figure that, the droplets reach their maximum velocity at the point when atomizing gas velocity is almost equal to the droplets velocity. This reveals that in

Eqn. (4-6), the drag force term, $\left(\frac{AC_{drag}\rho_g(v_{gz}-v_{dz})U_{dg}}{8}\right)$, is dominated in this equation, and the gravity force and buoyancy force term, $(V(\rho_d - \rho_g)g)$, has only a small influence on the changes of the droplet velocity.

59



Fig. 5-3. Axial velocity of atomizing gas and metal droplets with different droplet size vs. spray distance (droplet size unit: μ m)

§5.2. One-dimensional Thermal and solidification profile of metal droplets.

§5.2.1. One-dimensional Thermal and solidification profile of metal droplets of 20 μ m.

Figure. 5-4 shows the calculated thermal history and solidification profile of metal droplets of 20 μ m diameter. From Fig. 5-4, one can clearly identify four different thermal regimes.
The first section is cooling in liquid stage. The small molten droplet is cooled very rapidly, and undergoes very large undercooling. This is due to the fact that, at the beginning of the atomizing process, the temperature difference between the atomizing gas and the metal droplets is quite high.. The cold atomizing gas gives an intensive cooling to the high temperature molten metal droplets. This intensive cooling causes the liquid metal droplets to go into an undercooled state.



Fig. 5-4. The temperature of droplet with droplet size of 20 μ m vs. spray distance

The temperature of the liquid droplet of 20 μ m size can reach to 1316 K before the nucleation starts in the droplet.

61

The second region is the recalescence stage section. In this period, the temperature of the droplets increases sharply in a very small time span, as has been indicated before. In the present calculations, recalescence is considered to have occurred in one time-step (10^{-5} s) used in the simulation program. This is due to the onset of nucleation inside the droplet, and this resulted in the release of latent heat and consequently has led to recalescence. This action happened more rapidly in the droplet than the cooling action of the spray gas, so the temperature of the droplet increases during this stage. The temperature of the droplets of 20 μ m size can reach to 1785 K after recalescence.

The third stage is the segregated solidification regime. In this stage, the solidification takes place and the solidified fraction increases inside the droplets until the droplet is fully solidified. In the present calculations, the peritectic solidification stage is hardly identified in Fig. 5-4.

The fourth stage is period where the cooling of the solidified droplet takes place. Figure 5.1 shows that the solidification processes are finished in almost all the droplets, so the temperature of the droplets decrease rapidly until it reaches to the temperature of the atomizing gas. After that, the temperature of the droplets remains unchanged to any further flight distance.

In Fig.. 5-4, one can easily notice that for metal droplet of 20 μ m size, the flight distances from the atomizing point to the nucleation point and the fully solidified point are very short. Present calculations show that, the distance from the atomizing point to the nucleation point is 0.033 m, and the distance from the atomizing point to the fully solidified point is 0.055 m. From these calculations, one can easily identify that, in a real Osprey operation, the metal droplet of 20 μ m size will deposit in fully solidified state on to the collecting substrate. The comparison of the flight distances from the atomizing point to the nucleation point atomizing point to the nucleation from the atomizing point at the flight distances from the atomizing point to the nucleation point and the fully solidified point for different droplet sizes are listed in table 5-3.

§5.2.2. One-dimensional thermal and solidification profiles of metal droplets of 80 μ m.

Figure. 5-5 shows the calculated thermal history and solidification profile of metal droplets of 80 μ m in diameter. Similar to Fig. 5.4, one can clearly identify four different stages from Figure. 5-5.

The first stage, cooling in liquid stage section, takes longer time than for the case of droplets of $20 \ \mu m$. This is because, the cooling speed is lower in the case for droplets of 80 μm . Under-cooling can be clearly identified also, even though it is



Fig. 5-5. The temperature of droplet with droplet size of 80 μ m vs. spray distance

not as big as that in the case for droplets of 20 μ m. The temperature for the liquid droplets with the size of 80 μ m can reach to 1538 K before the nucleation starts in the droplet.

In the recalescence stage, the recalescence process takes place within one time step employed in the simulation, and the temperature of the droplet after recalescence increases to 1785 K. In this case, recalescence is seen to start at 0.184 meter from the atomization point.

The third stage for droplet of 80 μ m is also dominated by the segregated solidification stage and the peritectic solidification stage which can also hardly be identified. The distance from the atomization point to the fully solidified point is found to be 0.354 meter.

The cooling curve in the solid stage section for the droplet of 80 μ m is not as steep as that for the droplet of 20 μ m because the cooling speed is lower for the droplet of 80 μ m size. It takes a longer time for the larger droplets to reach to the environment temperature. In a real Osprey practice, the 80 μ m droplets will be deposited on to the collecting surface in fully solidified state or almost fully solidified state.

§5.2.3. One-dimensional Thermal and solidification profile of metal droplets of 180 μ m.

Figure. 5-6 shows the calculated thermal history and solidification profile of metal droplets of 180 μ m. The nature of the thermal curve for the droplets of 180 μ m is quite different from that for the droplets of 20 μ m and 80 μ m. In Figure 5-6, only three stages prevail. The droplet undergoes an undercooling of 1 K, and the undercooling and recalescence can hardly be identified from the thermal history curve of the droplet.

In Figure 5-6, the first section represents the cooling of liquid droplet. The second portion of the curve denotes the segregated solidification stage and the peritectic solidification phase. The solidification process takes much longer time from the start of nucleation to fully solidified state because of its bigger size. The initiation spray distance for nucleation seems to be around 0.053 meter from the atomization point, and the droplet is fully solidified within 0.59 meter from the atomization point.



Fig. 5-6. The temperature of droplet with droplet size of 180 μ m vs. spray distance

It is quite interesting to note that the distance from atomizing point to the starting point for nucleation for 180 μ m droplet is much shorter than that for droplet of 80 μ m, which are 0.053 meter and 0.184 meter, respectively.

The reason for this seems lie in the difference in the degree of undercooling for the two different droplet sizes. For 80 μ m droplets after undercooling, the nucleation temperature is 1538 K. It takes longer time to reach this temperature. But for 180 μ m droplets, after undercooling, the nucleation temperature is 1784 K. It takes much shorter time to reach this temperature.

The third section of the cooling curve represents the solidification of droplet. Because of its bigger droplet size, the cooling speed is slower. The droplet temperature at a distance of 1.2 m from the atomizing point is still 926 K.

§5.2.4. One-dimensional thermal and solidification profile of metal droplets of 300 μ m diameter.

Figure 5-7 shows the calculated thermal history and solidification profile of 300 μ m metal droplets. The trend of the cooling curve style for this size of droplets is similar to the cooling curve for the droplets of 180 μ m size. The major difference between these two is that, the second section, the segregated solidification period, for droplets of 300 μ m is much longer than that for the droplets of 180 μ m. This is easily anticipated since under identical thermal environment, bigger size droplets take longer time to complete their solidification process.

No undercooling and recalescence phenomenon can be observed in Fig. 5-7. For the droplets of 300 μ m, the nucleation seems to start at about 0.134 meter from the atomization point. It is still shorter than the distance for the 80 μ m droplets. This is because the undercooling delays the nucleation process for the 80 μ m droplets.

The 300 μ m droplet is fully solidified at about 1.044 meter from the atomization point. This distance is generally considered a bit long for the real Osprey process. It means that in the real Osprey practice, the 300 μ m droplets will be deposited onto the collecting substrate in a mushy state, that is, the droplet will be a mixture of liquid and solid phases, but will predominantly consists of the liquid phase. The droplet temperature at a distance of 1.2 meter from the atomizing point is still high and remains at1485 K.



Fig. 5-7. The temperature of droplet with droplet size of 300 μ m vs. spray distance

§5.2.5. One-dimensional thermal and solidification profile of metal droplets of 500 μ m diameter.

Figure 5-8 shows the calculated thermal history and solidification profile of 500 μ m metal droplets. The nature of the cooling curve for the droplets in the size of 500 μ m is much different from that for the other smaller size droplets. There is only two sections in the cooling curve as seen in Fig. 5-8, namely cooling in liquid stage section and segregated solidification stage section.

Similar to 300 μ m droplet, no undercooling and recalescence phenomenon can be observed in Fig. 5-8. For the droplets of 500 μ m, the nucleation starts at about 0.395 meter distance from the atomization point. After that point, it is the



Fig. 5-8. The temperature of droplet with droplet size of 500 μ m vs. spray distance

segregated solidification stage section. The vertical calculation domain for the simulation is 1.2 meters. From this figure it is seen that at 1.2 meters from the atomization point the segregated solidification process is not completed. It means that, at the distance of 1.2 meters from the atomization point, the solidification of the 500 μ m droplet is incomplete and the droplet remains in the state of partially liquid and partially solid.

§5.2.6. Comparison of one-dimensional thermal and solidification history of metal droplets with different droplet sizes.

Table 5-2 shows the droplets' temperatures after undercooling for droplets of various sizes. Since the liquidus temperature for γ -TiAl alloy is 1785 K, the undercoolings for the droplets in the size of 20 μ m and 80 μ m are more than 469 K and 247 K, respectively. But there is no undercooling for the droplets in the size of 300 μ m and 500 μ m.

Table 5-2. Droplets temperature after undercooling for various size droplets

Droplet size	Droplets temperature after undercooling
(μ m)	(К)
20	1316
80	1538
180	1784
300	-
500	-

Droplet size	Flying distance	Flying distance
(μm)	at nucleation point (m)	at fully solidified point (m)
20	0.033	0.055
80	0.184	0.354
180	0.053	0.594
300	0.134	1.044
500	0.395	-

Table 5-3. The nucleation initiation distance and fully solidified distancefor different size droplets in the spray trajectory.

Table 5-3 shows the nucleation initiation distance and fully solidified distance for different size droplets along the axis of the spray field. Combining the numerical values of table 5-2 and table 5-3, one can clearly observe the influence of the undercooling of the droplets onto the flying distance of the starting point of nucleation from the atomization point.

Since the present calculations ended at 1.2 m from the atomization point, the bigger size droplets are still in the partially liquid and partially solid state. Thus the flying distance from the atomization point where the bigger droplets will be fully solidified is beyond the present calculation domain and cannot be obtained by extrapolating the thermal curves for bigger droplets.

Table 5-4 shows the droplets' temperatures at different flying distances for different droplet sizes. From this table, one can notice that, at the same position, the droplet temperatures for different droplet sizes are quite different. For example, at the flying distance of 0.4 meter from the atomizing point, the droplet

500

temperature for the droplet size of 20 μ m is only 470 K, and the droplet temperature for the droplet size of 80 μ m is around 1459 K, but the droplet temperature for the droplet size of 300 μ m remains as high as 1781 K,

Droplet size	Droplet temperature at flying	Droplet temperature at flying
(μm)	distance of 0.4 m (K)	distance of 1.0 m (K)
20	470	474
80	1459	562
180	1773	1068
300	1781	1766

1785

Table 5-4. Droplet' temperature at different flying distancefor different droplet size..

Fig. 5-9 illustrated the states of droplets in different positions for different droplet sizes. In this figure, dash line represents the liquid state; thick solid line represents the partially liquid and partially solid state; and the dotted line represents the solid state.

1778



Fig. 5-9. The state of droplets in different position for different droplet size

CHAPTER 6: CONCLUSIONS

CHAPTER 6:

CONCLUSIONS

Through the momentum and thermal balances of the flying spray of droplets and using the numerical analysis, the following objectives were achieved concerning the process of Osprey technology:

- 1. Established one dimensional models for atomizing gas velocity (momentum) profile, metal droplets velocity (momentum) profile, and droplets thermal and solidification history profiles.
- The velocity of atomizing gas decreases in an exponential manner and it falls rapidly from its initial velocity of 150 m/s after it spurt out of the atomizer. At the spray distance of 0.8 m, the gas velocity decreased to almost zero (0.8 m/s).
- 3. The maximum velocity for a small size droplet is much higher than for a bigger size droplet. For the droplet of size 20 μ m, the maximum velocity can reach to 90.56 m/s within a flying distance of 0.077 m. For the droplet with size 300 μ m, the maximum velocity is only 30.16 m/s at the flying distance of 0.258 m.
- 4. For the metal droplets of 20 μm diameter, a total of four different thermal stages could be identified from the thermal and solidification profiles. For this size droplets, a large under-cooling appeared, and the temperature of the liquid droplets can reach to 1316 K after undercooling. The flying distance from the atomizing point to the nucleation point is found to be 0.033 m. And the distance from the atomizing point to the fully solidified point is calculated to be 0.055 m.
- 5. For the 80 μ m size metal droplets, four different thermal stages also were dentified from the thermal and solidification profiles. The droplets went

through an under-cooling, and the temperature for the liquid droplets is seen to reach to 1538 K after undercooling. The distance from the atomizing point to the nucleation point is seen to be 0.184 m. And the distance from the atomizing point to the fully solidified point is 0.354 m.

- 6. For the metal droplets of 180 μm size, only three different thermal stages could be identified from the thermal and solidification profiles. The calculated undercooling is only 1K, and the actual extent of undercooling and recalescence could hardly be identified in the thermal history curve. The distance from the atomizing point to the nucleation point is 0.053 m. And the distance from the atomizing point to the fully solidified point is 0.594 m.
- 7. For the metal droplets in the size of 300 μ m, there are also only three different thermal stages on the thermal and solidification profiles. Neither an undercooling nor the recalescence phenomenon could be observed in the thermal history curve. The distance from the atomizing point to the nucleation point is 0.134 m. And the distance from the atomizing point to the fully solidified point is 1.044 m.
- 8. For the metal droplets in the size of 500 μm, only the cooling in the liquid stage and the segregated solidification stage could be identified from the thermal and solidification profiles. Neither an undercooling nor the recalescence phenomenon could be observed in the thermal history curve. The distance from the atomizing point to the nucleation point is 0.395 m. And the distance from the atomizing point to the fully solidified point is beyond the limit of the present calculation domain which was fixed at 1.2 m.

CHAPTER 7: SUGGESTIONS FOR FUTURE WORK

CHAPTER 7

SUGGESTIONS FOR FUTURE WORK

CHAPTER 7: SUGGESTIONS FOR FUTURE WORK

The present model of the Osprey process considers heat transfer and solidification of the droplets. The model is based on transient one-dimensional momentum and heat transfer between a droplet and the inert atomizing gas. A number of improvements of the model are suggested below:

- 1. In order to model a more realistic situation prevailing in Osprey process, the one-dimensional transient momentum and heat transfer model for the droplets should be extended to a two-dimension model.
- Instead of prescribing the axial velocity profile of the atomizing gas, the gas velocity profile should be calculated based on the 2-D Reynolds averaged turbulent momentum equations for the gas phase.
- 3. The model should be extended and consider simultaneously not only the thermal history of the in-flight droplets but also deposition and solidification of the droplets on the substrate.
- 4. In an actual Osprey process, substrates are generally slowly rotated to produce performs with uniform properties. The model should take this into account to make the model more useful to the practitioners of the field. The size and shape of the substrate should also be taken into account.
- 5. In order to render the model more useful in its predictions, instead of tracking a droplet of fixed size, the model should simultaneously track multiple droplets of various sizes and should also take into account the interactions among the droplets and the surrounding gas.

CHAPTER 7: SUGGESTIONS FOR FUTURE WORK

6. During the solidification process, there could develop microsegregation within the droplets in flight. The solidification model should be extended and incorporate microsegregation

REFERENCES

- 1. A.R.E.Singer, Metals and Materials, pp. 246 257, June 1970.
- E.J.Lavernia and N.J. Grant, Materials Science and Engineering, Vol. 98, pp. 381 – 384, 1988.
- Zhong Guisong, Shi Likai and Liu Gang, Real Metals, Vol.19, No. 1, pp. 22 – 26, 1995.
- 4. A.G.Leatham, A.J.W.Ogilvy and P.F.Chesney, Modern Development in Powder Metallurgy, vol. 19, pp. 475 488, 1988.
- L.Cottignies, Y.Brechet, Maudier, F.Livet, F.Louchet and P,Sainfort, Journal De Physique IV, Colloque C7, Supplement au Journal de Physique III, Vol. 3, Nov., pp. 215 – 218, 1993.
- R.G.Brooks, A.G.Leatham and J.S.Coombs, Osprey Metals Ltd., and C.Moore, BOC Ltd., Metallurgia & Metal Forming, pp. 157 – 163, April 1977.
- 7. G.M.Bedford, R.P.Sharp, B.J.Wilsong, and L.G.Elias, Surface Engineering, Vol. 10, No. 2, pp. 118 – 121, 1994.
- A.G.Leatham, Second international Conference on Spay Forming, pp. 129 – 139, 1993.
- 9. E.J.Lavernia and E.Gutierrez-Miravete, Casting of Near Net Shape Products, The Metallurgical Society/AiME, pp. 275 – 295, 1988.
- 10.S.Connelly, J.S.Coombs and J.O.Medwell, Metal Powder Report, Vol. 41, pp. 653 661, 1986.
- 11. A.R.E.Singer, Metal Powder Report, Vol. 41, No. 2, pp.109 -115, 1986.
- R.W.Evans, A.G.Leatham, and R.G.Brooks, Powder Metallurgy, Vol. 28, No. 1, pp. 13 – 20, 1985.
- 13. A.R.E.Singer and S.Ozbek, Powder Metallurgy, Vol. 28, No. 1, pp. 72 78, 1985.
- 14. A.G.Leatham et al., Metals and Materials, p. 140, 1989.
- 15. A.R.E.Singer, Metal Powder Report, Vol. 41, No. 3, pp. 223 226, 1986.
- E.J.Lavernia G.Rai and N.J. Grant, Materiails Science and Engineering, Vol. 79, No. 2, pp. 211 -221, 1985.

- A.G.Leatham and A.Lawley, The International Journal of Powder Metallurgy, Vol. 29, No. 4, pp. 321 – 329, 1993
- 18. Y. Ikawa, T.Itami, K.Kumagai, Y.Kawashima, A.G.Leatham, J.S.Coombs and R.G.Brooks, ISIJ International, Vol. 30, No. 9, pp. 756–763, 1990.
- 19. E.J.Lavernia and N.J. Grant, Metal Powder Report, Vol. 4, 255 -260, 1986.
- SURESH Annavarapu, DIRAN Aperlian and ALAN Lawley, Metallurgical Transactions A, Vol. 21A, pp. 3237 – 3256, Dec. 1999.
- 21. E.J.Lavernia, E.M.Gutierrez, J.Szekely and N.J.Grant, International Journal of Rapid Solidification, Vol. 4, pp. 89 124, 1988.
- N.Muhamad, J.O.Medwell, and D.T.Gethin, Powder Metallurgy, Vol.38, No. 3, pp. 214 –220, 1995.
- 23. E. Gutierrez-Miravete, E.J. Lavernia, G.M.Trapaga, J. Szekely, and N.J. Grant, Metallurgical Transactions A, Vol. 20A, pp. 71 85, January 1989.
- 24. P. Mathur, D. Apelian and A. Lawley, Acta Metall., Vol. 37. No. 2, pp. 429 - 443, 1989
- C.G. Levi and R. Mehrabian, Metallurgical Transactions A, Vol. 13A, pp.
 221 234, Feb. 1982.
- 26. Q. Xu and E.J. Lavernia, Scripta Materialia, Vol. 41, No. 5, pp. 535-540, 1999.
- 27. A.K.Srivastava, S.N.Ojha and S.Ranganathan, Journal of Materials Science, Vol. 36, pp. 3335-3341, 2001.
- Yizhang Zhou, Steven Lee, Vincent G.McDonell, Scott Samuelsen, Robert L Kozarek, and Enrique J.Lvernia, Metallurgical and Materials Transactions B, Vol. 29B, pp. 793-806, Aug. 1998.
- 29. Q.Xu, R.W.Hayes, W.H.Hunt JR and E.J.Lavernia, Acta Mater., Vol. 47, No.1, pp. 43-53, 1999.
- Y.Y.Zhou, M.H.Jacobs, and A.L.Dowson, Metallurgical and Materials Transactions B, Vol. 29B, pp. 1357-1369, Dec. 1998.
- 31. M.J. Aziz, J. Appl. Phys. Vol. 53, No. 2, pp.1158-1168, Feb.1982.

- 32. P. Shukla, N.S. Mishra, and S.N.Ojha, Journal of Thermal Spray Technology, Vol. 12, No. 1, pp. 95-100, March 2003.
- S.M. El-Haggar, N. Muoio and C.T. Crowe, AIChE SYMPOSIUM SERIES, Heat Transfer – Portland, No. 306, Vol. 91, pp. 111-116, 1995.
- 34. B. Li, X. Liang, J.C. Earthman and E.J. Lavernia, Acta Mater. Vol. 44, No.6, pp. 2409-2420, 1996.
- 35. Dirk Bergmann, Udo Fritsching, Klaus Bauckhage, Int. J. Therm. Sci., Vol. 39, pp. 53-62, 2000.
- 36. Udo Fritsching, Spray Simulation, Cambridge University Press, 2004
- 37. B.P. Bewlay and B. Cantor, Metallurgical Transactions, 21B, p. 899, 1990.
- 38. P.S. Grant and B. Cantor, Cast Metals, Vol. 4, p. 140, 1991.
- H. Liu, R.H. Rangel and E.J. Lavernia, Material Science Engineering, Vol. 191A, p. 171, 1995.
- 40. J.P. Hirth, Metall. Trans. Vol. 9A, p. 401, 1978.
- 41. D. Turnbull, J. Chem. Phys. Vol. 20, p. 411, 1952.
- 42. E. Scheil, Zeitschrift fur Metallkunde, Vol. 34, p. 70, 1942.
- 43. Y.W. Kim and D.M. Dimiduk, JOM, Vol. 43, No. 8, p 40, 1991.
- 44. E.M. Gutierrez, E.J. Lavernia, G.M. Trapaga, J. Szekely and N.J. Grant, Metall. Trans., Vol. 20A, p. 71, 1989.
- 45. P.S. Grant, B. Cantor and L. Katgerman, Acta Metall. Mater., Vol. 41, p. 3097, 1983.
- S.P. Lin, Break-up of Liquid Sheets and Jets, Cambridge University Press, Chapter 7, pp. 116 – 125, 2003