PROCESSING FROM THE LIQUID STATE

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Summary

Processing from the liquid state is an integral stage in the production of most materials and components. Many components usually referred to as castings, receive their final shaping from the liquid state. Upon cooling of the molten material, it transforms into a

solid that can either be crystalline or non-crystalline. Crystallisation occurs by a process of nucleation and growth, while these mechanisms are suppressed when a non-crystalline material forms. The crystallisation process has significant impact on the rheological properties of the semi-solid material and these properties control the response of the material to stresses developed or applied during casting and therefore have significant impact on the formation of defects. Defects may impair the properties of the product, even making them unsuitable for certain applications.

Several techniques exist commercially for controlled processing from the liquid state. For metals, these are termed casting processes. These can be continuous or semi-continuous for the production of semi-finished products at high productivity and low cost, or they are aimed at net-shape production of castings.

1. Introduction

Most materials, particularly metals, are processed from the liquid state at some stage in their production route. Many metals are produced in smelting operations in which the metal is extracted from the ore as a liquid. Most recycling operations also remelt the input feedstock to produce a larger mass of material. Liquid processing operations therefore nearly always precede other manufacturing operations, for example mechanical forming. A liquid material contains much more heat than a solid material and therefore liquid forming processes rely on the controlled extraction of heat. During the cooling process the liquid is transformed into a solid with a certain size, shape and structure. The advantage of shaping with a liquid material is that it has high formability because of the low strength and viscosity of molten materials compared with solids. Components with complicated shapes can therefore be easily manufactured. Furthermore the presence of a material in the liquid state allows for control of its composition (the mixture of elements) and alloys are therefore almost always produced in the liquid state.

Liquid forming operations are commonly termed casting processes, and cooling of the liquid causes a transformation into a solid by a process termed solidification. Solidification results in a solid material that is either crystalline or non-crystalline (amorphous or glassy), and it is the solidification process that governs the properties of the final solid product. Because solidification is an integral part of most fabrication processes it is very important to control the solidification process so as to optimise the material's structure. The structure governs the properties that can finally be achieved. For example, defects formed during solidification are difficult to eliminate and can remain in the material throughout the manufacturing process.

Historically it is thought that mankind first processed materials from the liquid state in the period between 5000 and 3000 BC, and quite advanced lost wax casting of copper began in the Bronze Age. With the discovery of new metals and alloys, new techniques were developed and refined. A wide range of techniques is now available to process materials from the liquid state. They differ widely in their size, capacity, capital and operating cost, energy and personnel requirements, and in the degree of control required to produce a suitable product. Although casting processes have existed for many millennia, their development is still continuing and new techniques are being invented.

The main materials processed from the liquid state include metals and alloys, polymers and glassy ceramics.

A division can be made between casting techniques that produce a semi-finished product and those where casting represents the final shaping process. We have chosen to use the above two categories to separate the different casting processes. Casting techniques used for metals and metal alloys are presented in the section on processing methods, although the general principles discussed can be applied to all materials taking into account their inherent characteristics and manufacturing objectives. This article begins with a description of the principal mechanisms involved in controlling liquid processing methods, before a more detailed description and discussion of different manufacturing processes is given.

2. Liquid State

The liquid state is one of the three basic states of matter, the others being gas and solid. A material is liquid when the temperature is between the melting point and the boiling point. In the liquid state there is only short-range order, and the atoms or molecules or ions are in continuous random motion. Liquids takes up the shape of their container. The ability of the liquid to flow, ie. its response to a shear stress, is described by its viscosity. Pure materials melt and solidify at a single temperature.

When a material consists of more than one element (ie. an alloy), such as most engineering materials, there is not a definite melting point. The material instead melts over a range of temperatures in which both solid and liquid coexist and where the fraction of solid increases with decreasing temperature. This is often called the freezing range, or the mushy zone, and can vary from only a few degrees, to several hundred degrees in some alloys. The viscosity in this temperature range therefore increases with decreasing temperature as the fraction of solid increases. The thermal and physical properties of the liquid are generally different from those of the solid state.

Molten metals, such as aluminium and magnesium, react quite easily with oxygen in the atmosphere. The surface of the liquid towards the atmosphere will therefore consist of a thin layer of oxide. When the surface film on the liquid is broken, the exposed metal will rapidly react and reform the continuous protective oxide layer. However, the presence of the oxide film has been suggested to represent a problem if not properly controlled. This is discussed further in Section 3.5.1 on Porosity.

One advantage of the liquid state is the ease of forming because of the low viscosity. Complicated shapes can therefore be made with relative ease and at a low cost. Furthermore it is relatively easy to mix materials in the liquid state to produce materials with specifically tailored compositions.

3. Fundamentals of Processing from the Liquid State

In order to understand characteristics of the range of liquid processing or casting technologies and the differences between them it is necessary to consider the objective of each casting method. Generally a manufacturing operation is chosen because of its cost per item and whether it can generate a product with the desired characteristics such as size, shape and properties. The properties of the final product are generally determined by the internal structure (microstructure) of the product, and this structure is strongly dependent on the material composition, processing method and processing conditions. This is described further in the following sections.

3.1. Heat Flow

When a liquid, or molten, material is cast, the extraction of heat from the material occurs through a series of different media. One or a combination of these media are quite frequently the rate-limiting step of the process. The thermal resistances that are involved are: a) across the fully liquid zone, b) across the solidifying metal, c) the metal-mould interface, d) across the mould, e) the mould-air interface. The heat extraction rate often controls the productivity of the production process and varies significantly between different casting methods. The cooling rate of the metal is very important for controlling the internal structure of the product and therefore has a major impact on the mechanical properties, such as strength and ductility. Heat transfer may occur by conduction, convection and radiation and the significance of each depends on the casting technique used.

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Biographical Sketches

Dr Arne K. Dahle has a MSc and PhD in Metallurgy from the Norwegian University of Science and Technology in Trondheim, Norway. From 1997 he has been a Lecturer and now Senior Lecturer in Solidification Technology in the Department of Mining, Minerals and Materials Engineering at the University of Queensland. He is also involved in the Co-operative Research Centre for Cast Metals Manufacturing (CAST). His major research interest is the solidification and casting of light metals and he has published about 90 international journal and conference papers in the areas of casting, solidification and castability of aluminium and magnesium alloys. A particular research interest is the understanding of the mushy zone and its effects on casting defect formation. He is the youngest ever recipient of the prestigious dr.ing. Mathias Sems honours prize from the Norwegian Metallurgical Society in Norway.

Professor David StJohn has a BSc (Hons) and PhD in Physical Metallurgy from the University of Queensland in Brisbane Australia. From 1994 he has held a Chair in Solidification Technology at the University of Queensland and is also Research Program Leader in the Co-operative Research Centre for Cast Metals Manufacturing (CAST). Prior to this he was Manager Materials Technology, CRA - Advanced Technical Development, Perth from 1989, Lecturer and then Senior Lecturer, Department of Mining and Metallurgical Engineering, University of Queensland from 1986 and Lecturer, Department of Metallurgical Engineering, RMIT, Melbourne from 1983. He is currently on the Editorial boards of the International Journal of Cast Metals Research, Materials Forum and Journal of Light Metals. His major research interests are in the solidification and phase transformation processes in light alloys. In particular, the interaction between solidification and casting and forming processes, and the resultant development of microstructure and casting defects. Other interests include control of semisolid microstructure and mechanical behaviour during processing, grain refinement and the heat treatment of light alloys. He has gained significant industry sponsorship for this research. In addition to many publications on the aspects of aluminium alloy solidification, he is a co-inventor of a new aluminium foundry alloy product with Comalco Aluminium.