METALLURGICAL BENEFITS OF AIR INDUCTION MELTED—AOD REFINED—CONTINUOUS CAST NICKEL-, COBALT-, AND IRON-BASED ALLOYS

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ABSTRACT

The air induction melted-argon oxygen decarburized-horizontal continuous casting process (AIM-AOD-CC) is the premier process for the production of nickel-, cobalt-, and iron-base master alloys for remelting by precision casters. Since the introduction of the process by Cannon-Muskegon Corporation in 1981, over 12,000 heats have been produced.

This paper reviews the AIM-AOD-CC process and examines its benefits--stressing analytical consistency, metallurgical cleanliness, trace element control, and the importance of alloy chemistry balance on properties and performance. The paper further reviews remelting practices by precision casters, specifically deoxidation practices, use of filters, and inert cover gases.

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INTRODUCTION

The air induction melted-argon oxygen decarburized[1,2]-horizontal continuous casting[3] process (AIM-AOD-CC) is recognized and established as the preferred manufacturing process for the production of nickel-, cobalt-, and iron-base master alloys for the precision casting industry. Since the process was introduced[4] by Cannon-Muskegon Corporation in 1981, over 12,000 heats have been produced, establishing new levels of quality, analytical consistency, and metallurgical cleanliness.

AIM-AOD-CC PROCESS

The process (Figure 1) employs electric induction melting furnaces which, at Cannon-Muskegon Corporation, are 5- and 10- ton capacity. Induction melting is preferred due to its flexibility which accommodates a broad range of alloy systems while maintaining compositional accuracy. Induction stirring is effective in achieving homogeneity of alloy composition throughout the heat. The initial chemistry of the alloy is attained in the induction furnace.

INDUCTION/AOD/CONTINUOUS CAST PRODUCT FLOW

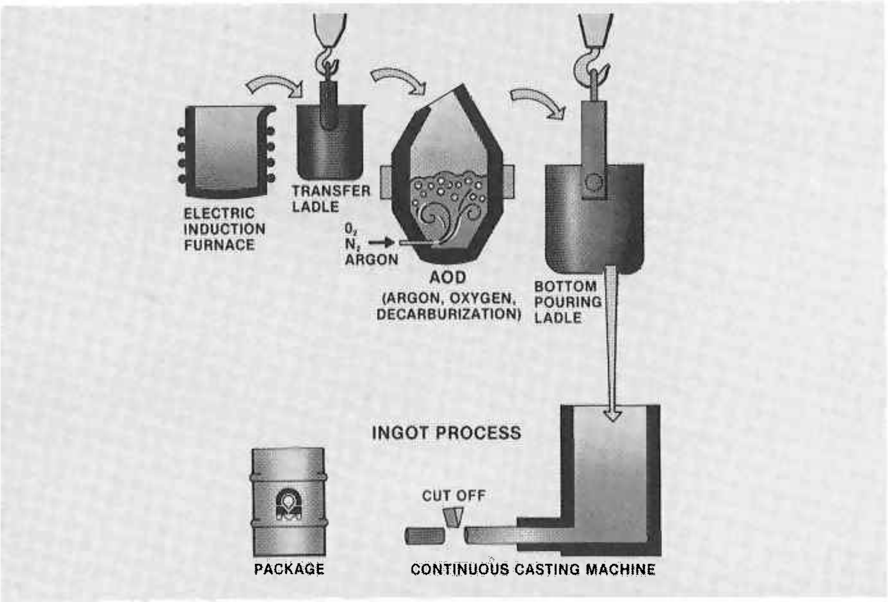

Figure 1. Induction-AOD-Continuous Cast Product Flow Chart

The major element composition is established in the induction melting furnaces. The alloy is then transferred to the AOD vessel for refining, which is accomplished by blowing argon and oxygen through the molten bath, and then adding aluminum (Al) and lime (CaO). The AOD process is particularly well-suited for reduction of carbon (C), sulfur (S), and silicon (Si). The process also reduces low-melting-point elements including lead (Pb), bismuth (Bi), and selenium (Se). Furthermore, it reduces the gaseous elements nitrogen (N_2), hydrogen (H_2), and oxygen (O_2). Nitrogen may be added to certain alloys for strengthening by the addition of nitrogen gas in AOD. This refining is accomplished without loss of valuable alloying elements, especially chromium (Cr).

After refining and confirmation of the desired chemistry, the melt is transferred by bottom pour ladle to the casting tundish, which bottom feeds the horizontal continuous caster, producing a 75mm (or other sizes) diameter bar (Figure 2). The bar is generally sound, with little center line shrinkage or porosity (Figure 3), and is metallurgically clean. The molten metal does not contact or become contaminated with molding materials, sand, or mold washes during solidification. The cast bar is subsequently cut to specified length or weight.

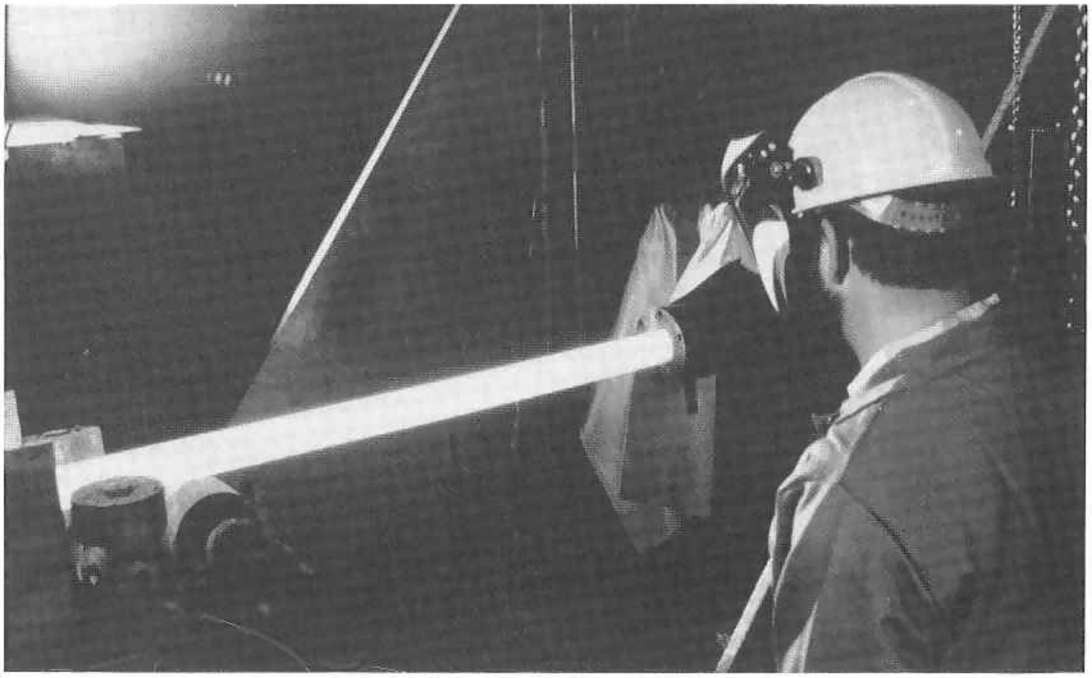

Figure 2. Continuous cast bar withdrawing from the horizontal caster cooler.

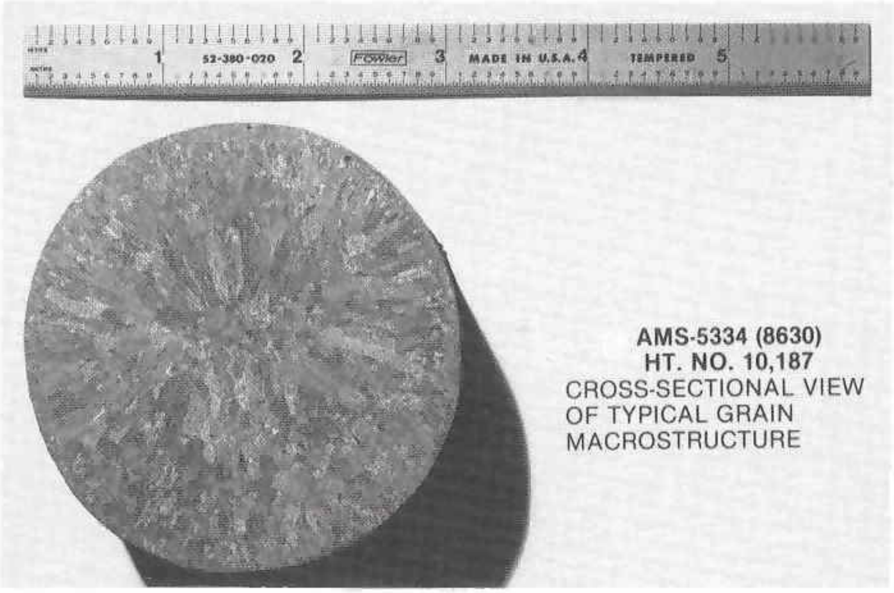

Figure 3. Cross-sectional view of typical grain macrostructure.

ALLOY SYSTEMS

The AIM-AOD-CC process has successfully produced most conventional air-melt grades of the carbon, alloy and tool steels, the more highly-alloyed heat- and corrosion-resistant stainless steels, as well as nickel- and cobalt-based superalloys (Table I). While some alloys present difficulties, most can be produced by this process once refining and casting parameters are established and fixed.

TABLE I ALLOYS PRODUCED BY AIM-AOD-CC

Fe BASE	Ni BASE	Co BASE
17-4, 15-5	Ni B	Co 6
Tool Steels	Ni C, Hastelloy® Alloy C-22	Co 21
Low Alloy	Ni X	Co 25
Ni-Cr Stainless Steel	Ni-Cu Series	Co 31
Cr Stainless Steel	CW-2M	X-45
Duplex Stainless Steel		FSX 414
		Ultimet®

METALLURGICAL CLEANLINESS

The inherent chemistry control and homogeneity of induction melting, combined with the refining characteristics of AOD, enable the metallurgist to refine and control the metallurgical cleanliness to extremely low levels of oxides, nitrides and sulfides. The bottom-pouring ladle, combined with bottom feed of the continuous caster, provide a double flotation which virtually eliminates siliceous slag as well as other remaining nonmetallic particles in the melt.

In addition, the melt is isolated from the atmosphere by the use of a protective slag blanket in the caster tundish which, combined with the elimination of contact with conventional mold materials, further enhances metallurgical cleanliness.

TRACE ELEMENT CONTROL

The elements N_2, H_2, and O_2 are routinely monitored and controlled to very low levels. Consistent control of these elements is required to assure satisfactory remelting characteristics. For example, nitrogen is known to strengthen certain alloys and can be added in these cases. However, when present in excessive quantities, nitrogen can cause subsurface microporosity in castings. Oxygen does not contribute to porosity but will form metallic oxides, reducing mechanical properties of cast alloys, particularly fatigue properties, and seriously reducing fluidity. Hydrogen may cause embrittlement.

Freedom from large deleterious nonmetallic oxides or nitrides is an important factor in producing quality castings with a fine surface finish, both in the as-cast and machined conditions, stressing the importance for accurate control of gases in master alloys.

Sulfur is a particularly detrimental tramp element, forming sulfides which seriously reduce ductility, impact properties and castability. Sulfur is generally controlled to less than 50ppm, typically and frequently <20ppm, through reaction with lime (CaO) during AOD refining.

The low melting point elements, such as lead (Pb), bismuth (Bi), selenium (Se), and others, are detrimental to mechanical properties and make the castings hotshort and prone to hot tears and cracking. Furthermore, they have a negative influence on casting performance in service. The AOD process is uniquely successful in reducing and controlling these trace, tramp and gaseous elements and enhancing alloy performance during the casting process and in the intended end use application. Table II identifies typical trace element and gas levels for three representative alloys.

TABLE II

TYPICAL TRACE ELEMENT LEVELS
5-TON HEATS
PPM

Alloys	N_2	O_2	S	Se	Pb	Sn	Ag	Bi	Tl	Te	Cd
Co-Cr-Mo	--	73	11	<1	.6	2	<.5	<.5	<.5	<.5	<.5
Ni X	180	110	34	<1	.6	14	<.5	<.5	<.5	<.5	<.5
Ni C	170	70	23	<1	.8	8	<.5	<.5	<.5	<.5	<.5

ANALYTICAL CONSISTENCY

The AIM-AOD-CC process facilitates the excellent carbon-oxidation and -reduction reactions, as well as excellent mixing of the molten bath. These reactions provide opportunity for the melter to control and maintain chemistry.

Table III examines the major element chemistry of 70 five-ton and 42 ten-ton heats of 15-5 precipitation-hardening stainless steel, presenting the average (wt. %) and the standard deviation. The larger heats exhibit slightly greater deviation; however, they still possess excellent consistency. The data are developed from multiple analyses (5 to 8 tests) from each heat.

TABLE III ALLOY CONSISTENCY 15-5 Stainless Steel 70 each 5-Ton AIM-AOD-CC Heats

	Mn	Si	Cr	Ni	S	N_2	O_2
Average	.5	.76	15.8	4.0	<.005	.02	.013
Std. Dev.	.03	.04	.12	.11	--	.003	.002

ALLOY CONSISTENCY 15-5 Stainless Steel 42 each 10-Ton AIM-AOD-CC Heats

	Mn	Si	Cr	Ni	S	N_2	O_2
Average	.5	.76	15.9	4.0	<.005	.02	.015
Std. Dev.	.03	.06	.18	.08	--	.005	.003

TABLE IV ALLOY CONSISTENCY Co Cr Mo ALLOY 100 each 5-Ton AIM-AOD-CC Heats

	C	Mn	Si	Cr	Ni	Mo	Fe	N_2
Average	.25	.68	.77	28.2	.28	5.9	.4	.16
Std. Dev.	.005	.01	.02	.10	.05	.03	.04	.007

Table IV summarizes the chemical consistency from 100 five-ton heats of the Co-Cr-Mo alloy used for medical applications, such as total knee and hip prostheses.

CHEMISTRY BALANCE

Producing a particular alloy only to the range permissible by specification is not adequate for optimized performance. The various elements must be related to each other and the alloy chemistry balanced to attain the desired and preferred properties. For example, the cast corrosion-resistant grades of stainless steel alloys have a duplex micro-structure of an austenitic matrix with typically 5 to 25% delta ferrite. The presence, as well as the amount, of delta ferrite influences the alloy behavior in many ways, including . . .

- mechanical (strength) properties
- corrosion resistance, particularly inter granular stress corrosion
- castability
- magnetic properties
- heat treatment
- machineability.

The volume percentage of delta ferrite is primarily influenced by alloy chemistry and, to a lesser extent, by the thermal history (remelt pouring temperature and casting cooling rate). Heat treatment factors, primarily time and temperature, also influence the amount of ferrite.

There is no optimum amount of delta ferrite for all applications. Table V suggests levels for desired properties in cast, corrosion resistant stainless steel alloys[5]. Cannon-Muskegon Corporation generally aims for a ferrite range of 5 to 15% unless specific property requirements or specifications dictate otherwise. As the amount of delta ferrite present relates directly to chemistry balance dictated by such elements as carbon (C), silicon (Si) and nitrogen (N_2), the AOD process is the tool of choice for maintaining pinpoint accuracy in desired delta ferrite volumetric percentages.

TABLE V

SUGGESTED DELTA FERRITE LEVELS
vs.
APPLICATION
Cast, Corrosion Resistant, Stainless Steels

	Requirement	Volume % Delta Ferrite
1.	MECHANICAL STRENGTH	
	A. Ambient Temperature*	
	1. Tensile/Yield	> 15
	2. Ductility	< 15
	3. Impact	> 15
	B. High Temperature**	
	1. Tensile/Yield	0 - 5
	2. Ductility	0 - 5
	3. Impact	0 - 5
	4. Creep Rupture	0 - 5
	C. Low Temperature***	
	1. Tensile/Yield	5 - 10
	2. Ductility	0
	3. Impact	0
II.	CORROSION RESISTANCE	
	A. General	5 +
	B. Intergranular (IGC)	3 - 15
	C. Stress (SCC)	3 - 15
	D. Pitting	0 - 5
	E. Cavitation	NE
III.	MAGNETIC	
	A. Non-Magnetic/Low Permeability	0
	B. High Magnetic Permeability	15 +
IV.	FOUNDRY PERFORMANCE	
	A. Fluidity	NE
	B. Resistance to Gassing	NE
	C. Resistance to Hot Tearing	5 - 15
	D. Resistance to Shrinkage	10 +
V.	MACHINABILITY	5 - 15

* Ambient Temperature = -100° to 800°F (-73 to 427°C)
** High Temperature = > 800°F (> 427°C)
*** Low Temperature = < -100°F (< -73°C)
NE = No Effect

REMELTING PRACTICES

The precision caster is challenged by many variables which influence the quality of castings. These include the quality and purity of the melt stock, superheat temperature, contact time with air, and total time molten. Refractory quality and atmospheric conditions also influence the quality of castings produced[6].

The use of high-quality, high-purity, AIM-AOD-CC master alloy provides a constant key ingredient in the casting process, eliminating many of the problems associated with remelting and casting. The goal is to eliminate as many of the variables as possible and simplify the operation. The ideal is to melt and pour rapidly, reducing elemental fade (Si, Mn, Cr, C, etc.), gas absorption from the atmosphere, and furnace refractory/molten metal reaction, thereby eliminating the need to make additions to the melt for replenishment and/or degassing purposes.

AIM-AOD-CC remelt alloy is designed to be remelted in air. However, to maximize the benefits of low gas levels and metallurgical cleanliness, it is often suggested that the use of a remelt inert cover gas be considered. Control of the atmosphere above the melt has important benefits and can improve castability and casting quality. The SPAL® process developed by the Liquid Air Corporation has demonstrated positive results[7]. The use of gaseous argon with a melt cover (Figure 4) can also offer significant benefit[8]. However, the use of argon protection will not reduce the effects of poor-quality melt stock.

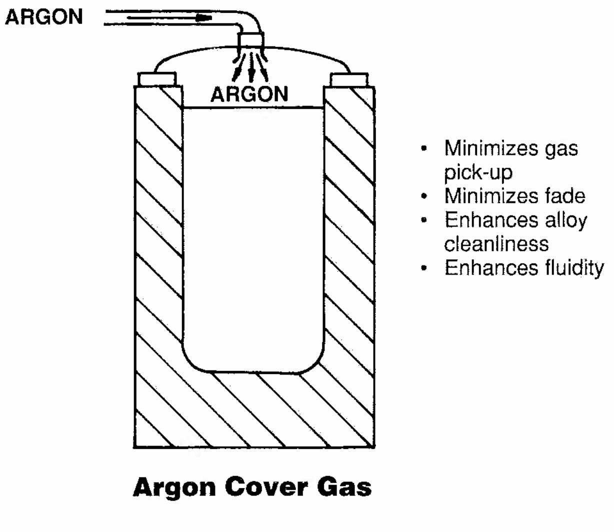

Figure 4. Induction furnace argon cover gas.

SUMMARY

The success of a precision caster is measured by the ability to produce premium quality castings consistently and profitably. To accomplish this, the caster must control many variables, reducing their number as much as possible, thereby achieving simplicity as well as consistency in the casting process. The use of the AIM-AOD-CC master alloy, as produced by Cannon-Muskegon Corporation, provides the foundation for consistency of alloy purity, chemistry balance, and metallurgical cleanliness. Control of the many casting variables is more manageable through the high quality and consistency of this unique remelt alloy product.

The AIM-AOD-CC process produces the ideal foundation for the attainment of a high-quality casting. It combines the characteristics of . . .

- low gas levels
- low trace element levels
- low sulfur
- metallurgical cleanliness
- alloy phase balance
- optimum mechanical properties

. . . repetitively, to yield castings of the highest quality and appearance at the lowest cost. For the precision caster, the process combines performance with simplicity through elimination of steps otherwise required for elemental replenishment and degassing. This is possible because of the low gas levels and metallurgical cleanliness attainable with the AIM-AOD-CC process.

Degassing may be required for only a few select alloys, such as carbon steel, low alloy steel, pure nickel and magnetic alloys. The need for filtering is also eliminated. This simplicity allows the melt floor personnel to melt and pour, to increase productivity, and to concentrate on the essential business of producing quality castings.

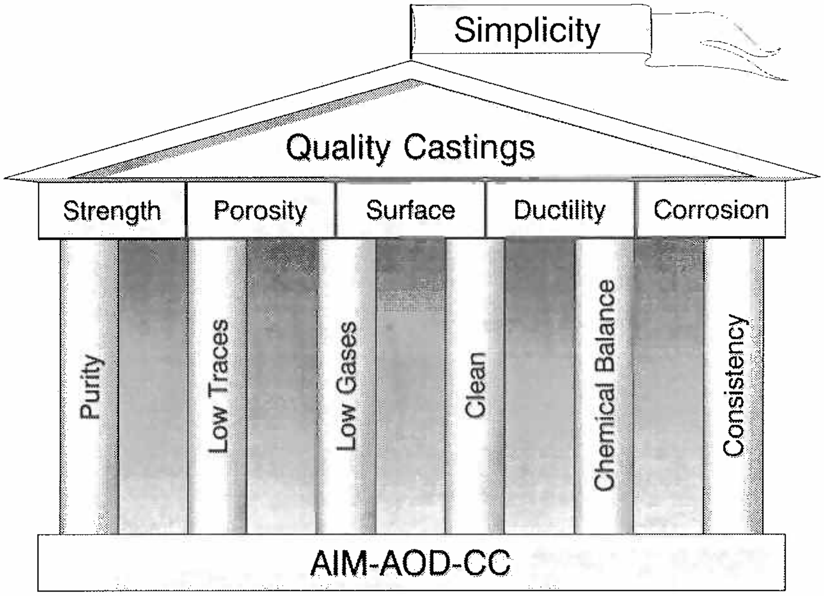

Figure 5. The Foundation of AIM-AOD-CC Supporting Production of Premium Quality Castings.

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