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Homogenization and heat-treatment of cast metals

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(71)   Applicant(s)
Novelis Inc.

(72)   Inventor(s)
Wagstaff, Robert Bruce;   Fenton, Wayne J.

(74)   Agent/Attorney
Griffith Hack, Level 3 509 St Kilda Road, Melbourne, VIC, 3004

Abstract

A method of continuously or semi-continuously direct chill casting an ingot made of a castable metal, comprising the steps of (a) providing a direct chill casting mold having one or more mold inlets and one or more mold outlets; (b) supplying molten metal to at least one inlet of the casting mold; (c) cooling the mold to solidify a peripheral portion of the metal, thereby forming an embryonic ingot having an external solid shell and an internal molten core; (d) continuously advancing the embryonic ingot beyond at least one outlet of the mold, thereby extending the molten core contained within the solid shell beyond said at least one outlet of the mold; (e) cooling the embryonic ingot emerging from the mold to continue the solidification thereof by directing a supply of coolant liquid onto an outer surface of the embryonic ingot; (f) causing said coolant liquid to be removed from the surface of the embryonic ingot at a position where the ingot has not yet been transformed into a fully solid ingot such that internal heat from the molten core reheats the solid shell adjacent to the core, thereby causing temperatures of said core and said shell to equilibrate at a convergence temperature, said coolant liquid being removed from said surface at a distance from said at least one mold outlet that causes said convergence temperature to become 425°C or higher; and (g) varying said position in step (f) in different phases of said casting of said ingot to minimize differences of said convergence temperature below said wiper during said different phases of casting.

AUSTRALIA

Patents Act 1990

COMPLETE SPECIFICATION

Standard Patent

Applicant(s):

NOVELIS INC.

Invention Title:

Homogenization and heat-treatment of cast metals

The following statement is a full description of this invention, including the best method for performing it known to me/us:

HOMOGENIZATION AND HEAT-TREATMENT OF CAST METALS

TECHNICAL FIELD

This invention relates to the casting of metals,
5 particularly metal alloys, and their treatment to make
them suitable to form metal products such as sheet and
plate articles.

BACKGROUND ART

Metal alloys, and particularly aluminum alloys,
10 are often cast from molten form to produce ingots or
billets that are subsequently subjected to rolling, hot
working, or the like, to produce sheet or plate
articles used for the manufacture of numerous products.
Ingots are frequently produced by direct chill (DC)
15 casting, but there are equivalent casting methods, such
as electromagnetic casting (e.g. as typified by U.S.
patents 3,985,179 and 4,004,631, both to Goodrich et
al.), that are also employed. The following discussion
relates primarily to DC casting, but the same
20 principles apply all such casting procedures that
create the same or equivalent microstructural
properties in the cast metal.

DC casting of metals (e.g. aluminum and aluminum
alloys -referred to collectively in the following as
25 aluminum) to produce ingots is typically carried out in
a shallow, open-ended, axially vertical mold which is
initially closed at its lower end by a downwardly
movable platform (often referred to as a bottom block).
The mold is surrounded by a cooling jacket through
30 which a cooling fluid such as water is continuously
circulated to provide external chilling of the mold
wall. The molten aluminum (or other metal) is

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introduced into the upper end of the chilled mold and,
as the molten metal solidifies in a region adjacent to
the inner periphery of the mold, the platform is moved
downwardly. With an effectively continuous movement of

5   the platform and correspondingly continuous supply of
molten aluminum to the mold, an ingot of desired length
may be produced, limited only by the space available
below the mold. Further details of DC casting may be
obtained from US patent 2,301,027 to Ennor (the

10 disclosure of which is incorporated herein by
reference), and other patents.

DC casting can also be carried out horizontally,
i.e. with the mold oriented non-vertically, with some
modification of equipment and, in such cases, the

15 casting operation may be essentially continuous. In
the following discussion, reference is made to vertical
direct chill casting, but the same principles apply to
horizontal DC casting.

The ingot emerging from the lower (output) end of

20 the mold in vertical DC casting is externally solid but
is still molten in its central core. In other words,
the pool of molten metal within the mold extends
downwardly into the central portion of the downwardly-
moving ingot for some distance below the mold as a sump

25 of molten metal. This sump has a progressively
decreasing cross-section in the downward direction as
the ingot solidifies inwardly from the outer surface
until its core portion becomes completely solid. The
portion of the cast metal product having a solid outer

30 shell and a molten core is referred to herein as an
embryonic ingot which becomes a cast ingot when fully
solidified.

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As an important feature of the direct chill casting process, a continuously-supplied coolant fluid, such as water, is brought into direct contact with the outer surface of the advancing embryonic ingot directly

5 below the mold, thereby causing direct chilling of the surface metal. This direct chilling of the ingot surface serves both to maintain the peripheral portion of the ingot in solid state and to promote internal cooling and solidification of the ingot.

10 Conventionally, a single cooling zone is provided below the mold. Typically, the cooling action in this zone is effected by directing a substantially continuous flow of water uniformly along the periphery of the ingot immediately below the mold, the water

15 being discharged, for example, from the lower end of the mold cooling jacket. In this procedure, the water impinges with considerable force or momentum onto the ingot surface at a substantial angle thereto and flows downwardly over the ingot surface with continuing but

20 diminishing cooling effect until the ingot surface temperature approximates that of the water.

Typically, the coolant water, upon contacting the hot metal, first undergoes two boiling events. A film of predominately water vapor is formed directly under

25 the liquid in the stagnant region of the jet and immediately adjacent to this, in the close regions above, to either side and below the jet, classical nucleate film boiling occurs. As the ingot cools, and the nucleation and mixing effect of the bubbles

30 subsides, fluid flow and thermal boundary layer conditions change to forced convection down the bulk of the ingot until, eventually, the hydrodynamic conditions change to simple free falling film across

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the entire surface of the ingot in the lowermost
extremities of the ingot.

Direct chill cast ingots produced in this way are
generally subjected to hot and cold rolling steps, or
5   other hot-working procedures, in order to produce
articles such as sheet or plate of various thicknesses
and widths. However, in most cases a homogenization
procedure is normally required prior to rolling or
other hot-working procedure in order to convert the
10   metal to a more usable form and/or to improve the final
properties of the rolled product. Homogenization is
carried out to equilibrate microscopic concentration
gradients. The homogenization step involves heating
the cast ingot to an elevated temperature (generally a
15   temperature above a transition temperature, e.g. a
solvus temperature of the alloy, often above 450°C and
typically (for many alloys) in the range of 500 to
630°C) for a considerable period of time, e.g. a few
hours and generally up to 30 hours.
20   The need for this homogenization step is a result
of the microstructure deficiencies found in the cast
product resulting from the early stages or final stages
of solidification. On a microscopic level, the
solidification of DC cast alloys are characterized by
25   five events: (1) the nucleation of the primary phase
(whose frequency may or many not be associated with the
presence of a grain refiner); (2) the formation of a
cellular, dendritic or combination of cellular and
dendritic structures that define a grain; (3) the
30   rejection of solute from the cellular/dendritic
structure due to the prevailing non-equilibrium
solidification conditions; (4) the movement of the
rejected solute that is enhanced by the volume change

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of the solidifying primary phase; and (5) the
concentration of rejected solute and its solidification
at a terminal reaction temperature (e.g. eutectic).

The resulting structure of the metal is therefore
5   quite complex and is characterized by compositional
variances across not only the grain but also in the
regions adjacent to the intermetallic phases where
relatively soft and hard regions co-exist in the
structure and, if not modified or transformed, will
10 create final gauge property variances unacceptable to
the final product.

Homogenization is a generic term generally used to
describe a heat treatment designed to correct
microscopic deficiencies in the distribution of solute
15 elements and (concomitantly) modify the intermetallic
structures present at the interfaces. Accepted results
of a homogenization process include the following:

1. The elemental distribution within a grain
20   becomes more uniform.

2. Any low melting point constituent particles
   (e.g. eutectics) that formed at the grain
   boundaries and triple points during casting are
   dissolved back into the grains.

25 3. Certain intermetallic particles (e.g.
   peritectics) undergo chemical and structural
   transformations.

4. Large intermetallic particles (e.g. peritectics)
   that form during casting may be fractured and
30   rounded during heat-up.

5. Precipitates (such as may be used to
   subsequently developed to strengthen the
   material) are formed during heat-up are

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dissolved and later precipitated evenly across
the grain after dissolution and redistribution
as the ingot is once again cooled below the
solvus and either held at a constant temperature
5   and allowed to nucleate and grow, or cooled to
room temperature and preheated to hot working
temperatures.

In some cases, it is necessary to apply thermal
10   treatments to ingots during the actual DC casting
process to correct differential stress fields induced
during the casting process. Those skilled in the art
characterize alloys into those that either crack post-
solidification or pre-solidification in response to
15   these stresses.

Post-solidification cracks are caused by
macroscopic stresses that develop during casting, which
cause cracks to form in a trans-granular manner after
solidification is complete. This is typically
20   corrected by maintaining the ingot surface temperature
(thus decreasing the temperature - hence strain -
gradient in the ingot) at an elevated level during the
casting process and by transferring conventionally cast
ingots to a stress relieving furnace immediately after
25   casting.

Pre-solidification cracks are also caused by
macroscopic stresses that develop during casting.
However, in this case, the macroscopic stresses formed
during solidification are relieved by tearing or
30   shearing the structure, inter-granularly, along low
melting point eutectic networks (associated with solute
rejection on solidification). It has been found that
equalizing, from center to surface, the linear

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temperature gradient differential (i.e. the temperature
derivative surface to center of the emerging ingot) can
successfully mitigate such cracking.

5   These defects render the ingot unacceptable for
many purposes. Various attempts have been made to
overcome this problem by controlling the surface
cooling rate of an ingot during casting. For instance,
in alloys prone to post-solidification cracking,
Zeigler, in U.S. Patent 2,705,353, used a wiper to
10   remove coolant from the surface of the ingot at a
distance below the mold so that the internal heat of
the ingot would reheat the cooled surface. The
intention was to maintain the temperature of the
surface at a level above about 300°F (149°C) and,
15   preferably, within a typical annealing range of about
400 to 650°F (204 to 344°C).

Zinniger, in U.S. Patent 4,237,961, showed another
direct chill casting system with a coolant wiping
device in a form of an inflatable, elastomeric wiping
20   collar. This served the same basic purpose as that
described in the above Zeigler patent, with the surface
temperature of the ingot being maintained at a level
sufficient to relieve internal stresses. In the
example of the Zinniger patent, the ingot surface is
25   maintained at a temperature of approximately 500°F
(260°C), which is again in the annealing range. The
purpose of this procedure was to permit the casting of
ingots of very large cross section by preventing the
development of excessive thermal stresses within the
30   ingot.

In pre-solidification crack prone alloys, Bryson,
in U.S. Patent 3,713,479, used two levels of water
spray cooling of lesser intensity to decrease the

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cooling rate and have it extend a greater distance down
the ingot as the ingot descends and, as a result of
this work, demonstrated the capability to increase
overall casting rates realized in the process.

5   Another design of direct chill casting device
using a wiper for removing cooling water is shown in
Ohatake et al. in Canadian Patent 2,095,085. With this
design, primary and secondary water cooling jets are
used, followed by a wiper to remove water, with the
10 wiper being followed by a third cooling water jet.

DISCLOSURE OF THE INVENTION

        A exemplary form or aspect is based an observation
that metallurgical properties equivalent or identical
15 to those produced during conventional homogenization of
a cast metal ingot (a procedure requiring several hours
of heating at an elevated temperature) can be imparted
to such an ingot by allowing the temperatures of the
cooled shell and still-molten interior of an embryonic
20 cast ingot to converge to a temperature at or above a
transformation temperature of the metal at which in-
situ homogenization of the metal occurs, which is
generally a temperature of at least 425°C for many
aluminum alloys, and preferably to remain at or near
25 that temperature for a suitable period of time for the
desired transformations to occur (at least in part).

        Surprisingly, desirable metallurgical changes can
often be imparted in this way in a relatively short
time (e.g. 10 to 30 minutes) and the procedure for
30 achieving such a result can be incorporated into the
casting operation itself, thereby avoiding the need for
an additional expensive and inconvenient homogenizing
step. Without wishing to be bound by any particular

theory, it is possible that this is because desirable
metallurgical changes are created or maintained as the
alloy is being cast by a significant backward-diffusion
effect (in either, or both, solid and liquid states and
5   their combined 'mushy' form) for a short period of time
rather than having undesirable metallurgical properties
form during conventional cooling, that then require
considerable time for correction in a conventional
homogenization step.

10   Even in those cases where homogenization is not
normally carried out with a conventionally cast ingot,
there can be gains in properties that make the ingot
easier to process or provide a product with improved
properties.

15   The method of casting involving *in-situ*
homogenization as set out above may optionally be
followed by a quenching operation before the ingot is
removed from the casting apparatus, e.g. by immersing
the leading part of the advancing cast ingot into a
20 pool of coolant liquid. This is carried out following
the removal of the coolant liquid supplied to the
surface of the embryonic ingot and after sufficient
time has been allowed for suitable metallurgical
transformations.

25   The term "*in-situ* homogenization" has been coined
by the inventors to describe this phenomenon whereby
microstructural changes are achieved during the casting
process that are equivalent to those obtained by
conventional homogenization carried out following
30 casting and cooling. Similarly, the term "*in-situ*
quench" has been coined to describe a quenching step
carried out after *in-situ* homogenization during the
casting process.

It is to be noted that embodiments may be applied to the casting of composite ingots of two or more metals (or the same metal from two different sources), e.g. as described in U.S. patent publication 2005-0011630

5   published on January 20, 2005 or U.S. patent 6,705,384 which issued on March 16, 2004. Composite ingots of this kind are cast in much the same way as monolithic ingots made of one metal, but the casting mold or the like has two or more inlets separated by an internal mold wall or

10 by a continuously-fed a strip of solid metal that is incorporated into the cast ingot. Once leaving the mold, through one or more outlets, the composite ingot is subjected to liquid cooling and the liquid coolant may be removed in the same way as for a monolithic ingot with the

15 same or an equivalent effect.

In an embodiment there is presented, a method of continuously or semi-continuously direct chill casting an ingot made of a castable metal, comprising the steps of:

(a) providing a direct chill casting mold having one

20 or more mold inlets and one or more mold outlets,

(b) supplying molten metal to at least one inlet of the casting mold;

(c) cooling the mold to solidify a peripheral portion of the metal, thereby forming an embryonic ingot having an

25 external solid shell and an internal molten core;

(d) continuously advancing the embryonic ingot beyond at least one outlet of the mold, thereby extending the molten core contained within the solid shell beyond said at least one outlet of the mold;

30 (e) cooling the embryonic ingot emerging from the mold to continue the solidification thereof by directing a supply of coolant liquid onto an outer surface of the embryonic ingot;

(f) causing said coolant liquid to be removed from

35 the surface of the embryonic ingot at a position where the ingot has not yet been transformed into a fully solid ingot such that internal heat from the molten core reheats

the solid shell adjacent to the core, thereby causing
temperatures of said core and said shell to equilibrate at
a convergence temperature, said coolant liquid being
removed from said surface at a distance from said at least
5   one mold outlet that causes said convergence temperature
to become 425°C or higher; and

(g) varying said position in step (f) in different
phases of said casting of said ingot to minimize
differences of said convergence temperature below said
10 wiper during said different phases of casting.

Certain exemplary embodiments can provide a method of
casting a metal ingot, comprising the steps of: (a)
supplying molten metal from at least one source to a
region where the molten metal is peripherally confined,
15 thereby providing the molten metal with a peripheral
portion; (b) cooling the peripheral portion of the metal,
thereby forming an embryonic ingot having an external
solid shell and an internal molten core; (c) advancing the
embryonic ingot in a direction of advancement away from
20 the region where the molten metal is peripherally confined
while supplying additional molten metal to the region,
thereby extending the molten core contained within the
solid shell beyond the region; (d) cooling an outer
surface of the embryonic ingot emerging from the region
25 where the metal is peripherally confined by directing a
supply of coolant liquid onto the outer surface; and (e)
removing an effective amount (and, most preferably, all)
of the

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coolant liquid from the outer surface of the embryonic
ingot at a location on the outer surface of the ingot
where a cross section of the ingot perpendicular to the
direction of advancement intersects a portion of the
5   molten core such that internal heat from the molten
core reheats the solid shell adjacent to the molten
core after removing the effective amount of coolant,
thereby causing temperatures of the core and shell to
each approach a convergence temperature of 425°C or
10   higher.

This convergence can, in preferred cases, be
tracked by measuring the outside surface of the ingot
which shows a temperature rebound after the coolant
liquid has been removed. This rebound temperature
15   should peak above the transformation temperature of the
alloy or phase, and preferably above 426°C.

In the above method, the molten metal in step (a)
is preferably supplied to at least one inlet of a
direct chill casting mold, the direct chill casting
20   mold thereby forming the region where the molten metal
is peripherally confined, and the embryonic ingot is
advanced in step (c) from at least one outlet of the
direct chill casting mold, with the location on the
outer surface of the ingot where the substantial
25   portion of coolant liquid is removed in step (e) being
spaced by a distance from the at least one outlet of
the mold. The casting method (i.e. supply of molten
metal) may be continuous or semi-continuous, as
desired.

30   The coolant liquid may be removed from the outer
surface by wiping or other means. Preferably, a wiper
encircling the ingot is provided and the position of
the wiper may be varied, if desired, during different

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phases of the casting operation, e.g. to minimize
differences of the convergence temperature that may
otherwise occur during such different phases.

5   According to another exemplary embodiment, there
is provided apparatus for continuously or semi-
continuously direct chill casting a metal ingot,
comprising: a casting mold having at least one inlet,
at least one outlet and at least one mold cavity; at
least one cooling jacket for the at least one mold
10   cavity; a supply of coolant liquid arranged to cause
the coolant liquid to flow along an exterior surface of
an embryonic ingot emerging from the at least one
outlet; means spaced at a distance from the at least
one outlet for removing the coolant liquid from the
15   exterior surface of the embryonic ingot; and apparatus
for moving the coolant removing means towards and away
from the at least one outlet, thereby enabling the
distance to be modified during casting of the ingot.

Another exemplary embodiment provides a method of
20   producing a metal sheet article, which includes
producing a solidified metal ingot by a method as
described above; and hot-working the ingot to produce a
worked article; characterized in that the hot-working
is carried out without homogenization of the solidified
25   metal ingot between the ingot-producing step (a) and
the hot-working step (b). The hot-working may be, for
example, hot-rolling, and this may be followed by
conventional cold-rolling, if desired. The term "hot-
working" may include, for example, such process as hot-
30   rolling, extrusion and forging.

Another exemplary embodiment provides a method of
producing a metal ingot that can be hot-worked without
prior homogenization, which method comprises casting a

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metal to form an ingot under conditions of temperature
and time effective to produce a solidified metal having
a non-cored microstructure, or, alternatively, a
fractured microstructure (intermetallic particles
5   exhibit are fractured in the cast structure).

At least in some of the exemplary emodiments,
solute elements which are segregated during
solidification towards the edge of the cell, which
exist at the edge of the ingot, near the surface
10 quenched below a transformation temperature, e.g. a
solvus temperature, during initial fluid cooling, are
allowed to re-distribute via solid state diffusion
across the dendrite/cell and those solute elements
which normally segregate to the edge of the
15 dendrite/cell in the center region of the ingot are
allowed time and temperature during solidification to
backwards diffuse solute from the homogenous liquid
back into the dendrite/cell prior to growth and
coarsening. The result of this backwards diffusion
20 removes solute elements from the homogenous mixture,
generating a reduced concentration of solute in the
homogenous mixture which in turn minimizes the volume
fraction of the cast intermetallics at the unit
dendrite/cell boundary, thereby reducing the overall
25 macro-segregation effect across the ingot. Any high
melting point cast constituents and intermetallics at
that point are, once solidified, easily modified by the
bulk diffusion of silicon (Si) or other elements
present in the metal, at the elevated temperatures,
30 yielding a denuded region at the dendrite/cell boundary
equivalent to or near the concentration corresponding
to the maximum solubility limit at that particular
convergence temperature. Similarly, high melting point

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eutectics (or metastable constituents and
intermetallics) may be further modified or can be
further modified/transformed in structure if the
convergence temperature is attained and held in a mixed
5   phase region common to two adjoining binary phase
regions. In addition to this, the nominally higher
melting point cast constituents and intermetallics may
be fractured and/or rounded, and low melting point cast
constituents and intermetallics are more likely to melt
10   or diffuse into the bulk material during the casting
process.

        Another exemplary embodiment provides a method of
heating a cast metal ingot to prepare the ingot for
hot-working at a predetermined hot-working temperature.
15   The method involves (a) pre-heating the ingot to a
nucleation temperature, below the predetermined hot-
working temperature, at which precipitate nucleation
occurs in the metal to cause nucleation to take place;
(b) heating the ingot further to a precipitate growth
20   temperature at which precipitate growth occurs to cause
precipitate growth in the metal; and (c) if the ingot
is not already at the predetermined hot-working
temperature after step (b), heating the ingot further
to said predetermined hot-working temperature ready for
25   hot-working. The hot-working step preferably comprises
hot-rolling, and the ingot is preferably cast by DC
casting.

        According to this method, dispersoids, commonly
formed during homogenization and hot rolling, are
30   produced in such a way that, on preheating the ingot in
two stages to a hot rolling temperature and holding for
a period of time, the dispersoid population size and
distribution in the ingot becomes similar to or better

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than that which is normally found following a full
homogenization process, but in a substantially shorter
period of time.

  Preferably, this method provides a process for
5 thermally processing a metal ingot comprising the steps
   of:

   (a) pre-heating an ingot to a temperature
        corresponding to a composition on the solvus
        where,

10 (b) the portion of supersaturated material
        precipitating out of solution during heating
        contributes to the nucleation of a
        precipitate,

   (c) holding the ingot at that temperature for a
15   period of time then,

   (d) increasing the temperature of the ingot to a
        temperature which corresponds to a
        composition on the solvus and,

   (e) allowing the portion of the supersaturated
20   material precipitating out of solution on the
        second stage heating to contribute to the
        growth of a precipitate then,

   (f) holding the ingot at that temperature for a
        period of time to allow continued diffusion
25   of solute from the smaller (thermally-
        unstable) precipitates which enhance the
        growth of the larger more stable precipitates
        or, alternatively, gradually increasing the
        temperature, thereby increasing the solute
30   concentration which contributes to growth
        with out requiring a temperature hold.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a vertical cross-section of a Direct
Chill casting mold showing one preferred form of a
process according to an exemplary embodiment, and
5   particularly illustrating a case in which the ingot
remains hot during the entire cast.

Fig. 2 is a cross-section similar to that of Fig.
1, illustrating a preferred modification in which the
position of the wiper is movable during the cast.

10   Fig. 3 is a cross-section similar to that of Fig.
1, illustrating a case in which the ingot is
additionally cooled (quenched) at the lower end during
the cast.

Fig. 4 is a top plan view of a J-shaped casting
15   mold illustrating a preferred form of an exemplary
embodiment.

Fig. 5 is a graph showing distances X of Fig. 1
for a mold of the type shown in Fig. 4, the values of X
corresponding to points around the periphery of the
20   mold measured in a clockwise direction from point S in
Fig. 4.

Fig. 6 is a perspective view of a wiper designed
for the casting mold of Fig. 4.

Fig. 7 is a graph illustrating a casting procedure
25   according to one form of an exemplary embodiment,
showing the surface temperature and core temperature
over time of an Al-1.5%Mn-0.6%Cu alloy as it is DC cast
and then subjected to water cooling and coolant wiping.
The thermal history in the region where solidification
30   and reheat takes place of an Al-1.5%Mn-0.6%Cu alloy
similar to that of US patent 6,019,939 in the case
where the bulk of the ingot is not forcibly cooled (the

lower temperature trace is the surface, and the upper
(dashed) trace is the center).

Fig. 8 is a graph illustrating the same casting
operation as Fig. 7 but extending over a longer period

5   of time and showing in particular the cooling period
following temperature convergence or rebound.

Fig. 9 is a graph similar to Fig. 7 but showing
temperature measurements of the same cast carried out
at three slightly different times (different ingot

10 lengths as shown in the figure). The solid lines show
the surface temperatures of the three plots, and the
dotted lines show the core temperatures. The times for
which the surface temperatures remain above 400°C and
500°C can be determined from each plot and are greater

15 than 15 minutes in each case. The rebound temperatures
of 563, 581 and 604°C are shown for each case.

Fig. 10a shows transmission electron micrographs
of Al-1.5%Mn-0.6%Cu alloy similar to that of US Patent
No. 6,019,939 with a solidification and cooling history

20 according to the commercial Direct Chill Process, and
thermal and mechanical processing history according to
Sample A in the following Example, showing the typical
precipitate population at 6mm thickness, found 25mm
from the surface and the center of the ingot.

25 Fig. 10b is a photomicrograph of the same area in
the sheet of Fig. 10a, but shown in polarized light to
reveal the recrystallized cell size.

Fig. 11a shows transmission electron micrographs
of Al-1.5%Mn-0.6%Cu, alloy similar to that of US Patent

30 No. 6,019,939 with a solidification and cooling history
according to the commercial Direct Chill Process, and
thermal and mechanical processing history according to
Sample B of the following Example, showing the typical

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precipitate population at 6mm thickness, found 25mm
from the surface and the center of the ingot.

Fig. 11b is a photomicrograph of the same area in
the sheet as Fig. 11a but shown in polarized light to
5   reveal the recrystallized cell size.

Fig. 12a shows transmission electron micrographs
of Al-1.5%Mn-0.6%Cu, alloy similar to that of US Patent
No. 6,019,939 with a solidification and cooling history
according to Fig. 7 and Fig. 8, and thermal and
10   mechanical processing history according to Sample C in
the following Example, showing the typical precipitate
population at 6mm thickness, found 25mm from the
surface and the center of the ingot.

Fig. 12b is a photomicrograph of the same area in
15   the sheet as Fig. 12a but shown in optical polarized
light to reveal the recrystallized cell size.

Fig. 13a shows transmission electron micrographs
of Al-1.5%Mn-0.6%Cu, alloy similar to that of US Patent
No. 6,019,939 with solidification and cooling history
20   according to Fig.9, and a thermal and mechanical
processing history according to Sample D of the
following Example, showing the typical precipitate
population at 6mm thickness, found 25mm from the
surface and the center of the ingot.

25   Fig. 13b is a photomicrograph of the same area in
the sheet as Fig. 13a but shown in polarized light to
reveal the recrystallized cell size.

Fig. 14a shows transmission electron micrographs
of Al-1.5%Mn-0.6%Cu alloy similar to that of US Patent
30   No. 6,019,939 with a solidification and cooling history
according to the commercial Direct Chill Process, and
thermal and mechanical processing history according to
Sample E in the following Example, showing the typical

precipitate population at 6mm thickness, found 25mm
from the surface and the center of the ingot.

Fig. 14b is a photomicrograph of the same area in
the sheet of Fig. 14a, but shown in polarized light to
5   reveal the recrystallized cell size.

Fig. 15a shows transmission electron micrographs
of Al-1.5%Mn-0.6%Cu alloy similar to that of US Patent
No. 6,019,939 with a solidification and cooling history
according to the commercial Direct Chill Process, and
10   thermal and mechanical processing history according to
Sample F in the following Example, showing the typical
precipitate population at 6mm thickness, found 25mm
from the surface and the center of the ingot.

Fig. 15b is a photomicrograph of the same area in
15   the sheet of Fig. 15a, but shown in polarized light to
reveal the recrystallized cell size.

Fig. 16 is a scanning electron micrograph with
Copper (Cu) Line Scan of Al-4.5%Cu through the center
of a solidified grain structure showing the typical
20   microsegregation common to the Conventional Direct
Chill Casting process.

Fig. 17 is an SEM Image with Copper (Cu) Line Scan
of Al-4.5%Cu with a wiper and a rebound/convergance
temperature (300°C)in the range taught by Ziegler,
25   2,705,353 or Zinniger, 4,237,961.

Fig. 18 is an SEM Image with Copper (Cu) Line Scan
of Al-4.5%Cu according to an exemplary embodiment in
the case where the bulk of the ingot is not forcibly
cooled (See Fig. 19).

30   Fig. 19 is a graph illustrating the thermal
history of an Al-4.5%Cu alloy in the region where
solidification and reheat takes place in the case where

20

the bulk of the ingot is not forcibly cooled (See Fig. 18).

Fig. 20 is an SEM Image with Copper (Cu) Line Scan of Al-4.5%Cu according to an exemplary embodiment in
5   the case where the bulk of the ingot is forcibly cooled after an intentional delay (See Fig. 21).

Fig. 21 is a graph showing the thermal history in the region where solidification and reheat takes place of an Al-4.5%Cu alloy in the case where the bulk of the
10   ingot is forcibly cooled after an intentional delay (See Fig. 20).

Fig. 22 is a graph showing representative area fractions of cast intermetallic phases compared across three various processing routes.
15   Fig. 23 is a graph illustrating the thermal history in the region where solidification and reheat takes place of an Al-0.5%Mg-0.45%Si alloy (6063) in the case where the bulk of the ingot is not forcibly cooled.
20   Fig. 24 is a graph illustrating the thermal history in the region where solidification and reheat takes place of an Al-0.5Mg-0.45%Si alloy (AA6063) in the case where the bulk of the ingot is forcibly cooled after an intentional delay.
25   Figs. 25a, 25b and 25c are each diffraction patterns of the alloy treated according to Fig. 23 and Fig. 24 is an XRD phase identification.

Fig. 26a, 26b and 26c are each graphical representations of FDC techniques carried out on the
30   ingots conventionally cast, and also treated according to the procedures of Figs. 23 and 24.

Figs. 27a and 27b are optical photomicrographs of an as-cast intermetallic, Al-1.3%Mn alloy (AA3003)

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processed according to an exemplary embodiment,
fractured;

Fig. 28 is an optical photomicrograph of an as
cast intermetallic, Al-1.3%Mn alloy processed according
5   to an exemplary embodiment, modified;

Fig. 29 is a transmission electron micrograph of
as cast intermetallic phase, cast according to this
exemplary embodiment, modified by diffusion of Si into
the particle, showing a denuded zone;

10 Fig. 30 is a graph illustrating the thermal
history of an Al-7%Mg alloy conventionally processed;

Fig. 31 is a graph illustrating the thermal
history of an Al-7% Mg alloy in the region where
solidification and reheat takes place in the case where
15 the bulk of the ingot is not forcibly cooled with a
rebound temperature which is below the dissolution
temperature for the beta (ß) phase.;

Fig. 32 is a graph illustrating the thermal
history of an Al-7%Mg alloy in the region where
20 solidification and reheat takes place in the case where
the bulk of the ingot is not forcibly cooled with a
rebound temperature which is above the dissolution
temperature for the beta (ß) phase;

Fig. 33 is the output trace of a Differential
25 Scanning Calorimeter (DSC) showing beta (ß) phase
presence in the 451-453°C range (Conventionally Direct
Chill Cast Material)(see Fig. 30);

Fig. 34 is the output trace of a Differential
Scanning Calorimeter (DSC) showing beta (ß) phase
30 absent)(see Fig. 31); and

Fig. 35 is the output trace of a Differential
Scanning Calorimeter (DSC) trace showing beta (ß) phase
absent (see Fig. 32).

BEST MODES FOR CARRYING OUT THE INVENTION

The following description refers to the direct chill
casting of aluminum alloys, but only as an example. The
5   present exemplary embodiment is applicable to various
methods of casting metal ingots, to the casting of most
alloys, particularly light metal alloys, and especially
those having a transformation temperature above 450°C and
that require homogenization after casting and prior to hot-
10   working, e.g. rolling. In addition to alloys based on
aluminum, examples of other metals that may be cast include
alloys based on magnesium, copper, zinc, lead-tin and iron.
The exemplary embodiment may also be applicable to the
casting of pure aluminum or other metals in which the
15   effects of one of the five results of the homogenization
process may be realized (see the description of these steps
above).

Fig. 1 of the accompanying drawings shows a
simplified vertical cross-section of one example of a
20   vertical DC caster 10 that may be used to carry out at
least part of a process according to one exemplary form
of the present exemplary embodiment. It will, of
course, be realized by persons skilled in the art that
such a caster could form part of a larger group of
25   casters all operating in the same way at the same time,
e.g. forming part of a multiple casting table.

Molten metal 12 is introduced into a vertically
orientated water-cooled mold 14 through a mold inlet 15
and emerges as an embryonic ingot 16 from a mold outlet
30   17. The embryonic ingot has a liquid metal core 24
within a solid outer shell 26 that thickens as the
embryonic ingot cools (as shown by line 19) until a
completely solid cast ingot is produced. It will be

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understood that the mold 14 peripherally confines and
cools the molten metal to commence the formation of the
solid shell 26, and the cooling metal moves out and
away from the mold in a direction of advancement

5   indicated by arrow A? in Fig. 1. Jets 18 of coolant
liquid are directed onto the outer surface of the ingot
as it emerges from the mold in order to enhance the
cooling and to sustain the solidification process. The
coolant liquid is normally water, but possibly another

10   liquid may be employed, e.g. ethylene glycol, for
specialized alloys such as aluminum-lithium alloys.
The coolant flow employed may be quite normal for DC
casting, e.g. 1.04 liters per minute per centimeter of
periphery to 1.78 liters per minute per centimeter of

15   periphery (0.7 gallons per minute (gpm)/inch of
periphery to 1.2 gpm/inch).

     An annular wiper 20 is provided in contact with
the outer surface of the ingot spaced at a distance X
below the outlet 17 of the mold and this has the effect

20   of removing coolant liquid (represented by streams 22)
from the ingot surface so that the surface of the part
of the ingot below the wiper is free of coolant liquid
as the ingot descends further. The streams 22 of
coolant are shown streaming from the wiper 20, but they

25   are spaced at a distance from the surface of the ingot
16 so that they do not provide a cooling effect.

     The distance X is made such that removal of
coolant liquid from the ingot takes place while the
ingot is still embryonic (i.e. it still contains the

30   liquid center 24 contained within the solid shell 26).
Put another way, the wiper 20 is positioned at a
location where a cross section of the ingot taken
perpendicular to the direction of advancement A

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intersects a portion of the liquid metal core 24 of the embryonic ingot. At positions below the upper surface of the wiper 20, continued cooling and solidification of the molten metal within the core of the ingot

5   liberates latent heat of solidification and sensible heat to the solid shell 26. This transference of latent and sensible heat, with the lack of continued forced (liquid) cooling, causes the temperature of the solid shell 26 (below the position where the wiper 20

10   removes the coolant) to rise (compared to its temperature immediately above the wiper) and converge with that of the molten core at a temperature that is arranged to be above a transformation temperature at which the metal undergoes *in-situ* homogenization. At

15   least for aluminum alloys, the convergence temperature is generally arranged to be at or above 425°C, and more preferably at or above 450°C. For practical reasons in terms of temperature measurement, the "convergence temperature" (the common temperature first reached by

20   the molten core and solid shell) is taken to be the same as the "rebound temperature" which is the maximum temperature to which the solid shell rises in this process following the removal of coolant liquid.

The rebound temperature may be caused to go as

25   high as possible above 425°C, and generally the higher the temperature the better is the desired result of *in-situ* homogenization, but the rebound temperature will not, of course, rise to the incipient melting point of the metal because the cooled and solidified outer shell

30   26 absorbs heat from the core and imposes a ceiling on the rebound temperature. It is mentioned in passing that the rebound temperature, being generally at least 425°C, will normally be above the annealing temperature

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of the metal (annealing temperatures for aluminum
alloys are typically in the range of 343 to 415°C).

The temperature of 425°C is a critical temperature
for most alloys because, at lower temperatures, rates
5 of diffusion of metal elements within the solidified
structure are too slow to normalize or equalize the
chemical composition of the alloy across the grain. At
and above this temperature, and particularly at and
above 450°C, diffusion rates are suitable to produce a
10 desired equalization to cause a desirable *in-situ*
homogenizing effect of the metal.

In fact, it is often desirable to ensure that the
convergence temperature reaches a certain minimum
temperature above 425°C. For any particular alloy,
15 there is usually a transition temperature between 425°C
and the melting point of the alloy, for example a
solvus temperature or a transformation temperature,
above which microstructural changes of the alloy take
place, e.g. conversion from ß-phase to α-phase
20 constituent or intermetallic structures. If the
convergence temperature is arranged to exceed such
transformation temperatures, desired transformational
changes can be introduced into the structure of the
alloy.

25   The rebound or convergence temperature is
determined by the casting parameters and, in
particular, by the positioning of the wiper 20 below
the mold (i.e. the dimension of distance X in Fig. 1).
Distance X should preferably be chosen such that: (a)
30 there is sufficient liquid metal remaining in the core
after coolant removal, and sufficient excess
temperature (super heat) and latent heat of the molten
metal, to allow the temperatures of the core and shell

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of the ingot to reach the desired convergence
temperature indicated above; (b) the metal is exposed
to a temperature above 425°C for a sufficient time
after coolant removal to allow desired micro-structural
5   changes to take place at normal rates of cooling in air
at normal casting speeds; and (c) the ingot is exposed
to coolant liquid (i.e. before coolant liquid removal)
for a time sufficient to solidify the shell to an
extent that stabilizes the ingot and prevents bleeding
10   or break-out of molten metal from the interior.

It is usually difficult to position the wiper 20
closer than 50mm to the mold outlet 17 while allowing
sufficient space for liquid cooling and shell
solidification, so this is generally the practical
15   lower limit (minimum dimension) for the distance X.
The upper limit (maximum dimension) is found as a
practical matter to be about 150mm, regardless of ingot
size, in order to achieve the desired rebound
temperatures, and the preferred range for distance X is
20   normally 50mm to 100mm. The optimal position of the
wiper may vary from alloy to alloy and from casting
equipment to casting equipment (as ingots of different
sizes may be cast at different casting speeds), but is
always above the position at which the core of the
25   ingot becomes completely solid. A suitable position
(or range of positions) can be determined for each case
by calculation (using heat-generation and heat-loss
equations), or by surface temperature measurements
(e.g. using standard thermocouples embedded in the
30   surface or as surface contact or non-contact probes),
or by trial and experimentation. For DC casting molds
of normal capacity forming an ingot of 10 to 60 cm in
diameter, casting speeds of at least 40 mm/minute, more

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preferably 50 to 75 mm/min (or 9.0×10^{-4} to 4.0×10^{-3}
meters/second), are normally employed.

    In some cases, it is desirable to make the
distance X vary at different times during a casting
5 procedure, i.e. by making the wiper 20 movable either
closer to the mold 14 or further away from the mold.
This is to accommodate the different thermal conditions
encountered during the transient phases at the start
and end of the casting procedure.

10   At the start of casting, a bottom block plugs the
mold outlet and is gradually lowered to initiate the
formation of the cast ingot. Heat is lost from the
ingot to the bottom block (which is normally made of a
heat-conductive metal) as well as from the outer
15 surface of the emerging ingot. However, as casting
proceeds and the emerging part of the ingot becomes
separated from the bottom block by an increasing
distance, heat is lost only from the outer surface of
the ingot. At the end of casting, it may be desirable
20 to make the outer shell cooler than normal just before
casting is terminated. This is because the last part
of the ingot to emerge from the mold is normally
gripped by a lifting device so that the entire ingot
can be raised. If the shell is cooler and thicker, the
25 lifting device is less likely to cause deformation or
tearing that may endager the lifting operation. In
order to achieve this, the rate of flow of cooling
liquid may be increased at the end phase of casting.

    In the start-up phase, more heat is removed from
30 the ingot than during the normal casting phase due to
the heat lost to the bottom block. In such a case, the
wiper may be moved temporarily closer to the mold to
reduce the length of time that the surface of the ingot

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is exposed to the cooling water, thus reducing heat
extraction. After a certain time, the wiper may be
relocated to its normal position for the normal casting
phase. In the end-phase, it is found in practice that

5 no movement of the wiper may be required but, if
necessary, the wiper can be raised to compensate for
the additional heat removed by the increased rate of
flow of the coolant liquid.

The distance through which the wiper is moved

10 (variation in X, i.e. ΔX) and the times at which the
movements are made can be calculated from theoretical
heat-loss equations, assessed from trial and
experimentation, or (more preferably) based on the
temperature of the ingot surface above (or possibly

15 below) the wiper determined by an appropriate sensor.
In the latter case, an abnormally low surface
temperature may indicate the need for a shortening of
the distance X (less cooling) and an unusually high
surface temperature may indicate the need for a

20 lengthening of the distance X (more cooling). A sensor
suitable for this purpose is described in U.S. patent
6,012,507 which issued on January 11, 2000 to Marc
Auger et al. (the disclosure of which is incorporated
herein by reference).

25   At the start of casting, the adjustment of the
position of the wiper is usually required just for the
first 50 cm to 60 cm of the casting procedure. Several
small incremental changes may be made, e.g. by a
distance of 25mm in each case. For an ingot of 68.5cm

30 in thickness, the first adjustment may be within 150-
300mm of the start of the ingot, and then similar
variations may be made at 30cm and 50-60cm. For a 50cm
thick ingot, the adjustments may be made at 15 cm,

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30cm, 50cm and 80cm. The final position of the wiper
is the one required for the normal casting procedure,
so the wiper starts at the closest point to the mold
and is then moved down as casting proceeds. This

5   approximates the reduction of heat-loss as the emerging
part of the ingot becomes more widely separated from
the bottom block as casting proceeds. The distance X
thus starts out shorter than in the normal casting
phase, and gradually lengthens to the distance required

10   for normal casting.

At the end of casting, if any adjustment is
required at all, it may be made within the last 25cm of
the cast, and there is normally a need for only one
adjustment by one to two centimeters.

15   The adjustment of the wiper position of the wiper
may be adjusted manually (e.g. if the wiper is
supported by chains having links or eyelets through
which projections (e.g. hooks) on the wiper are
inserted, the wiper may be supported and raised so that

20   the projections can be inserted through different links
or eyelets). Alternatively, and more preferably, the
wiper may be supported and moved by electrical,
pneumatic or hydraulic jacks optionally liked by
computer (or equivalent) to a temperature sensing

25   apparatus of the type mentioned above so that the wiper
may be moved according to a feedback loop with inbuilt
logic. An arrangement of this type is shown in
simplified form in Fig. 2.

The apparatus shown in Fig. 2 is similar to that

30   of Fig. 1, except that the wiper 20 is adjustable in
height, e.g. from an upper position shown in solid
lines to a lower position shown in broken lines. Thus,
the distance X from the outlet of mold 14 can be

30

modified by ΔX (either up or down). This adjustability
is possible because the wiper 20 is supported on
adjustable supports 21 which are hydraulic piston and
cylinder arrangements operated by a hydraulic engine

5   23. The hydraulic engine 23 is itself controlled by a
computer 25 based on temperature information delivered
by a temperature sensor 27 that monitors the surface
temperature of the ingot 16 immediately below the
outlet 17 of mold 14. As noted above, if the

10 temperature recorded by sensor 27 is lower than a
predetermined value, the wiper 20 may be raised, and if
the temperature is above a predetermined value the
wiper may be lowered.

    Desirably, in all forms of the exemplary

15 embodiments, the convergence temperature of the ingot
below the wiper 20 should remain above the
transformation temperature for in-situ homogenization
(generally above 425°C) for a sufficient period of time
to allow desired micro-structural transformations to

20 take place. The exact time will depend on the alloy,
but is preferably in the range of 10 minutes to 4 hours
depending on the elemental diffusion rates and the
amount to which the rebound temperature rises above
425°C. Normally, desirable changes have taken place

25 after no longer than 30 minutes, and often in the range
of 10 to 15 minutes. This is in sharp contrast to the
time required for conventional homogenization of an
alloy, which is normally in the range of 46 to 48 hours
at temperatures above a transformation temperature

30 (e.g. solvus) of the metal (often 550 to 625°C).
Despite the much-reduced time of the process of the
exemplary embodiments compared to conventional
homogenization, the resulting microstructure of the

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metal is essentially the same in both cases, i.e. the
cast product of the exemplary embodiments has the
microstructure of a homogenized metal without having
undergone conventional homogenization, and can be

5   rolled or hot-worked without further homogenization.
The present exemplary embodiment of the invention is
therefore referred to as "in-situ homogenization", i.e.
homogenization brought about during casting rather than
afterwards.

10   As a result of the coolant liquid application and
subsequent removal, the emerging ingot surface is first
subjected to the rapid cooling characteristic of film
and nucleate film boiling regimes, thereby ensuring
that the surface temperature is reduced quickly to a

15   low level (e.g. 150°C to 300°C), but is then subjected
to coolant liquid removal, thereby allowing the excess
temperature and latent-heat of the molten center of the
ingot (as well as the sensible heat of the solid metal)
to reheat the surface of the solid shell. This ensures

20   that temperatures necessary for desirable micro-
structural transitions are reached.

It is to be noted that, if the coolant is allowed
to contact the ingot for a longer time than is
desirable before being removed from the ingot surface

25   (or if the coolant is not removed at all), it is no
longer possible to make use of the substantial effect
of the super- and latent-heat of solidification of the
molten core to reheat the ingot shell sufficiently to
achieved the desired metallurgical changes. While

30   there would be some temperature equilibration across
the ingot with such a procedure, and while this could
possibly result in beneficial stress reduction and
crack reduction, the desired metallurgical changes are

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not obtained and a conventional additional
homogenization procedure would then be required before
rolling the ingots to gauge or desired thickness. The
same problem may occur if the coolant is removed from
5   the ingot surface in the desired manner, and then
further coolant is contacted with the ingot before
temperature equilibration throughout the ingot, and
desired micro-structural changes within the metal, have
taken place.

10   In some cases, coolant (particularly water-based
coolant) may be temporarily and at least partially
removed from the surface of the ingot by natural
nucleate film boiling, such that steam generated at the
metal surface forces liquid coolant away from the
15   ingot. Generally, however, the liquid returns to the
surface as further cooling takes place. If this
temporary removal of coolant takes place in advance of
the wiper used in this exemplary embodiment, the ingot
surface may show a double dip in its temperature
20   profile. The coolant cools the surface until it is
temporarily removed by nucleate film boiling, so that
the temperature then rises to some extent, then the
surface of the ingot passes through a pool of coolant
held on the upper surface of the wiper (the wiper may
25   be dished inwardly towards the ingot to promote the
formation of a pool of coolant) and the temperature
falls again, only to rise once again when the wiper
removes all coolant from the ingot surface. This
produces a characteristic "W" shape in the cooling
30   curve of the ingot shell (as can be seen from Figs. 23
and 24).

        The wiper 20 of Fig. 1 may be in the form of an
annulus of soft, temperature-resistant elastomeric

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material 30 (e.g. a high-temperature-resistant silicon
rubber) held within an encircling rigid support housing
32 (made, for example, of metal).

    While Fig. 1 illustrates a physical wiper 20,
5 other means of coolant removal may be employed, if
desired. In fact, it is often advantageous to provide
non-contact methods of coolant removal. For example,
jets of gas or a different liquid may be provided at
the desired location to remove the coolant flowing
10 along the ingot. Alternatively, use may be made of
nucleate film boiling as indicated above, i.e. the
coolant may be prevented from returning to the ingot
surface after temporary removal due to nucleate film
boiling. Examples of such non-contact methods of
15 coolant removal are shown, for example, in US patent
2,705,353 to Zeigler, German patent DE 1,289,957 to
Moritz, US patent 2,871,529 to Kilpatrick and US patent
3,763,921 to Beke et al. (the disclosures of which
patents are specifically incorporated herein by
20 reference). Nucleate film boiling may be assisted by
adding a dissolved or compressed gas, such as carbon
dioxide or air, to the liquid coolant, e.g. as
described in U.S. patent no. 4,474,225 to Yu, or U.S.
patents 4,693,298 and 5,040,595 to Wagstaff (the
25 disclosures of which are incorporated herein by
reference).

    Alternatively, the rate of delivery of the coolant
in the streams 18 may be controlled to the point that
all of the coolant evaporates from the ingot surface
30 before the ingot reaches the critical point (Distance
X) below the mold or before the surface of the ingot is
cooled below a critical surface temperature. This may
be done using a coolant supply as shown in US patent

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5,582,230 to Wagstaff et al. issued on December 10,
1996 (the disclosure of which is incorporated herein by
reference). In this arrangement, the coolant liquid is
supplied through two rows of nozzles connected to
5   different coolant supplies and it is a simple matter to
vary the amount of coolant applied to the ingot surface
to ensure that the coolant evaporates where desired
(Distance X). Alternatively, or in addition, heat
calculations may be made in a manner similar to those
10   of US patent 6,546,995 based on annularly successive
part annular portions of the mold to ensure that a
volume of water is applied that will evaporate as
required.

     Aluminum alloys that may be cast according to the
15   exemplary embodiments include both non-heat-treatable
alloys (e.g. AA1000, 3000, 4000 and 5000 series) and
heat-treatable alloys (e.g. AA 2000, 6000 and 7000
series). In the case of heat-treatable alloys cast in
the known manner, Uchida et al. taught in
20   PCT/JP02/02900 that a homogenization step followed by a
quench to a temperature below 300°C, preferably to room
temperature, prior to heating and hot rolling, and
subsequent solution heat treatment and aging, exhibits
superior properties (dent resistance, improved blank
25   formed values and hard properties) when compared to
conventionally processed materials. Unexpectedly, this
characteristic can be duplicated in the exemplary
embodiments during the ingot casting procedure, if
desired, by subjecting the ingot (i.e. the part of the
30   ingot that has just undergone in-situ homogenization)
to a quench step after a sufficient period of time has
passed (e.g. at least 10 to 15 minutes) following
coolant liquid removal to allow homogenization of the

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alloy, but prior to substantial additional cooling of
the ingot.

This final quench (*in-situ* quench) is illustrated
in Fig. 3 of the accompanying drawings where a DC
5   casting operation (essentially the same as that of
Fig. 1) is carried out, but the ingot is immersed in a
pool 34 of water (referred to as a pit pool or pit
water) at a suitable distance Y beneath the point at
which the coolant is removed from the ingot. The
10 distance Y must, as stated, be sufficient to allow the
desired *in-situ* homogenization to proceed for an
effective period of time, but insufficient to allow
substantial further cooling. For example, the
temperature of the outer surface of the ingot just
15 prior to immersion in the pool 34 should preferably be
above 425°C, and desirably in the range of 450 to
500°C. The immersion then causes a rapid water quench
of the temperature of the ingot to a temperature (e.g.
350°C) below which transformations of the solid
20 structure do not take place at an appreciable rate.
After this, the ingot may be cut to form a standard
length used for rolling or further processing.

Incidentally, to enable an ingot to be water
quenched over its entire length, the casting pit (the
25 pit into which the ingot descends as it emerges from
the mold) should be deeper than the length of the
ingot, so that when no further molten metal is added to
the mold, the ingot can continue to descend into the
pit, and into the pool 34 until it is fully submerged.
30 Alternatively, the ingot may be partially submerged to
a maximum depth of the pool 34, and then more water may
be introduced into the casting pit to raise the level

of the surface of the pool until the ingot is fully
submerged.

It should be noted that the exemplary embodiments
are not limited to the casting of cylindrical ingots
5   and it can be applied to ingots of other shapes, e.g.
rectangular ingots or those formed by a shaped DC
casting mold as disclosed in Fig. 9 or Fig. 10 of U.S.
patent No. 6,546,995, issued on April 15, 2003 to
Wagstaff (the disclosure of this patent is incorporated
10   herein by reference). Fig. 10 of the patent is
duplicated in the present application as Fig. 4, which
is a top plan view looking into the casting mold. It
will be seen that the mold is approximately "J"-shaped
and it is intended to produce an ingot having a
15   corresponding cross-sectional shape. An embryonic
ingot produced from such a mold would have a molten
core that is spaced from the outer surface by different
distances at points around the circumference of the
ingot, and thus, given equal cooling termination around
20   the ingot circumference (distance X), different amounts
of super- and latent-heat of solidification would be
delivered to different parts of the ingot shell.

It is, in fact, desirable to subject all parts of
the shell around the periphery to the same convergence
25   temperature. In U.S. patent 6,546,995, equal casting
characteristics around the mold are assured by
adjusting the geometry of the casting surfaces of the
mold to suit the shape of the cast ingot. In the
exemplary embodiments, it is possible to ensure that
30   each part of the embryonic ingot shell (after
termination of cooling) is subjected to the same heat
input from the molten core and the same convergence
temperature by dividing the ingot circumference into

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notional segments according to the shape of the ingot,
and removing coolant fluid at different distances from
the mold outlet in different segments. Some segments
(the ones that will be subjected to higher heat inputs
5   from the core) will be exposed to the cooling fluid for
a longer period of time than other segments (those that
will have less heat exposure). Some segments of the
shell will therefore have a lower temperature than
others after the cooling fluid is removed, and this
10   lower temperature will compensate for the higher heat
input to those segments from the core so that
convergence temperatures equalize around the
circumference of the ingot.

Such a procedure may be achieved, for example, by
15   designing a wiper (a) shaped to fit snugly around the
shaped ingot, and (b) having different planes or a
shaped contour at the end of the wiper facing the mold,
the different planes or sections of the contour having
different spacing from the outlet of the mold. Fig. 5
20   is a plot showing variations in distance X around the
periphery of the mold of Fig. 4 designed to produce
even convergence temperatures around the ingot (the
plot begins at point S in Fig. 4 and proceeds in a
clockwise direction). A wiper having a corresponding
25   peripheral shape is then used to cause the desired
equalization of convergence temperature around the
periphery of the ingot.

Fig. 6 illustrates a wiper 20' that could be
effective for casting an ingot having a shape similar
30   to that of Fig. 4. It will be seen that the wiper 20'
has a complex shape with parts that are elevated with
respect to other parts, thereby ensuring that the
cooling liquid is removed from the outer surface of the

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emerging ingot at positions designed to equalize the
convergence temperature around the ingot at positions
below the wiper 20'.

5   The points at which the coolant is removed from
the various segments, and the width of the segments
themselves, can be decided by computer modeling of the
heat flux within the cast ingot, or by simple trial and
experimentation for each ingot of different shape.
Again, the goal is to achieve the same or very similar
10   convergence temperatures around the periphery of the
ingot shell.

As already discussed at length, the exemplary
embodiments, at least in its preferred forms, provides
an ingot having a microcrystalline structure resembling
15   or identical to that of the same metal cast in a
conventional way (no wiping of coolant liquid) and
later subjected to conventional homogenization.
Therefore, the ingots of the exemplary embodiments can
be rolled or hot-worked without resorting to a further
20   homogenization treatment. Normally, the ingots are
first hot-rolled and this requires that they be pre-
heated to a suitable temperature, e.g. normally at
least 500°C, and more preferably at least 520°C. After
hot-rolling, the resulting sheets of intermediate gauge
25   are then normally cold-rolled to final gauge.

As a further aspect of the exemplary embodiments,
it has been found that at least some metals and alloys
benefit from a particular optional two-stage pre-
heating procedure after ingot formation and prior to
30   hot-rolling. Such ingots may ideally be produced by the
"in-situ homogenization" process described above, but
may alternatively be produced by conventional casting
procedures, in which case advantageous improvements are

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still obtained. This two-stage pre-heating procedure
is particularly suitable for alloys intended to have
"deep-draw" characteristics, e.g. aluminum alloys
containing Mn and Cu (e.g. AA3003 aluminum alloy having

5   1.5 wt.% Mn and 0.6 wt.% Cu). These alloys rely on
precipitation or dispersion strengthening. In the two-
stage pre-heating procedure, DC cast ingots are
normally scalped and then set in a preheat furnace for
a two-stage heating process involving: (1) heating

10   slowly to an intermediate nucleating temperature below
a conventional hot-rolling temperature for the alloy
concerned, and (2) continuing to heat the ingot slowly
to a normal hot-rolling pre-heat temperature, or a
lower temperature, and holding the alloy at that

15   temperature for a number of hours. The intermediate
temperature allows for nucleation of the metal and for
the re-absorption or destruction of unstable nuclei and
their replacement with stable nuclei that form centers
for more robust precipitate growth. The period of

20   holding at the higher temperature allows time for
precipitate growth from the stable nuclei before
rolling commences.

        Stage (1) of the heating process may involve
holding the temperature at the nucleating temperature

25   (the lowest temperature at which nucleation commences)
or, more desirably, involves gradually raising the
temperature towards the higher temperature of stage
(2). The temperature during this stage may be from
380-450°C, more preferably 400-420°C, and the

30   temperature may be held or slowly raised within this
range. The rate of temperature increase should
preferably be below 25°C/hr, and more preferably below
20°C/hr, and generally extends over a period of 2 to 4

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hours. The rate of heating to the nucleating
temperature may be higher, e.g. an average of about
50°C/hour (although the rate in the first half hour or
so may be faster, e.g. 100-120°C/hr, and then slows as
5   the nucleating temperature is approached).

After stage (1), the temperature of the ingot is
raised further (if necessary) either to the hot-rolling
temperature or to a lower temperature at which
precipitate growth may take place, usually in the range
10 of 480-550°C, or more preferably 500-520°C. The
temperature is then held constant or slowly raised
further (e.g. to the hot-rolling temperature) for a
period of time that is preferably not less than 10
hours and not more than 24 hours in total for the
15 entire two-stage heating process.

While heating the ingot directly to the rolling
pre-heat temperature (e.g. 520°C) makes the secondary
crystal or precipitate population high, the resulting
precipitates are generally small in size. The preheat
20 at the intermediate temperature leads to nucleation and
then the continued heating to or below the rolling pre-
heat temperature (e.g.520°C) leads to growth in size of
the secondary precipitates, e.g. as more Mn and Cu
comes out of solution and the precipitates continue to
25 grow.

After heating to the hot-rolling temperature,
conventional hot-rolling is normally carried out
without delay.

The process herein described involving *in-situ*
30 homogenization can also be used to cast composite
ingots as described in U.S. patent application Serial
No. 10/875,978 filed June 23, 2004, and published on
January 20, 2005 as U.S. 2005-0011630, and also as

described in U.S. patent 6,705,384 issued on March 16,
2004, the complete disclosures of which are
incorporated herein by this reference.

   The invention is described in more detail in the
5 following Examples and Comparative Examples, which are
provided for illustrative purposes only and should not
be considered limiting.

10   EXAMPLE 1

   Three direct chill cast ingots were cast in a 530
mm and 1,500 mm Direct Chill Rolling Slab Ingot Mold
with a final length of greater than 3 meters. The
15 ingots had an identical composition of Al 1.5% Mn; 6%
Cu according to U.S. Patent No. 6,019,939 (the
disclosure of which is incorporated herein by
reference). A first ingot was DC cast according to a
conventional procedure, a second was DC cast with in-
20 situ homogenization according to the procedure shown in
Figs. 7 and 8, where the coolant is removed and the
ingot is allowed to cool to room temperature after
being removed from the casting pit, and the third was
DC cast with in-situ quench homogenization according to
25 the procedure of Fig. 9, where the coolant is removed
from the surface of the ingot and the ingot is allowed
to reheat then quench in a pit of water approximately
one meter below the mold.

   In more detail, Fig. 7 shows the surface
30 temperature and the center (core) temperature over time
of an Al-Mn-Cu alloy as it is DC cast and then
subjected to water cooling and coolant wiping. The
plot of the surface temperature shows a deep dip in

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temperature immediately after casting as the ingot
comes into contact with the coolant, but the
temperature in the center remains little changed. The
surface temperature dips to a low of about 255°C just
5   prior to coolant removal. The surface temperature then
ascends and converges with the central temperature at a
convergence or rebound temperature of 576°C. After the
convergence (when the ingot is fully solid) the
temperature falls slowly and is consistent with air
10 cooling.

Fig. 8 shows the same casting operation as Fig. 7,
but extending over a longer period of time and showing
in particular the cooling period following temperature
convergence or rebound. It can be seen from this that
15 the temperature of the solidified ingot remains above
425°C for more than 1.5 hours, which is ample to
achieve the desired in-situ homogenization of the
ingot.

Fig. 9 is similar to Fig. 7 but showing
20 temperature measurements of the same cast carried out
at three slightly different times (different ingot
lengths as shown in the figure). The solid lines show
the surface temperatures of the three plots, and the
dotted lines show the temperatures at the center of the
25 thickness of the ingot. The times for which the
surface temperatures remain above 400°C and 500°C can
be determined from each plot and are greater than 15
minutes in each case. The rebound temperatures of 563,
581 and 604°C are shown for each case.
30   Samples of these ingots were then rolled either
with a conventional pre-heat to a hot-rolling
temperature, or with various pre-heats to demonstrate
the nature of the exemplary embodiments.

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The casting procedures were carried out under industry-typical cooling conditions e.g., 60mm/min, 1.5 liters/min/cm, 705°C metal temperature.

Each ingot was sectioned along the center (mid-
5   section) yielding two portions of each ingot of width 250mm, then, while maintaining the thermal history at the center and at the surface, each 250mm slab was sectioned into multiple rolling ingots, 75mm thick, 250mm wide (in the original ingot ⅓ thickness) and
10   150mm long (in the cast direction).

The rolling ingots were then treated in the following ways.

Sample A (Direct Chill cast with conventional thermal history and modified conventional
15   homogenization) was placed in a 615°C furnace, where approximately after two and one half (2.5) hours the metal temperature stabilized and was held for an additional 8 hours at 615°C. The sample received a furnace quench over three hours to 480°C and was then
20   soaked at 480°C for 15 hours, then removed and hot rolled to 6mm in thickness. A portion of this 6mm gauge was then cold rolled to 1mm thickness, heated to an annealing temperature of 400°C at a rate of 50°C/hr, and held for two hours, and then furnace cooled.
25   Transmission electron micrographs showing the secondary precipitate distribution, were characterized in longitudinal sections taken within one inch from either edge (surface and center) of the 6mm material (Fig. 10a). Recrystallized grain structures were
30   characterized in longitudinal sections taken within one inch from either edge (surfaces and center) of the 1mm thick material (Fig. 10b).

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This sample represents conventional casting and
homogenization, except that the homogenization step was
abbreviated to a total of 26 hours, whereas normal
conventional homogenization is carried on for 48 hours.

5   **Sample B** (Direct Chill cast with a conventional
cast thermal history and with modified two-stage pre-
heat) was placed in a 440°C furnace, where
approximately after two (2) hours the metal temperature
stabilized and was held for an additional 2 hours at

10   440°C. Furnace temperatures were raised to allow the
metal to heat to 520°C over two (2) hours and the
sample was held for 20 hours then removed and hot
rolled to 6mm in thickness. A portion of this 6mm
gauge was then cold rolled to 1mm thickness, heated to

15   an annealing temperature of 400°C at a rate of 50°C/hr,
and held for two hours, and then furnace cooled.

Transmission electron micrographs showing the
secondary precipitate distribution, were characterized
in longitudinal sections taken within one inch from

20   either edge (surface and center) of the 6mm thick
material (Fig. 11a). Recrystallized grain structures
were characterized in longitudinal sections taken
within one inch from either edge (surfaces and center)
of the 1mm thick material (Fig. 11b).

25   **Sample C** (Direct Chill cast with *in-situ*
homogenization (according to Figs. 7 and 8) cast
thermal history and with modified two-stage pre-heat)
was placed in a 440°C furnace, where approximately
after two (2) hours the metal temperature stabilized

30   and was held for an additional 2 hours at 440°C.
Furnace temperatures were raised to allow the metal to
heat to 520°C over two (2) hours and the sample was
held for 20 hours then removed and hot rolled to 6mm in

thickness. A portion of this 6mm gauge was then cold
rolled to 1mm thickness, heated to an annealing
temperature of 400°C at a rate of 50°C/hr, and held for
two hours, and then furnace cooled.

5   Transmission electron micrographs showing the
secondary precipitate distribution, were characterized
in longitudinal sections taken within one inch from
either edge (surface and center) of the 6m thick
material (Fig. 12a). Recrystallized grain structures

10 were characterized in longitudinal sections taken
within one inch from either edge (surfaces and center)
of the 1mm thick material (Fig. 12b).

        Sample D (Direct Chill casting with *in-situ*
homogenization and quick quench (Figure 9) with a two-

15 stage pre heat) was placed in a 440°C furnace, where
after two (2) hours the metal temperature stabilized
and held for an additional 2 hours at 440°C. Furnace
temperatures were raised to allow the metal to heat to
520°C over two (2) hours and held for 20 hours then

20 removed and hot rolled to 6mm in thickness. A portion
of this 6mm gauge was then cold rolled to 1mm
thickness, heated to an annealing temperature of 400°C
at a rate of 50°C/hr, and held for two hours, and then
furnace cooled.

25   Transmission electron micrographs showing the
secondary precipitate distribution, were characterized
in longitudinal sections taken within 25mm from either
edge (surface and center) of the 6mm thick material
(Fig. 13a). Recrystallized grain structures were

30 characterized in longitudinal sections taken within
25mm from either edge (surfaces and center) of the 1mm
thick material (Fig. 13b).

Sample F (Direct Chill cast with conventional
thermal history and modified conventional
homogenization) was placed in a 615°C furnace, where
approximately after two and one half (2.5) hours the
5   metal temperature stabilized and was held for an
additional 8 hours at 615°C. The sample received a
furnace quench over three hours to 480°C and was then
soaked at 480°C for 38 hours, then removed and hot
rolled to 6mm in thickness. A portion of this 6mm
10 gauge was then cold rolled to 1mm thickness, heated to
an annealing temperature of 400°C at a rate of 50°C/hr,
and held for two hours, and then furnace cooled.

Transmission electron micrographs showing the
secondary precipitate distribution, were characterized
15 in longitudinal sections taken within one inch from
either edge (surface and center) of the 6mm material
(Fig. 14a). Recrystallized grain structures were
characterized in longitudinal sections taken within
25mm from either edge (surfaces and center) of the 1mm
20 thick material (Fig. 14b). This sample represents
conventional casting and homogenization, whereas normal
conventional homogenization is carried on for 48 hours.

Sample G (Direct Chill cast with a modified
single-stage pre-heat) was placed in a 520°C furnace,
25 where approximately after two (2) hours the metal
temperature stabilized and was held for 20 hours at
520°C, then removed and hot rolled to 6mm in thickness.
A portion of this 6mm gauge was then cold rolled to 1mm
thickness, heated to an annealing temperature of 400°C
30 at a rate of 50°C/hr, and held for two hours, and then
furnace cooled.

Transmission electron micrographs showing the
secondary precipitate distribution, were characterized

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in longitudinal sections taken within one inch from
either edge (surface and center) of the 6mm thick
material (Fig. 15a). Recrystallized grain structures
were characterized in longitudinal sections taken
5 within 25mm from either edge (surfaces and center) of
the 1mm thick material (Fig. 15b).

COMPARATIVE EXAMPLE 1

10   In order to illustrate the difference of the
exemplary embodiments from known casting procedures,
ingots of an Al-4.5wt%Cu alloy were cast according to
conventional DC casting, according to the procedure of
U.S. patent 2,705,353 to Ziegler or U.S. patent
15 4,237,961 to Zinniger, and according to the exemplary
embodiments. The Ziegler/Zinniger casting employed a
wiper positioned to generate a rebound/convergence
temperature of only 300°C. The casting process of the
exemplary embodiments employed a wiper positioned to
20 generate a rebound temperature of 453°C. Scanning
electron micrographs of the three resulting products
were produced and are shown in Figs. 16, 17 and 18,
respectively. Fig. 19 shows the core and surface
temperatures of the casting procedure carried out
25 according to the exemplary embodiments without a quench
(see Fig. 18).
        The SEMs show how the concentration of copper
varies across the cell in the product of the casting
procedures carried out not in accordance with the
30 exemplary embodiments (Figs. 16 and 17 - note the
upward curve of the plots between the peaks). In the
case of the product of the exemplary embodiments,
however, the SEM shows much less variation of Cu

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content within the cell (Fig. 18). This is typical of
a microstructure of a metal that has undergone
conventional homogenization.

5   EXAMPLE 2

        An Al-4.5% Cu ingot was cast according to the
invention and the ingot was cooled (quenched) at the
end of the cast. Fig. 20 is and SEM with Copper (Cu)
10 Line Scan of the resulting ingot. The absence of any
coring of Copper in the unit cell is to be noted.
Although the cells are slightly larger than those of
Fig. 16, there is a reduced amount of cast
intermetallic at the intersection of the unit cells and
15 the particles are rounded.
        Fig. 21 shows the thermal history of the casting
of the ingot illustrating the final quench at the end
of the cast. The convergence temperature (452°C) in
this case is below the solvus for the composition
20 chosen, but desirable properties are obtained.

                        COMPARATIVE EXAMPLE 2

        Fig. 22 shows representative area fractions of
25 cast intermetallic phases comparing the three various
processing routes as indicated above (conventional DC
casting and cooling (labeled DC), DC casting and
cooling without final quench according to the exemplary
embodiments (labeled In-Situ Sample ID), and DC casting
30 with final quench according to the exemplary
embodiments (labeled In-Situ Quench). A smaller area
is considered better for mechanical properties of the
resulting alloy. This comparison shows a decreasing

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cast intermetallic phase area fraction according to the
different methods in the given order. The highest
phase area is produced by the conventional DC route and
the lowest by the invention with final quench.

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<div align="center">EXAMPLE 3</div>

An ingot of an Al-0.5%Mg-0.45%Si alloy (6063) was
cast according to a process as illustrated in the graph
10 of Fig. 23. This shows the thermal history in the
region where solidification and reheat takes place in a
case where the bulk of the ingot is not forcibly
cooled.

The same alloy was cast under the conditions shown
15 in Fig. 24 (including a quench). This shows the
temperature evolution of an ingot where the surface and
core temperatures converged at a temperature of 570°C,
and which is then forcibly cooled to room temperature.
This can be compared to the procedure shown in Fig. 8
20 which involved a high rebound temperature and slow
cooling, which is desirable when a more rapid
correction of the cellular segregation is needed, or
when the alloy contains elements that diffuse at a slow
pace. The use of a high rebound temperature
25 (considerably above the solvus of the alloy), held for
a prolonged period of time, allows elements near the
grain boundary to diffuse quite quickly into the cast
intermetallic phases, thereby allowing modification or
a more complete transformation to more useful or
30 beneficial intermetallic phases, and the formation of a
precipitate free zone around the cast intermetallic
phases. It will be noted that Fig. 24 shows the "W"

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shape of the cooling curve for the shell characteristic
of nucleate film boiling in advance of the wiper.

COMPARATIVE EXAMPLE 3

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Figs. 25a, 25b and 25c are X-Ray diffraction
patterns taken from of 6063 alloy differentiating the
amount of α and ß phases contrasting conventional DC
casting and two in-situ procedures of Figs. 18 and 19.
10 The upper trace of each figure represents a
conventionally cast DC alloy, the middle trace
represents a rebound temperature below the
transformation temperature of the alloy, and the lower
trace represents a rebound temperature above the
15 transformation temperature of the alloy.

COMPARATIVE EXAMPLE 4

Figs. 26a, 26b and 26c are graphical
20 representations of FDC techniques in which Fig. 26a
represents conventionally DC cast ingot, Fig. 26b
represents the alloy of Fig. 23 and Fig. 26c represents
the alloy of Fig. 24. The figures show an increase in
the presence of the desirable α-phase as the rebound
25 temperature passes the transformation temperature.
Incidentally, more information about both the FDC
and SiBut/XRD techniques, as well as their application
to the study of phase transformations, can be obtained
from: "Intermetallic Phase Selection and Transformation
30 in Aluminium 3xxx Alloys", by H.Cama, J.Worth, P.V.
Evans, A.Bosland and J.M.Brown, Solidification
Processing, Proceedings of the 4th Decennial
International Conference on Solidification Processing,

University of Sheffield, July 1997, eds J.Beech and
H.Jones, p.555 (the disclosure of which is incorporated
herein by reference).

5   EXAMPLE 4

        Figs. 27a and 27b show two optical
photomicrographs of a cast intermetallic, Al-1.3%Mn
alloy (AA3003) processed according to the invention.
10 It can be seen that the intermetallics (dark shapes in
the figure) are cracked or fractured.
        Fig. 28 is an optical photomicrograph similar to
those of Figs. 27a and 27b again showing that the
intermetallic is cracked or fractured. The large region
15 of the particle is of $MnAl_6$. The ribbed features show
Si diffusion into the intermetallic, forming AlMnSi.

                         EXAMPLE 5

20   Fig. 29 is a Transmission Electron Microscope TEM
image of an as-cast intermetallic phase of an AA3104
alloy cast without a final quench, as shown in Fig. 31.
The intermetallic phase is modified by diffusion of Si
into the particle, showing a denuded zone. The sample
25 was taken from the surface where the initial
application of coolant nucleates particles. However,
the rebound temperature modifies the particle and
modifies the structure.

30

COMPARATIVE EXAMPLE 5

Fig. 30 shows the thermal history of the Al-7%Mg alloy processed conventionally. It can be seen that there is no rebound of the shell temperature due to continued presence of coolant.

Figs. 31 and 32 show the thermal history of an Al-7%Mg alloy where the ingot is not cooled during the cast. This alloy forms the basis of Fig. 30.

COMPARATIVE EXAMPLE 6

Fig. 33 is a trace from a Differential Scanning Calorimeter (DSC) showing Beta (β) phase presence in the 450°C range of the conventionally direct chill cast alloy which forms the basis of Fig. 30. The β-phase causes problems during rolling. The presence of the beta phase can be seen by the small dip in the trace just above 450°C as heat is absorbed to convert β-phase to α-phase. The large dip descending to 620°C represents melting of the alloy.

Fig. 34 is a trace similar to that of Fig. 33 showing the absence of Beta (β) phase in the material cast according to this invention where the ingot remains hot (no final quenching) during the cast (see Fig. 31) .

Fig. 35 is again a trace similar to that of Fig. 33 for the material cast according to this invention where the ingot remains hot (no final quenching) during the cast (see Fig. 32) . Again, the trace shows an absence of Beta (β) phase.

It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

In the claims which follow and in the preceding description of the invention, except where the context

requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but

5   not to preclude the presence or addition of further features in various embodiments of the invention.

CLAIMS:

1.   A method of continuously or semi-continuously direct chill casting an ingot made of a castable metal,
5   comprising the steps of:
        (a) providing a direct chill casting mold having one or more mold inlets and one or more mold outlets,
        (b) supplying molten metal to at least one inlet of the casting mold;
10   (c) cooling the mold to solidify a peripheral portion of the metal, thereby forming an embryonic ingot having an external solid shell and an internal molten core;
        (d) continuously advancing the embryonic ingot beyond at least one outlet of the mold, thereby extending the
15   molten core contained within the solid shell beyond said at least one outlet of the mold;
        (e) cooling the embryonic ingot emerging from the mold to continue the solidification thereof by directing a supply of coolant liquid onto an outer surface of the
20   embryonic ingot;
        (f) causing said coolant liquid to be removed from the surface of the embryonic ingot at a position where the ingot has not yet been transformed into a fully solid ingot such that internal heat from the molten core reheats
25   the solid shell adjacent to the core, thereby causing temperatures of said core and said shell to equilibrate at a convergence temperature, said coolant liquid being removed from said surface at a distance from said at least one mold outlet that causes said convergence temperature
30   to become 425°C or higher; and
        (g) varying said position in step (f) in different phases of said casting of said ingot to minimize differences of said convergence temperature below said wiper during said different phases of casting.

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2.   The method according to claim 1, characterized in that said position is moved closer to said mold during an initial phase of casting than in a subsequent phase.

5   3.   The method according to claim 1, characterized in that said position is moved in relation to said mold during a final phase of casting.

4.   An apparatus for continuously or semi-continuously
10   direct chill casting a metal ingot, comprising:
       a casting mold having at least one inlet, at least one outlet and at least one mold cavity;
       at least one cooling jacket for said at least one mold cavity;
15   a supply of coolant liquid arranged to cause the coolant liquid to flow along an exterior surface of an embryonic ingot emerging from said at least one outlet;
       means spaced at a distance from said at least one outlet for removing said coolant liquid from said exterior
20   surface of said embryonic ingot; and
       apparatus for moving said coolant removing means towards and away from said at least one outlet, thereby enabling said distance to be modified during casting of said ingot.
25

5.   The apparatus according to claim 4 characterized in that said casting mold is a direct chill casting mold.

6.   A method of continuously or semi-continuously direct
30   chill casting an ingot made of a castable metal substantially as herein described with reference to the accompanying examples and figures excluding the comparative examples.

35   7.   An apparatus for continuously or semi-continuously direct chill casting a metal ingot substantially as herein described with reference to the accompanying examples and

figures, excluding the comparative examples.

Fig. 1

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Fig. 2

Fig. 3

S

Fig. 4

Fig. 5

Fig. 6

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-66-
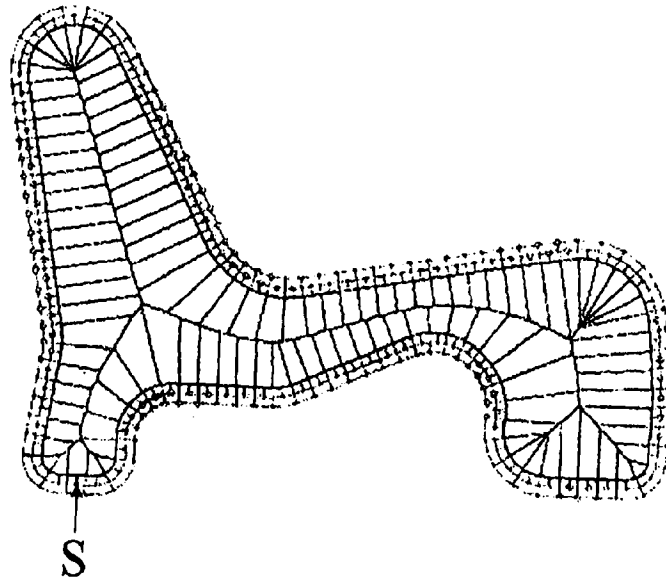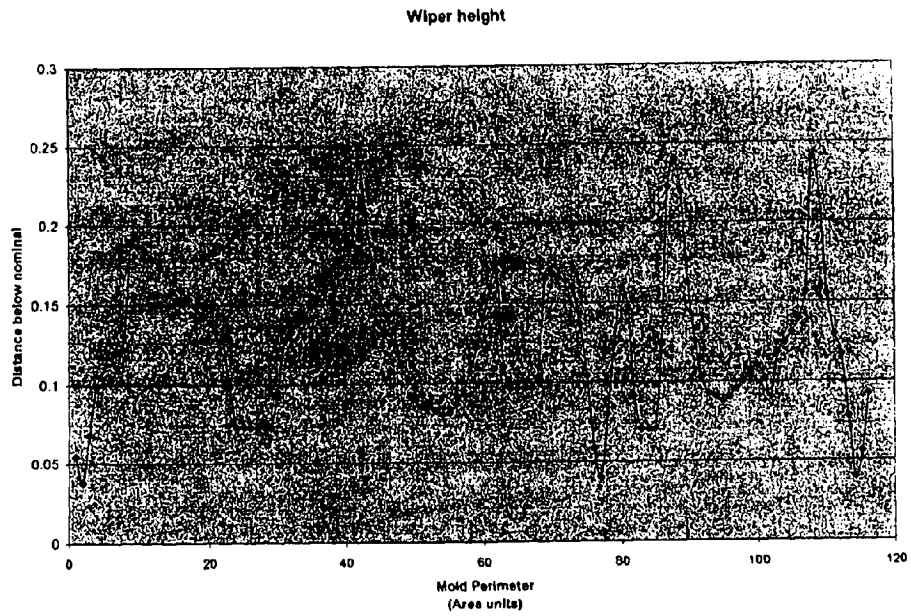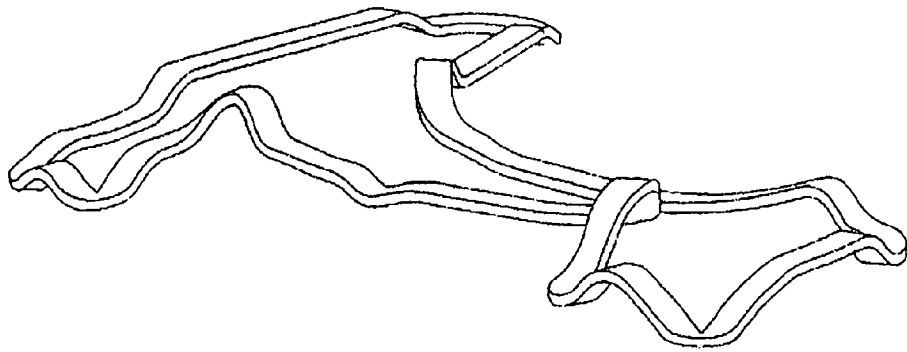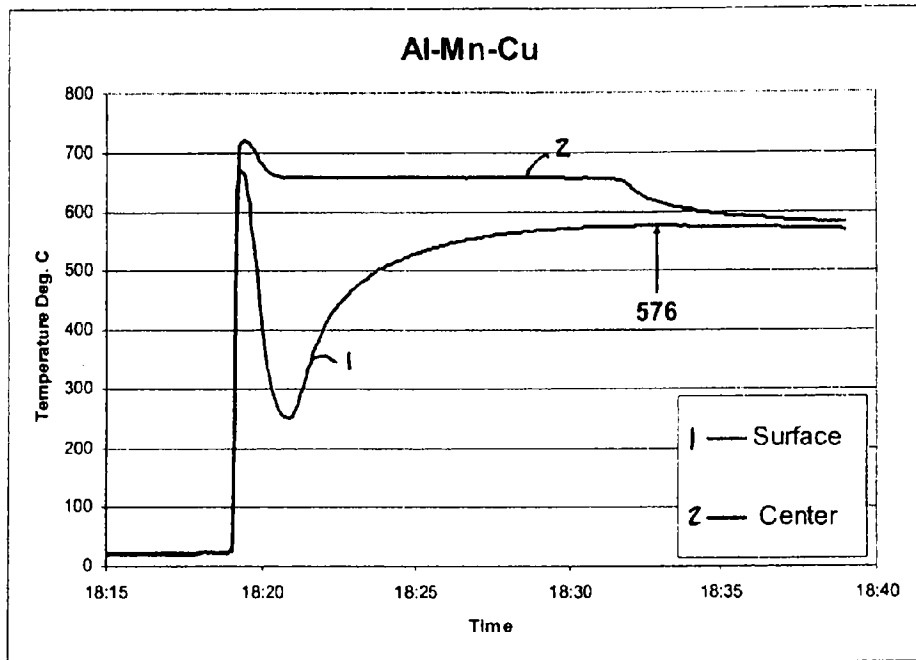
Fig. 7
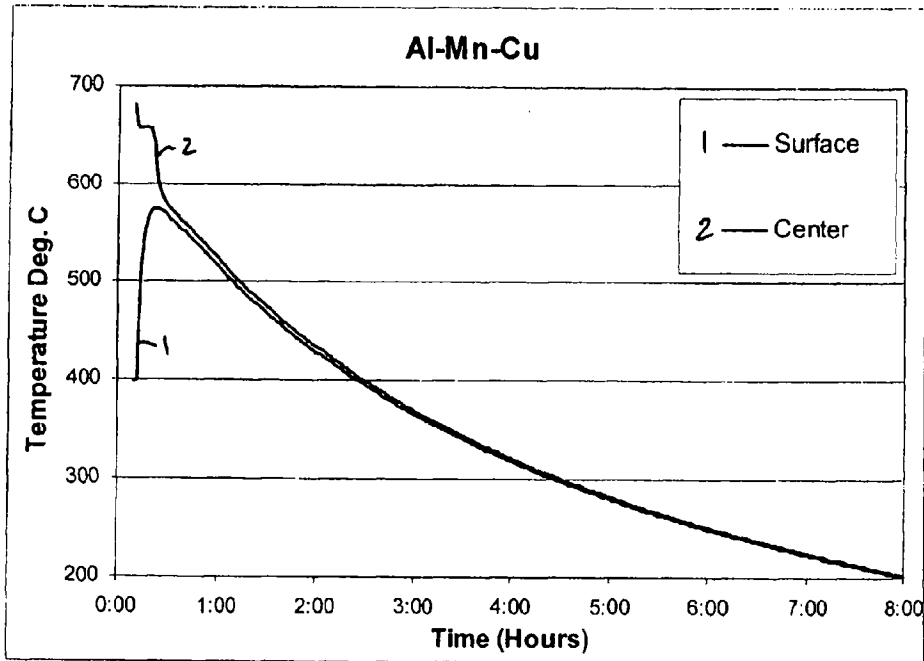
Fig. 8
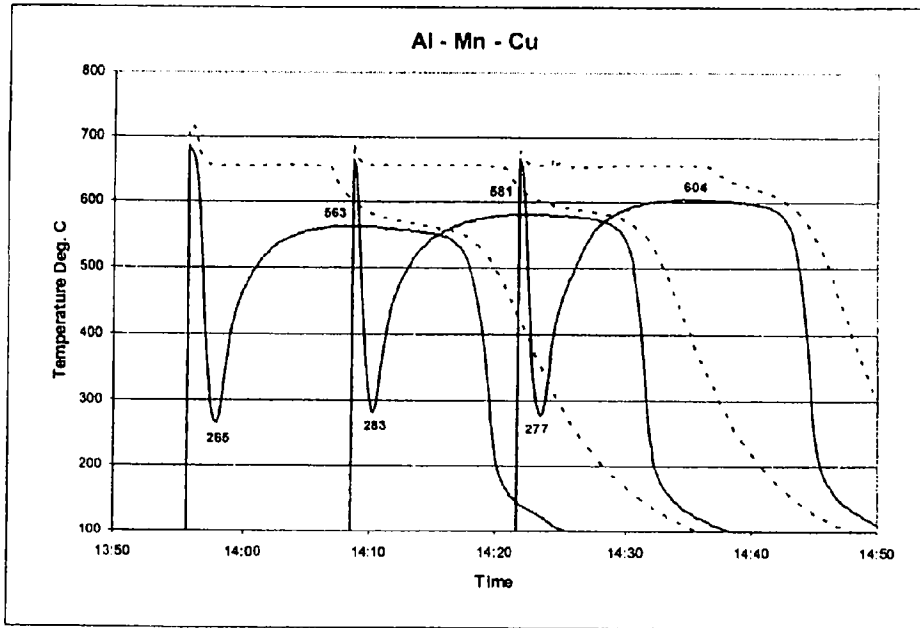
Fig. 9
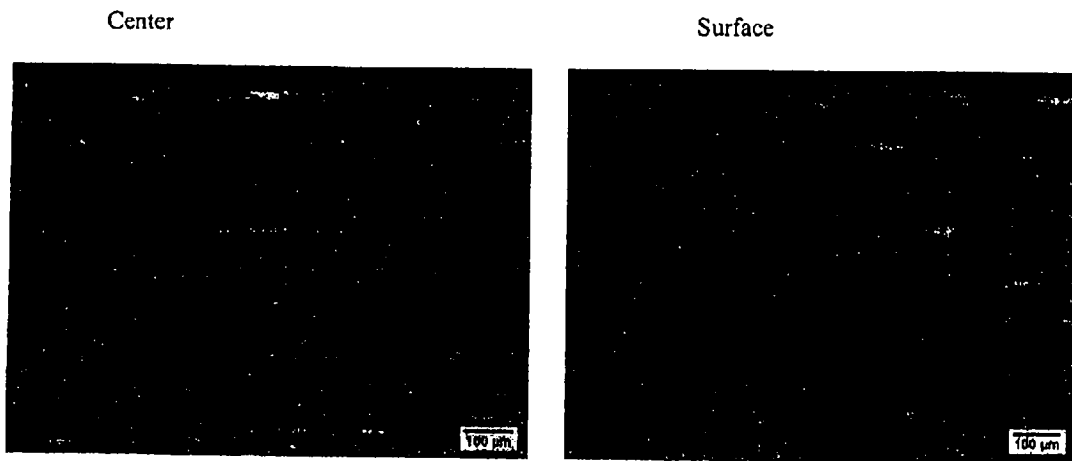
Center   Surface

Fig. 10a

Center   Surface

Fig. 10b
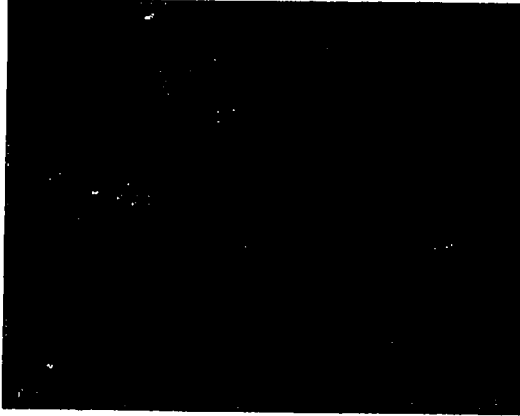
Center

Surface

Fig. 11a

Center
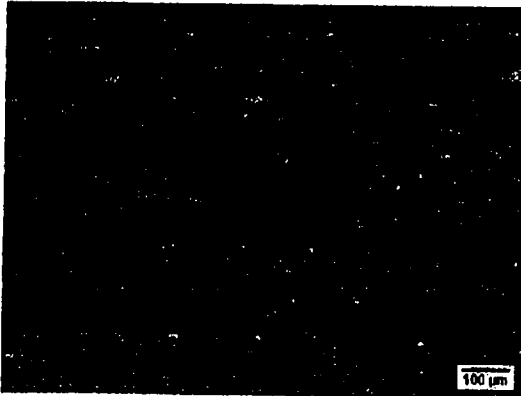
Surface

Fig. 11b
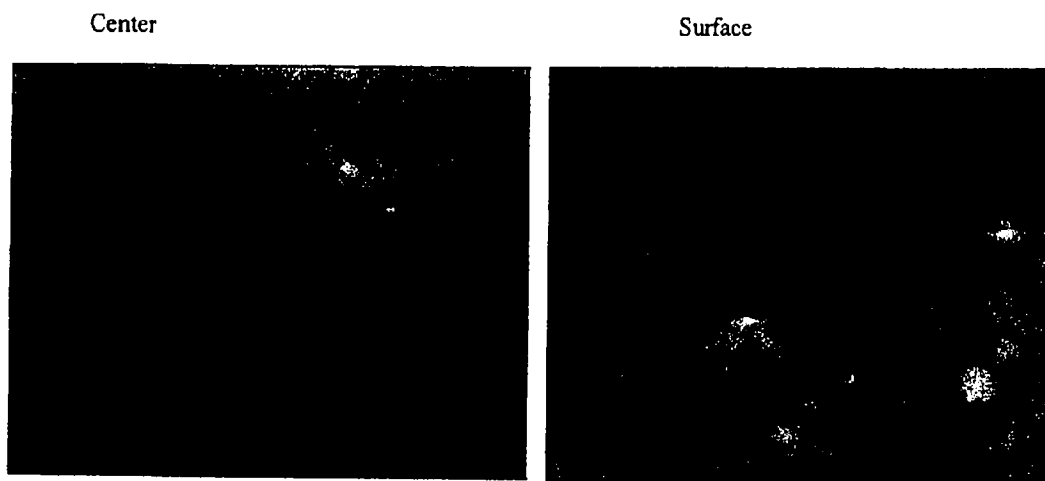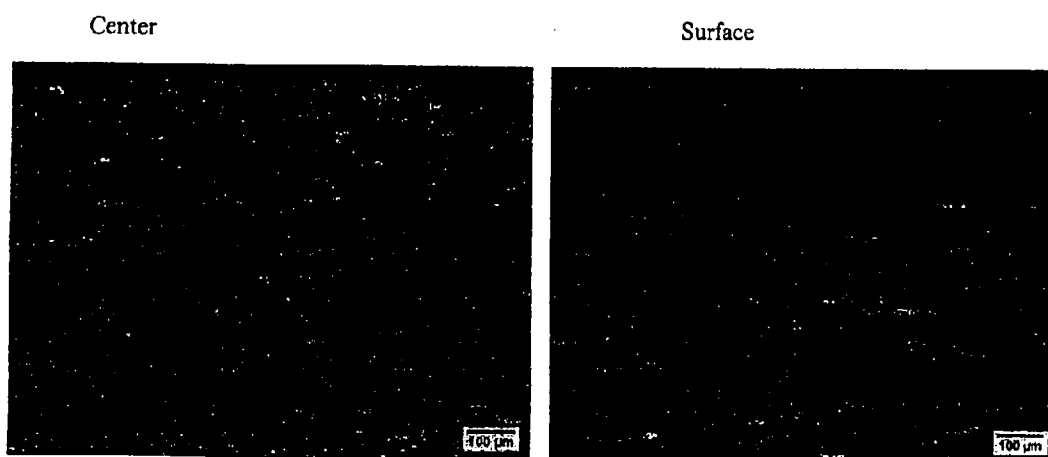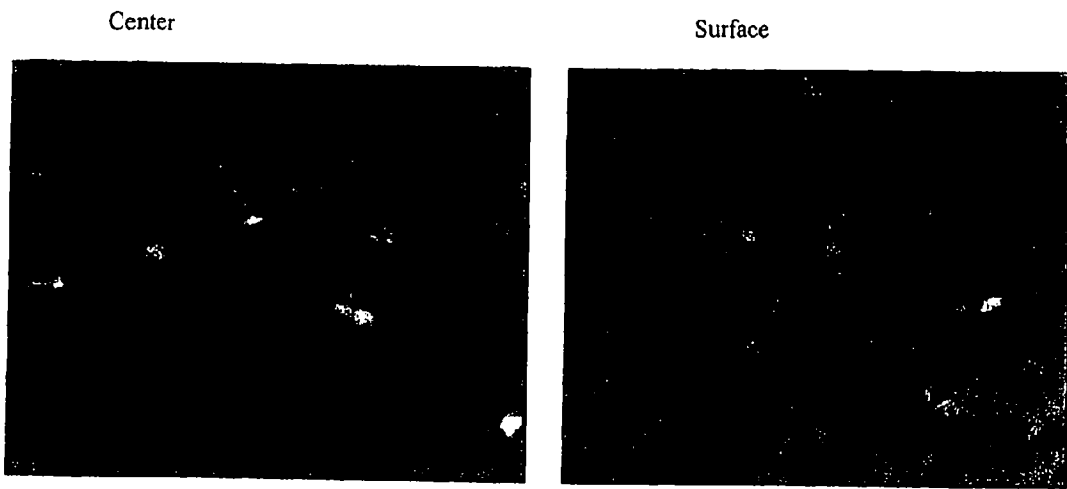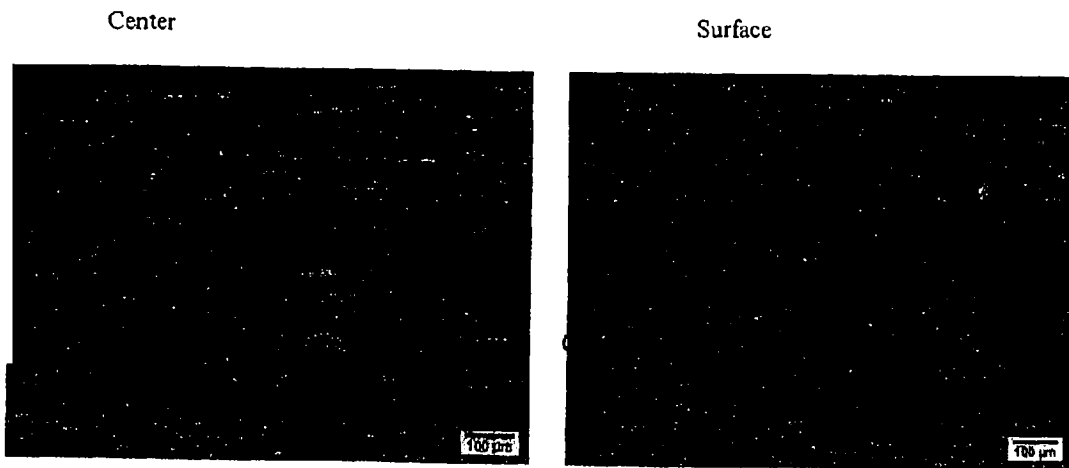
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Center   Surface

Fig. 12a

Center   Surface

Fig. 12b

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Center   Surface

Fig. 13a

Center   Surface

Fig.13b

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Center

Surface

Fig. 14a

Center

Surface

Fig.14b

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Center   Surface

Fig. 15a

Center   Surface

Fig. 15b

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Fig.16

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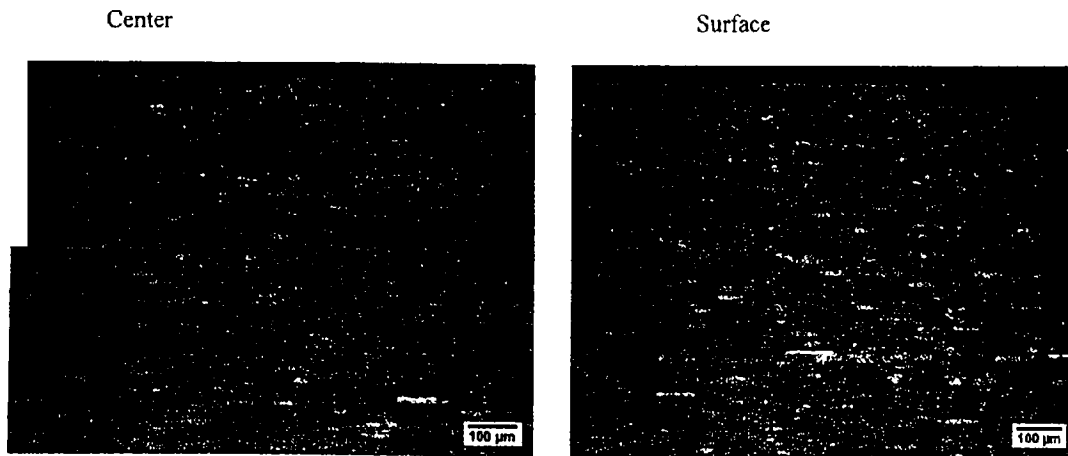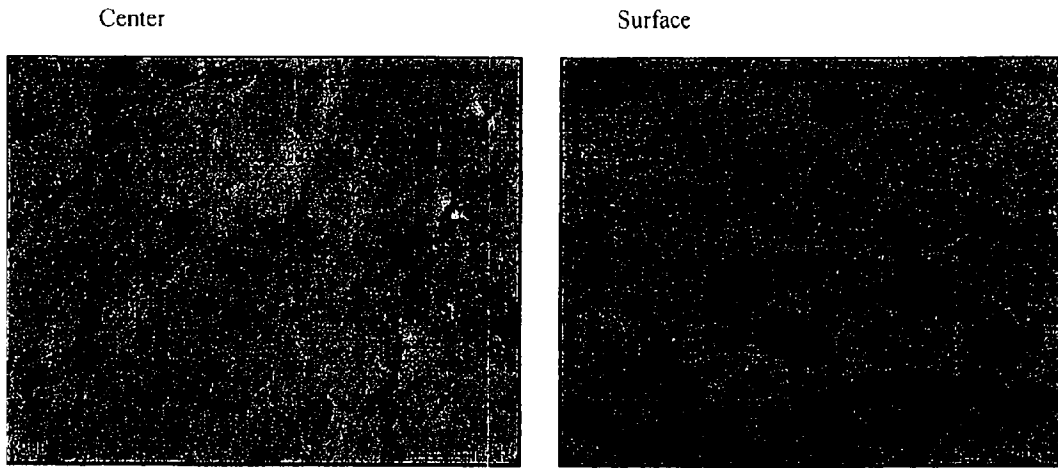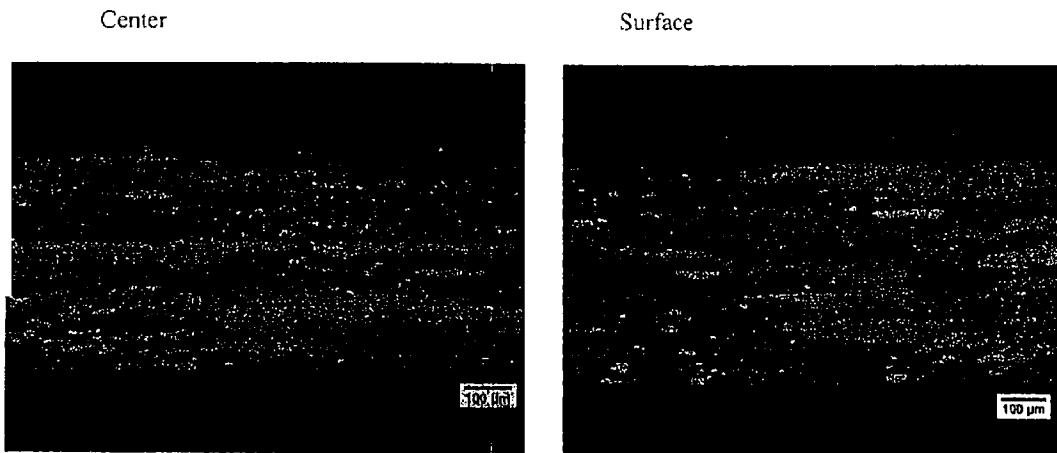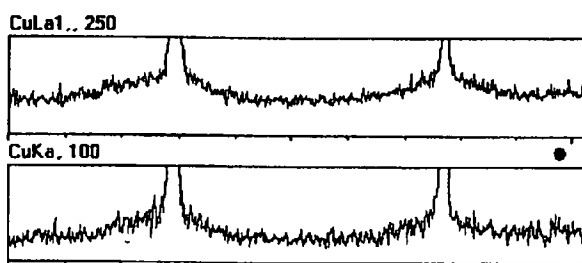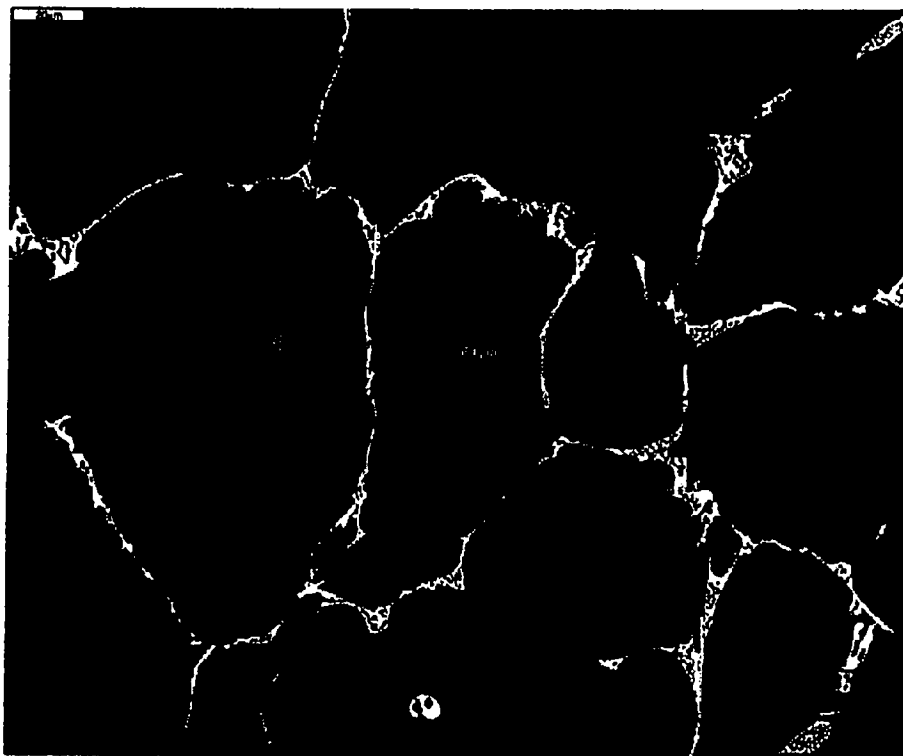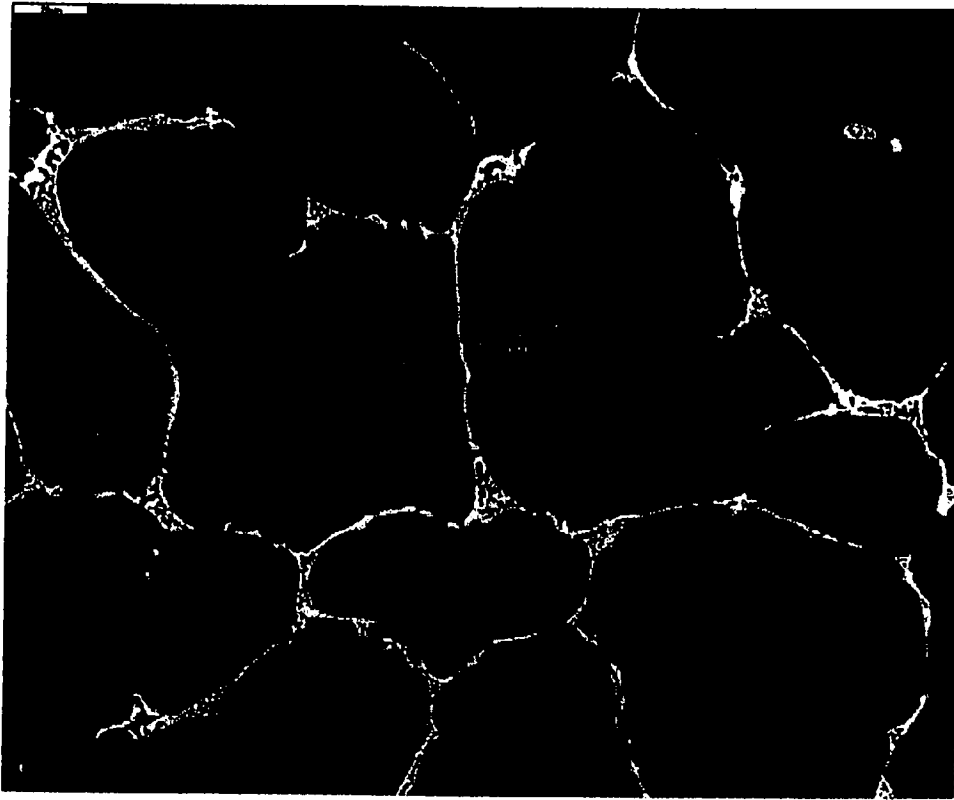
In-situ Al-4.5%Cu with rebound temperature of 300°C. Quarter position (FE4628)
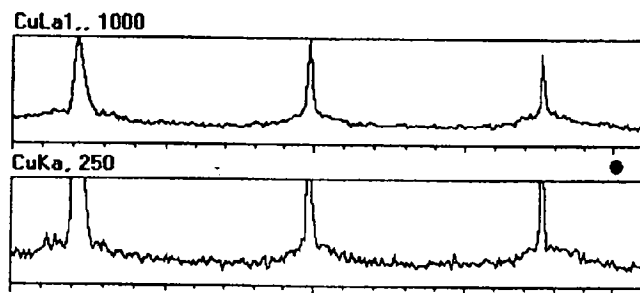
Fig. 17

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Fig. 18

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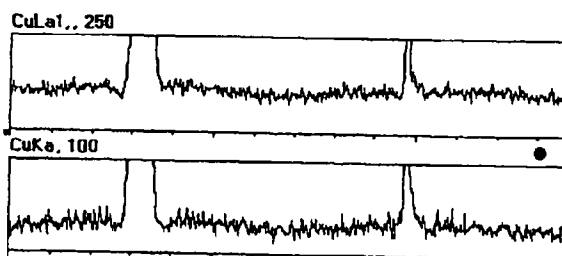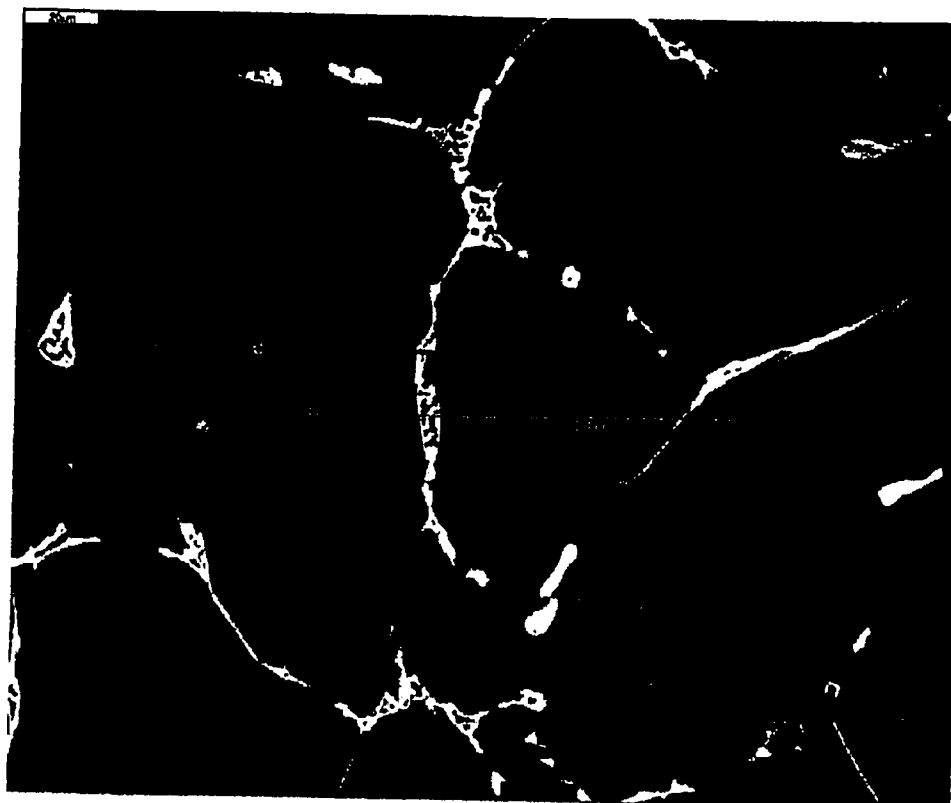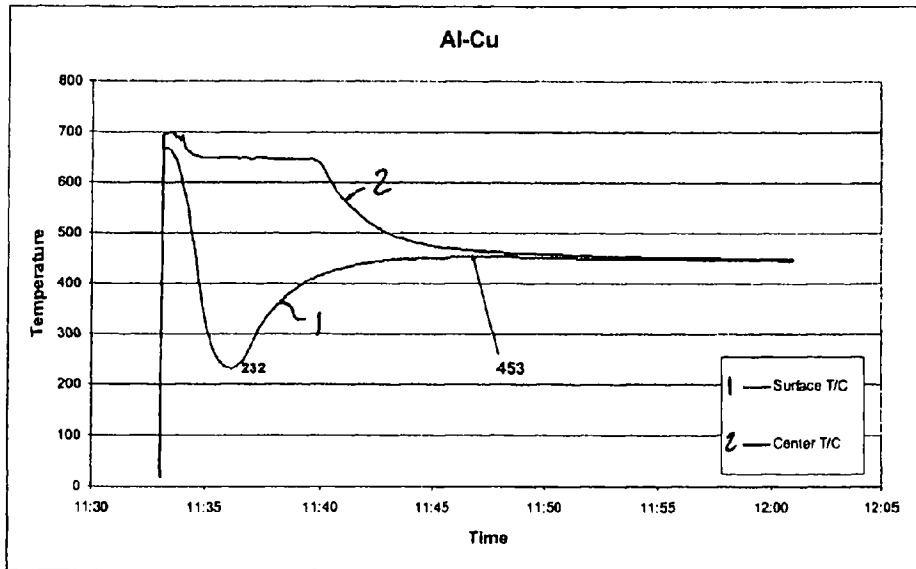
Fig. 19
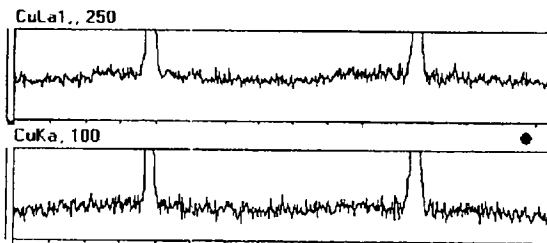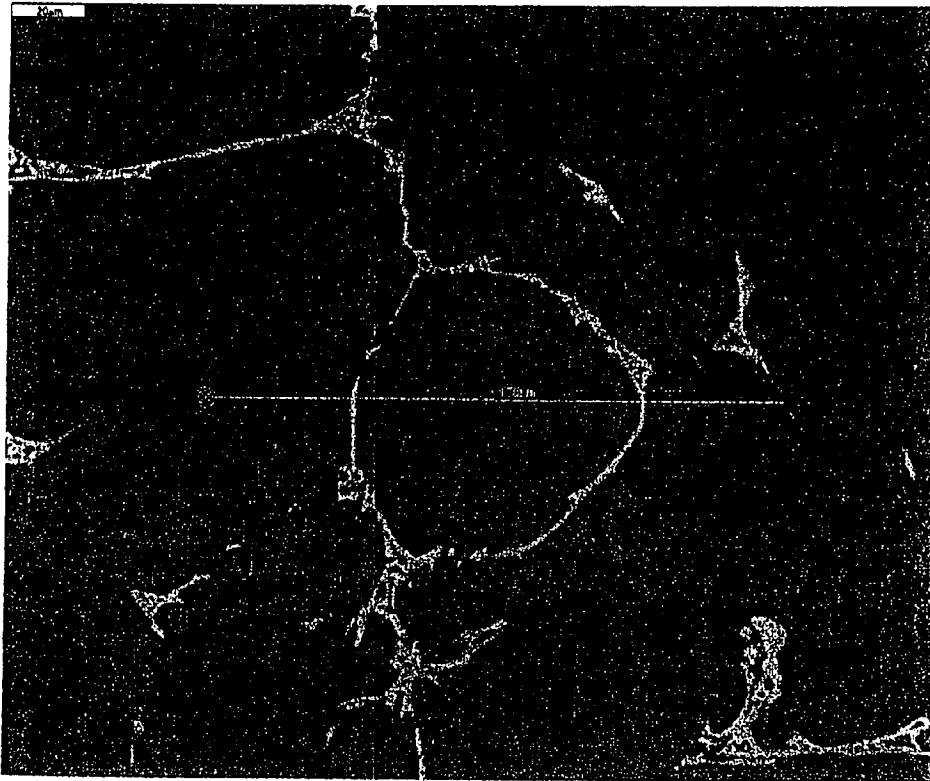
Fig. 20

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Fig. 21

Mean Eutectic Area Fraction
(95% CI over 30 fields, SEM BSE, 500X)
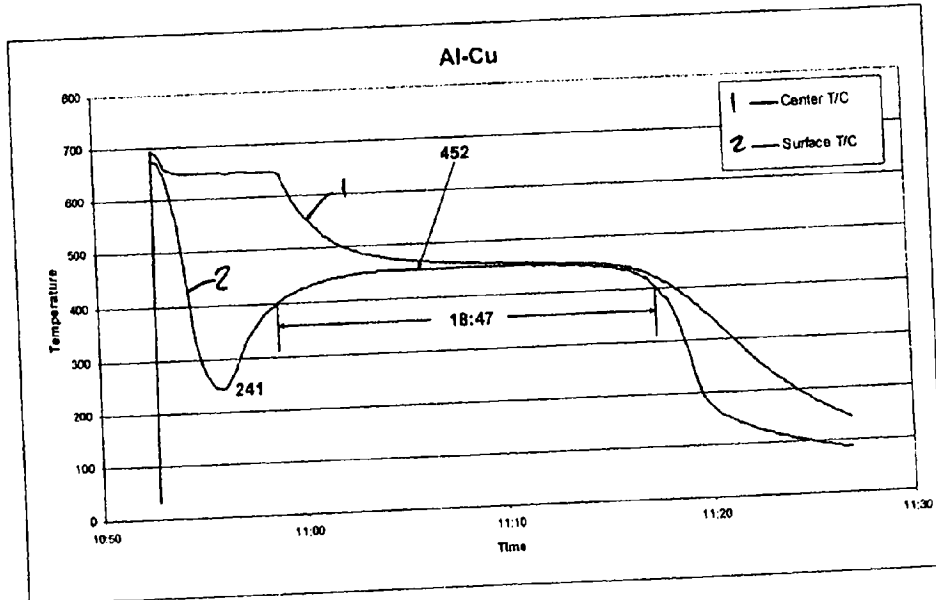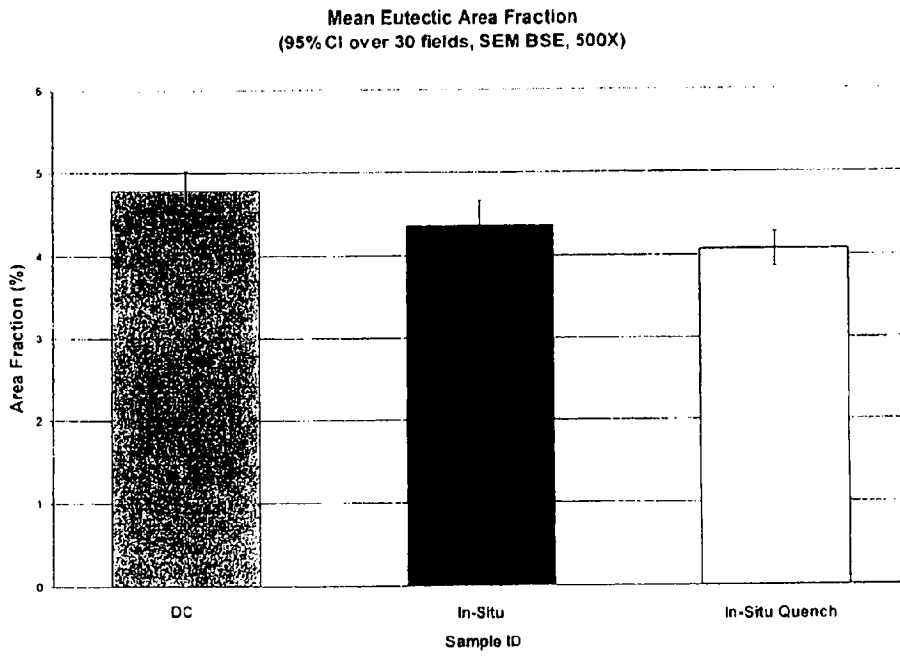
Fig. 22
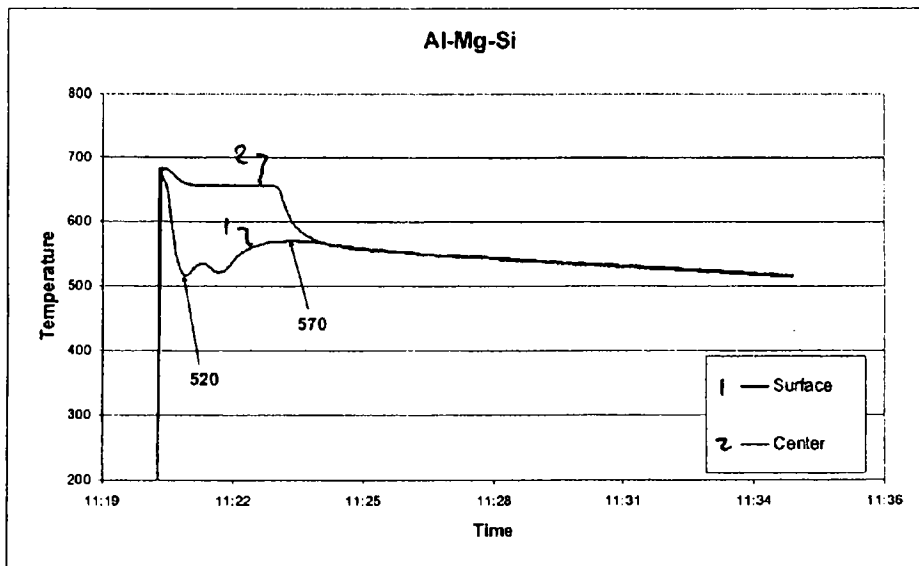
Fig. 23
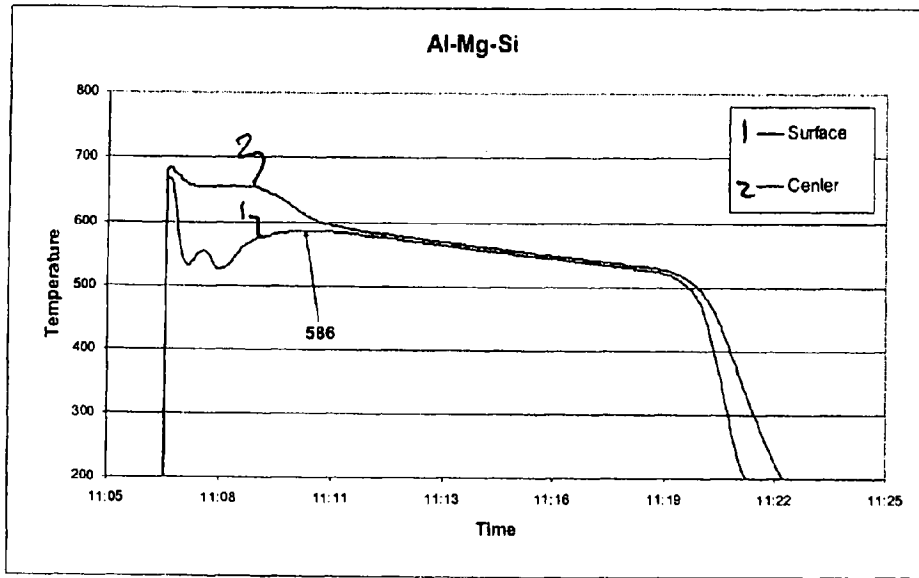
Fig. 24
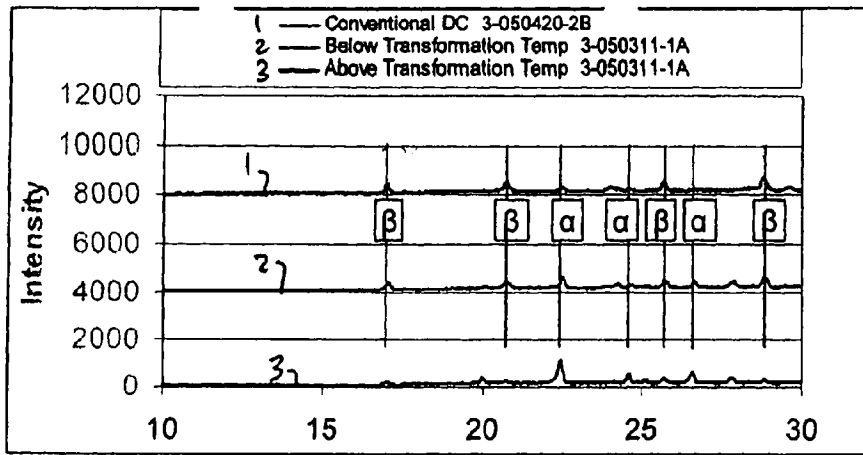
Fig. 25a

Fig. 25b

Fig. 25c

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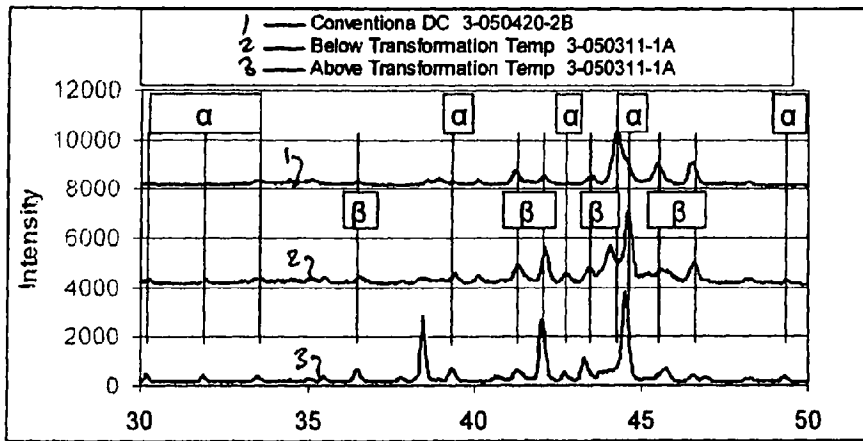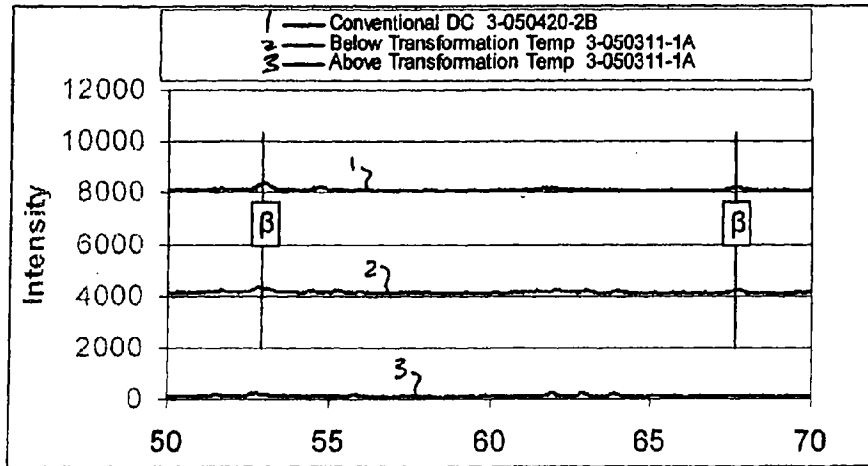
Split: Alpha / Beta

Fig. 26a
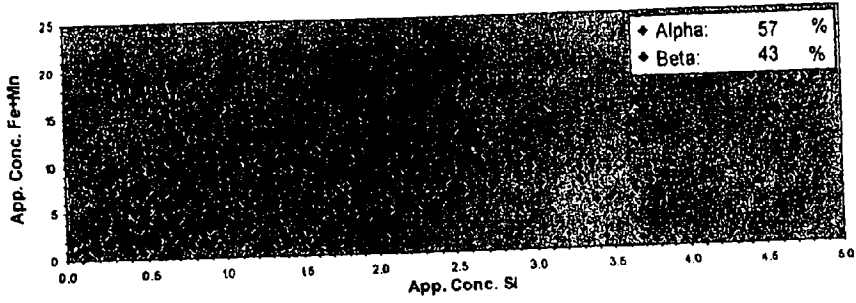
Fig. 26b
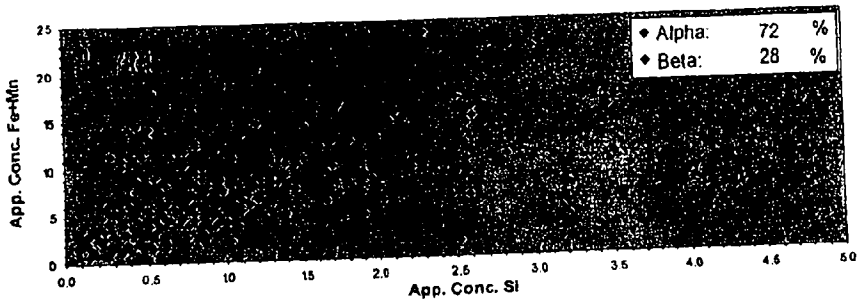
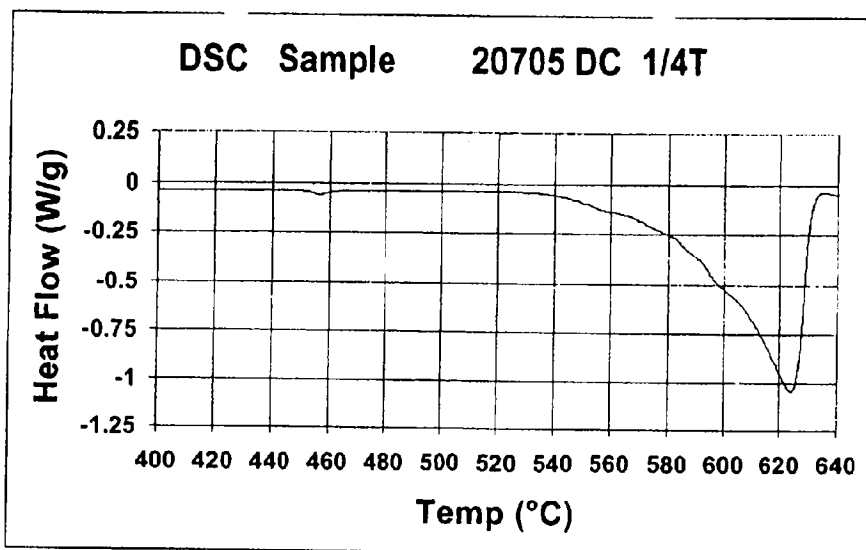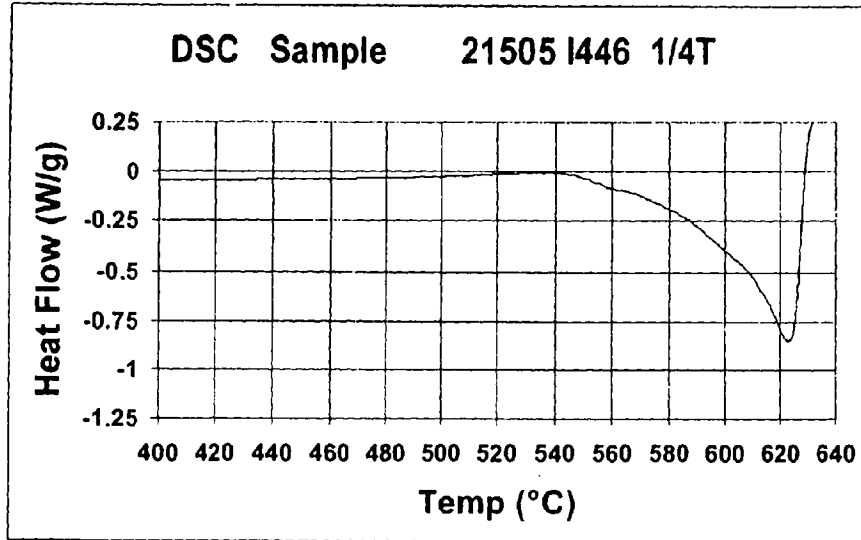Fig. 26c

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Fig. 27a
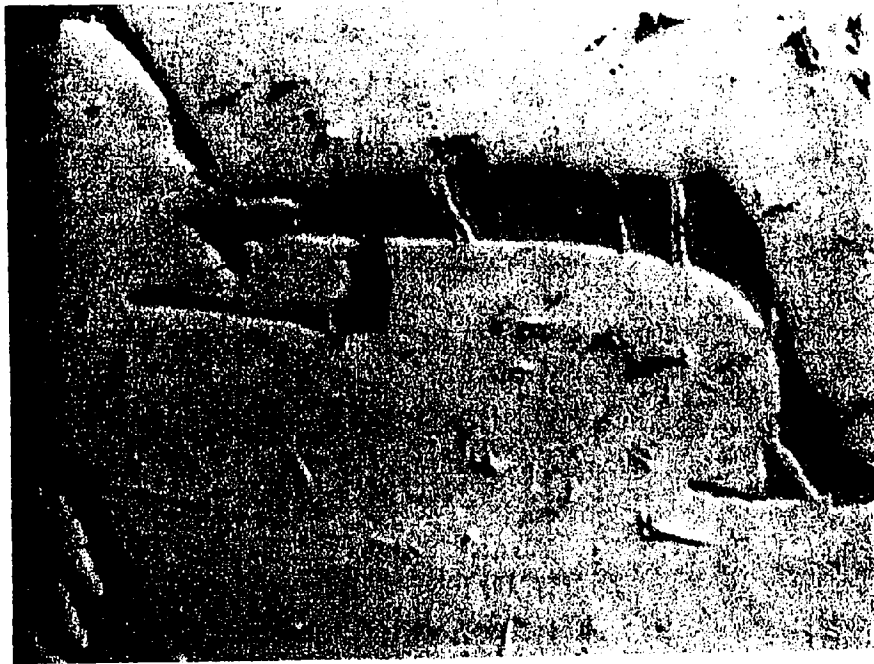
Fig. 27b

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Fig. 28

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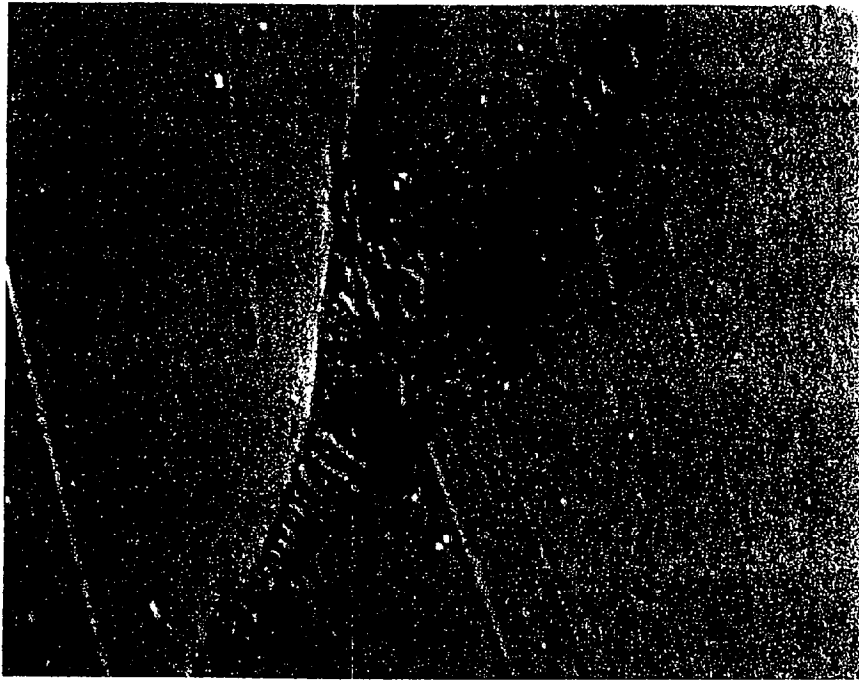
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Fig. 29

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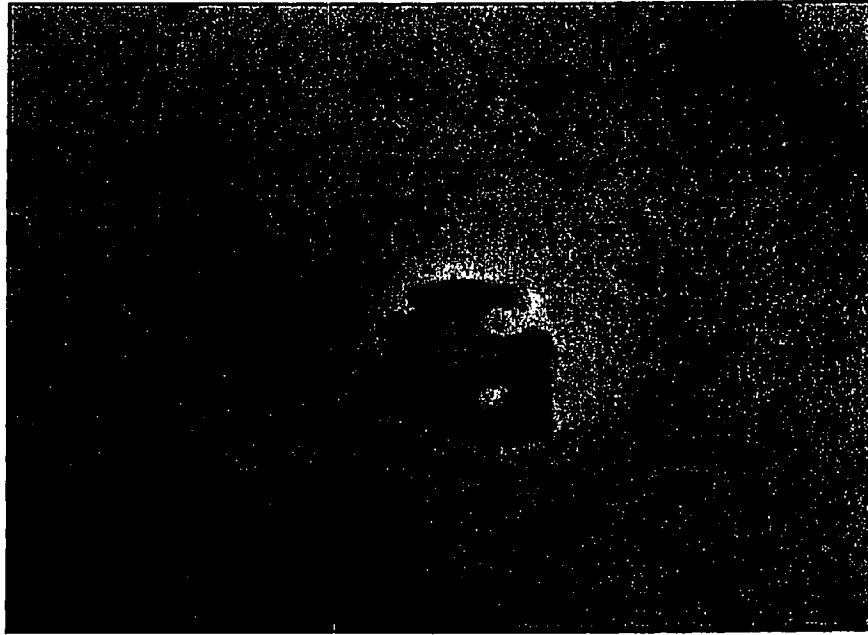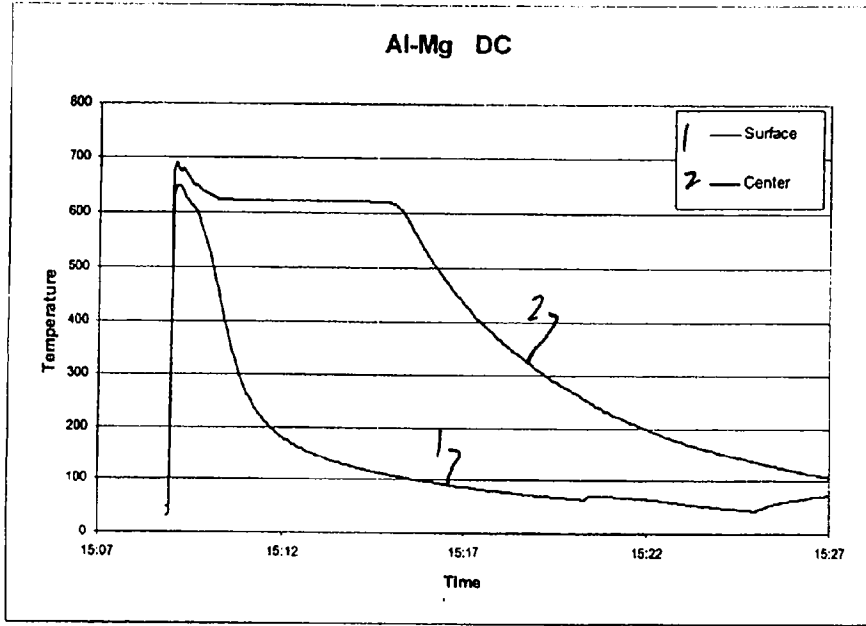
Fig 30

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Fig 31

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Al-Mg

Fig. 32

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Fig. 33

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Fig. 34

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Fig. 35