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Continuous Casting of Dilute Copper Alloys for Drawing to Wire in Specialist Applications

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Background

Rautomead was established in Scotland in 1978 to develop and exploit the technology of continuous casting of non-ferrous metals and to build equipment for those applications. Continuous casting machines for processing of copper and copper alloys have always played a significant part in the company's business. Close to 400 installations have been supplied to customers in 40 countries around the world.

Drivers for Change

While the intrinsic properties of copper, its wide availability and outstanding electrical conductivity still make the red metal the preferred choice for electrical conductors in most applications around the world, much is spoken also about "Megatrends" in society. Some of these highlight the limitations of copper conductors and call for improvements in other physical properties. While the list below is not exhaustive, among the major trends relating to uses of copper are:

High speed rail

While high speed rail has been a reality in the world since the first electrically-powered Shinkansen trains ran commercially in 1964 in Japan, this initiative has been taken forward extensively in Europe and in China in recent years, where for reasons of safety and efficiency higher design speeds require higher tensile strength both in the catenary and contact wires than electrolytic tough pitch copper can provide.

Automotive

Society's pressure on the automotive industry is strong and multi-faceted.

- Weight. Vehicles need to be lighter in order to use less fuel.
- Emissions. Fossil fuels now heavily frowned on and increasingly taxed. New electrically powered vehicles are emerging throughout the world. Major research funding is also supporting the prospect of hydrogen propulsion.
- Gadgetry. Increasingly, a key selling point and almost always electrically driven.
- Life-time costs. Manufacturers' warranties are now offered typically for five years, putting increasing importance on long-term reliability of highly ductile non-corroding wiring harnesses.

Industrial

- Automated production techniques now causing manufacturing industry to relocate from areas of low labour cost to developed economies, making extensive use of robotic arms where conductor wiring is subjected to repetitive bending forces.

Aeronautical

- Weight. Planes need to be lighter to save fuel, fly greater distances and reduce atmospheric pollution.

Electronics

- Manufacturers of devices are packing more and more features into miniature hand-held devices calling for superfine wire in the highest conductivity materials possible.

Dilute Copper Alloys
Standard Designations
(Cast Alloys C81400-C82800; Wrought Alloys C16200-C19600)
ASTM designations are as high-copper alloys with Cu contents greater than ~94% to which Ag may be added for special properties. While exceptions exist to every rule, the broad definition is indicative of the material types.

In selecting an alloy for a particular application, the user is almost invariably conceding some sacrifice in electrical conductivity for corresponding benefits in other properties of the material. According to the alloying elements chosen these other properties may include

- higher tensile strength
- higher softening temperature
- greater ductility
- improved abrasion resistance
- better creep resistance
- better corrosion resistance
- avoidance of toxic hazards

These additional properties and the constraints which accompany their use are of key significance in the development of electrical conductors in an increasingly demanding modern world.

This paper will discuss successful development work which Rautomead has carried out in recent years in continuous casting of wire rods eight dilute copper alloy types, divided for convenience into two groups according to the process required to produce them.

Group A	Group B
Copper Chrome Zirconium	Copper Magnesium
Copper Zirconium	Copper Tin
Copper Iron Titanium Magnesium	Silver-bearing Copper
Copper Titanium	Copper Silicon Manganese

At the outset, it should be acknowledged that none of these materials is new and most of them are already available in world markets as wire rods and in other forms. What is novel in many cases is reliable, accurate commercial-scale production of these materials to fine chemical tolerances and consistent physical properties by continuous casting on a small to medium scale.

These processes contrast sharply with conventional technology of static billet casting, reheating and hydraulic extrusion.

Continuous casting, as the name suggests, enables long lengths to be produced with a greatly reduced number of joins and close to 100% production yield, comparing favourably with the extrusion process where batch size is determined by weight of each billet and with significant process yield losses inherent in the batch extrusion process itself.

Continuous casting also lends itself to comparatively low investment and small to medium scale production which in many cases reflects the scale of market demand for these specialist high margin materials.

Apart from copper itself, the work in which Rautomead has been engaged involves conductor alloys variously including nine other elements, each with its own distinct physical properties, some of them markedly different from those of copper. The table below lists those elements and six of their individual key physical properties. The table is ranked in terms of increasing resistivity of a copper alloy per 1 wt.% addition.

Comparative Physical Properties

	resistivity increase per wt% addn	atomic mass gm/mol	density gm/cc	elec. cond. S/m@20degC	melting point deg C	specific heat J/kgK
Ti	21.6	47.87	4.54	$2.5\ 10^6$	1668	520
Fe	10.6	55.85	7.87	1×10^7	1538	449
Zr	8	91.22	6.52	2.4×10^6	1855	278
Si	7	28.09	2.33	1000	1414	710
Cr	4.9	52.00	7.19	$7.9\ 10^6$	1907	448
Mg	4.2	24.31	1.74	2.3×10^7	650	1020
Mn	3.37	54.94	7.47	620000	1247	479
Sn	1.65	118.71	7.31	$9.1\ 10^6$	232	217
Ag	0.355	107.87	10.49	$6.2\ 10^7$	962	235

Technical Challenges
Principal factors addressed in continuous cast of copper alloys including small percentages of these elements include:

- solubility in copper
- formation of oxides and nitrides in the presence of oxygen and/or nitrogen gas
- effective mixing in the molten state and in the casting process
- volatility of individual elements while maintaining strict alloy composition
- aggressive nature of individual elements with its constraints in selection of materials for containment systems and casting dies
- material losses
- process yield
- economic production cost

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Recent Work
Group A Alloys - Materials

Copper Chrome Zirconium
Continuous casting of CuCrZr rod is one of the most recent innovations by Rautomead. The material combines an outstanding balance of high tensile strength, good corrosion resistance and minimal loss of electrical conductivity. The material may be precipitation-hardened and retains its strength at elevated temperatures. The alloys are easily formed and have good hot-working properties. Uses are in resistance welding electrodes, switchgear, cable connectors, circuit-breaker parts and other conductors requiring high strength. As design train speeds rise over 400km/hour, CuCrZr is a leading contender as contact wires (tensioned to >32kN) in the next generation of catenary wire systems.

Copper Zirconium
Small additions of Zr have little effect on the conductivity of copper, but significantly raise softening temperature (c.500 deg C). Gains in tensile strength are achieved, but not comparable with other dilute copper alloys discussed. CuZr alloys which may be heat treated are thus used as welding electrodes, commutator bars, contacts, circuit breakers, switches and in miniaturised electronic devices.

Copper Iron Titanium Magnesium
These alloys have higher strength than pure copper while maintaining reasonable electrical conductivity. They possess excellent welding, soldering and brazing properties. Uses include lead frames, connector pins, contacts, switches, sockets, electrical springs and more recently also as automotive wire. These alloys may be age-hardened.

Copper Titanium
While CuTi has relatively low electrical conductivity, this material is heat-treatable and a very high strength copper alloy (>1000 N/mm^2) and is seen as a future alternative to Beryllium Copper in applications where high strength is a key requirement.

Group A Alloys - Process
For continuous casting of Group A alloys, Rautomead has developed a patented sealed lid furnace using an argon gas cover to protect the surface of the melt from the presence of oxygen. Feedstock is 8mm oxygen-free copper rod with one, two or three cored wire feeds for addition of the alloying elements. In these ways, accurate control can be maintained of both the feed and the alloying process, while substantially eliminating formation of oxides and nitrides in a sealed furnace continuous process. In copper chrome zirconium alloys for example, typical output in 30mm diameter rod is 500kg per hour in a two-strand configuration to produce 2,000kg coils. Chromium tolerance +/-0.05%; Zirconium tolerance +/- 0.01%.

Fig.1: RSL 1400 sealed lid system

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Group B Alloys - Materials

Copper Magnesium

In high speed rail catenary applications, the alloy requirement ranges from 0.2-0.7Mg and the cast size from 19mm up to 30mm according to local standard specifications and individual cable producer downstream process sequences. As a rapidly work-hardening material, high tensile strength is achievable with relatively small amounts of cold work.

The table below shows by way of comparison the physical properties of copper magnesium and other materials currently used for catenary wires in railway applications.

Material		resistivity 10^{-08} Ohm.m	elong (min)* %	tensile strength (min)* N/mm^2	max speed (kmph)
electrolytic copper	Cu-ETP	1.777	3	355	160
copper-silver alloy	Cu-Ag 0.1	1.777	3	360	250
copper-tin alloy	Cu-Sn 0.4	2.155	3	430	360
copper-magnesium alloy	Cu-Mg 0.5	2.778	5	490	400+

* nom. cross section $100mm^2$

Source: European Standard EN 50149:2012

In the past few years, an important market segment has emerged for copper magnesium alloys as signal wires in the automotive sector. The alloys used are CuMg0.16 to CuMg2.0 usually cast at 8mm and drawn down typically to 0.15mm before stranding, though these alloys may also be drawn down successfully to superfine wires at 50 microns. Driven in this case by the needs for weight reduction, reduced fuel consumption and reduced emissions, smaller diameter cables can be used with a saving of up to 50% in the weight of copper used in a vehicle without sacrifice of performance. With the progressive introduction of electrically-powered vehicles the imperative to reduce weight will remain, though the objective will alter from one of reducing emissions to another objective of increasing range between re-charging of batteries.

Copper Tin

As in the high speed rail industry, copper tin now competes with copper magnesium as a dilute copper alloy in manufacture of automotive signal cables. Tensile strength is significantly higher than electrolytic tough pitch copper, though as a combination of properties, the electrical conductivity and tensile strength are not as favourable as copper magnesium. Continuous casting of copper tin is also by upwards vertical casting. Tin is added in the form of grain using an automatic grain feeder accurately calibrated to production rate. These alloys feature good corrosion resistance and good wear characteristics. Recycling of tin-bearing soudronic welding wire for the can industry has been developed as a means whereby can manufacturers can avoid the need to sell off scrap arisings at discounted prices.

Silver-bearing Copper
Silver-bearing copper has long been accepted as the alloy of choice where high conductivity (100-101.5% IACS) is essential, but where an increase in softening temperature and a greater resistance to creep is necessary to accommodate operation at elevated temperatures. Examples of applications include electric motor components, commutator sections, transformer windings, soldering alloys and more recently in micro-speakers as found in mobile phones.

Copper Silicon Manganese
Copper silicon Manganese is used as welding wire in the automotive industry.

Group B Alloys - Process
While the early Rautomead installations to continuous cast Group B alloys was by horizontal casting, all the more recent installations have been upwards vertical machines in which whole cathode sheets fed automatically, melted and the alloying element added in a single, twin-chamber furnace. Cathodes are weighed individually and the alloy addition accurately measured to match output rate. In its most automated form, alloying element additions are made using a continuous cored wire feed. Chemical tolerance within +/- 0.015% is regularly achieved on a continuous basis. Other alloying techniques include use of master alloys and automated grain feed. The introduction of upwards casting brought immediate benefits of substantially higher casting speeds – 100kgs per strand/hour compared with 30kg in the horizontal process and quicker and safer procedures for changing of casting dies. Cast rod sizes range from 8mm to 30mm diameter with the wire rods formed into coils. Cast sizes are selected according size and physical properties required in the final product and the downstream working processes selected by the wire and cable manufacturer. These can include continuous extrusion, cold-rolling, profile drawing, rod breakdown, intermediate drawing, multiwire drawing and superfine wire drawing.

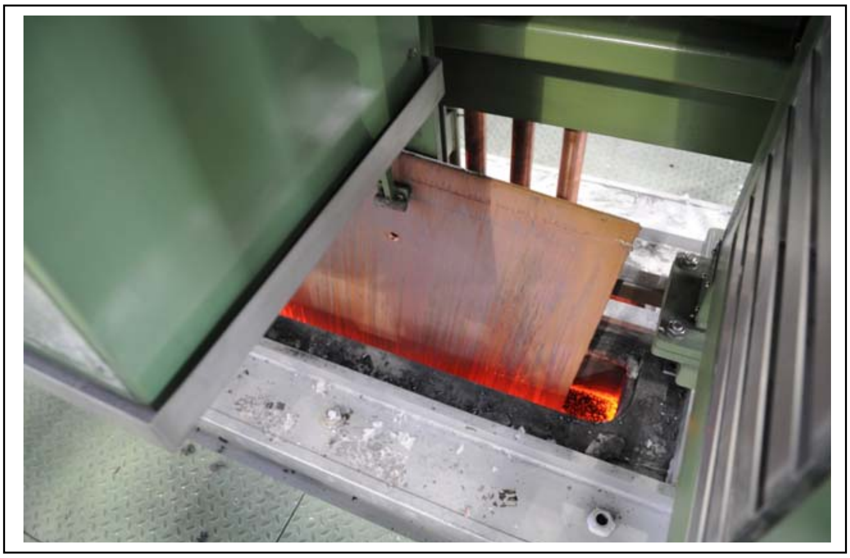

Fig.2: RS 3000S automatic cathode feed system

Graphite Furnace Technology

A distinguishing feature of Rautomead continuous casting technology is the use of an electrically heated graphite crucible furnace. This contrasts with almost all competing channel induction systems using rammed ceramic furnace linings. Mechanical properties of graphite are similar to those of ceramic materials, while thermal conductivity and electrical resistivity correspond to those of metals. It is this unique combination of refractory and metallic properties which makes graphite so well suited for use in electro-thermal processes at higher temperatures. As the quality and consistency of graphite materials available around the world has improved, so the applications available for the process have grown.

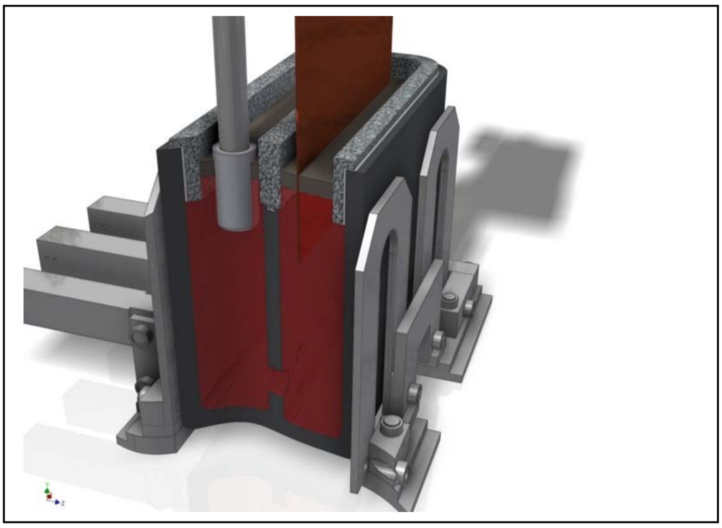

Fig.3: RS 3000S graphite crucible schematic

Technical Innovation

Development projects are structured in one of three forms:

- bilateral projects between Rautomead and one or more industrial partners in which strict commercial confidentiality between the parties applies
- bilateral projects with universities which may also involve post-graduate student studies
- in-house developments where Rautomead sees opportunities to capitalise on existing skills and experience to extend technology to new fields and new applications

Rautomead prides itself on maintaining one of the most advanced centres for development of copper alloy production in the world. This is the direct result of a long-standing policy of operating pre-production-scale machines at our works and the daily involvement of Rautomead technical staff in the continuous casting process. This facility is now supported by Dundee University Department of Engineering with whom Rautomead enjoys a close working relationship.

The company welcomes new challenges from the wire and cable industry to engage with us in opportunities to make real technological advances in the field of commercial production of electrical conductors in the modern world.

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Looking Ahead

Significant resources are currently being applied to gain a better understanding of all the variables in the continuous casting process with objectives of predicting performance and increasing casting speeds. The potential benefits of this work cover the whole spectrum of Rautomead technology.

Exciting current projects involve wire rod applications in copper tellurium free-machining alloys and in copper aluminium alloys as automotive welding wire.

Other work in progress includes continuous casting applications of nickel chrome alloys but is outside the scope of this paper.

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