CONTINUOUS CASTING OF COPPER MAGNESIUM CONDUCTOR ALLOYS

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SUMMARY

CuMg wire rod must be produced consistently to a fine alloy tolerance to provide an acceptable balance of tensile strength and electrical resistivity in the finished wire. Given the reactive nature of Mg, this calls for highly specialised technology.

The totally enclosed Rautomead graphite furnace technology has been proved over many years to be well suited to this application with important markets emerging in high speed rail and the automotive industries.

BACKGROUND

HORIZONTAL PROCESS

Rautomead supplied its first two continuous casting machines for production of CuMg wire rod in 1990. These were 8 strand horizontal machines built to produce a range of Cu-Mg alloys from 0.2% to 0.5% Mg for high speed rail applications. Cathode and elemental Mg were added direct to the graphite crucible in accurately measured proportions. Cast diameter was 19mm and 28mm. Production speed was relatively low at around 30kg/strand/hour, but rod quality was sound and consistent, both in terms of alloy composition and physical properties. These horizontal machines are still in use today.

UPWARDS VERTICAL PROCESS

The upwards vertical adaptation of the Rautomead continuous casting process was developed in the early 1990s. It became apparent that upwards casting brought advantages over the horizontal process in production of many copper-based alloys, including CuMg, as well as tin-bronzes and a range of binary brasses. Crystalline structure was notably improved with enhanced tensile properties (UTS and % elongation) which benefited subsequent cold rolling or drawing. The vertical cast rod presents greatly superior structural symmetry compared with horizontally cast rod. The latter tends to lean forward owing to the uneven effects of gravity around the circumference of the solidifying metal. In the upwards vertical mode, the characteristic mix of central equiaxed grains and fine chill grains on the outer diameter remain, but the larger columnar grains were of a steeper angle towards the direction of cast, typically 50 – 70 deg. rather than 40 – 45 deg. in horizontal casting. Higher rates in casting (cooling) also led to the grains being more refined and more evenly distributed.

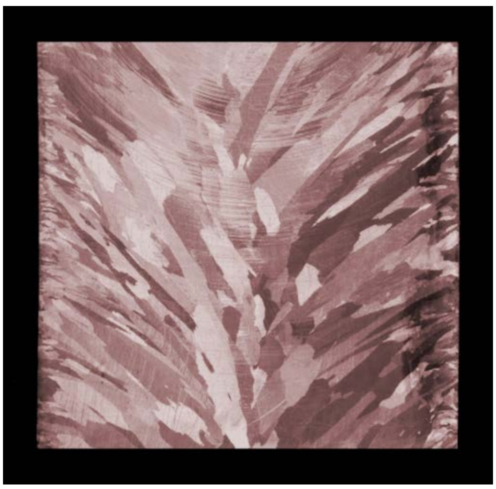

fig 1. grain structure in as cast CuMg

Casting speeds of around 100 kg/hour are achievable in production of 28mm diameter rod in CuMg – a three-fold increase from horizontal casting. Time taken to change casting dies was reduced and made significantly safer than in the horizontal process. Rautomead's first upwards vertical casting machine for CuMg production was supplied in 1997, since when this has become something of an industry-standard specification in contact wire applications for high speed rail. Eight machines of this type have been supplied to customers in China over the past three years.

MARKET APPLICATIONS

International demand for copper conductors with high tensile strength and high electrical conductivity stems from many industries. Two major applications are in **high speed rail** and in the **automotive industry.**

HIGH SPEED RAIL

Overhead single strand contact wire conductors are used to transmit electrical current to drive the train via a pantograph mounted on the roof. To avoid arcing, to minimise abrasive wear and to maintain an uninterrupted supply of power, the pantograph should be in constant contact with the stationery wire. The catenary system requires to have minimum vibration and motion to ensure smooth operation at high train speeds and in strong wind conditions. It must be corrosion resistant and be able to withstand hot ambient temperature conditions. As design train speeds have increased, demands placed on performance of the catenary have risen significantly. For safety reasons, maximum train speed should not exceed 70% of the wave propagation velocity. Two means of achieving that objective are to heighten the tension in the contact wire and to adopt lightweight materials. In recent years, copper-magnesium alloys have been widely adopted as the electrical conductors in catenary systems to meet these requirements.

fig.2 grooved trolley wire in CuMg0.5

AUTOMOTIVE

Increasing complexity in automotive design has led to a sophistication in wiring harnesses not in contemplation twenty years ago. The weight of copper used in the construction of a car now ranges from around 15kg in a low cost model to over 28kg in a luxury saloon.

AUTOMOTIVE (cont'd)

This tendency towards greater weight and greater cost of materials has coincided with a time when automotive manufacturers are under pressure to reduce manufacturing costs, to reduce vehicle weight and to reduce fuel consumption. Hence, pressure is being exerted to achieve smaller copper section sizes used in control and signal cables, whilst not jeopardising performance or reliability. Copper-magnesium (CuMg) alloys meet many of these requirements as a direct replacement for tough-pitch copper (CuETP), enabling significantly reduced wire gauges to be used.

OTHER APPLICATIONS

Other important applications for CuMg alloys occur in manufacture of connectors and semi-conductor pins, where the combination of high tensile strength, low resistivity, good solderability and plateability make this material an attractive option.

STANDARDS

CuMg rod is specified in accordance with ASTM B250, designated as C18661. This covers the range of Cu alloys with Mg content from 0.1 to 0.7%.

COMPARISON OF MATERIALS

Table 1 below compares the tensile strength and electrical resistivity properties of various available materials.

Material	tensile strength N/mm^2	elongation (min) %*	electrical resistivity 10^{-08} Ohm.m
CuETP	360	3	1.777
CuAg0.1	375	3	1.777
CuSn0.3	420	3	2.155
CuCd0.7	430	2	2.005
CuCd1.0	445	2	2.155
CuMg0.2	430	3	2.778
CuMg0.5	490	5	2.778

*percentage elongation after fracture. nom. x section $100mm^2$

table 1

Despite its good combination of physical properties, CuCd is no longer accepted in most applications as a conductor alloy on account of the toxicity hazard and risks of respiratory disease associated with Cd, both in initial manufacturing and in later recycling.

Traditionally, CuETP was a standard material used for trolley wire and is still used in train and tramway applications up to a running speed of around 160 km/hour. Above that speed, a higher tensile strength material is required to match the higher tension required in the trolley wire.

Alternatives to CuCd include CuAg, CuSn and CuMg. CuAg possesses higher tensile properties than CuETP and is suitable for train speeds up to around 250 km/hour. For higher train speeds in excess of 250 km/hour, CuSn and CuMg are the preferred alloys. High speed trains in Europe at regular operating speeds up to 320 km/hour are now running under trolley wire made in these alloys. Grooved contact wire in Europe must conform to the relevant European standard (EN 50149:2012).

Repeated attempts have been made to introduce aluminium for trolley wire applications, but this forms a hard non-conductive surface oxide layer, leading to arcing and erosion. The reduced conductivity of aluminium also predicates a 60% increase in cross-sectional area to achieve the same conductivity as copper. Aluminium is thus not generally favoured.

As shown in table 2, relationships between design train speeds and the tension applied to contact wire are indicative of the technical requirements in the material.

material	grooved conta wire sectior sq.mm	max design tra speed km/hour	contact wire ten kN
CuETP	100	160	10-15
CuAg0.1	120	250	15
CuSn0.3	150	360	27
CuMg0.5	120	400	27

table 2

CASTING PROCESSES

CuETP and CuAg wire rod are most conveniently produced on a Properzi™, Southwire™ or Contirod™ line. By contrast, CuMg cannot be produced efficiently by those processes on account of the volatility of magnesium and the demanding requirement to maintain a tight tolerance of magnesium content over long lengths in the alloyed material. Production of CuMg alloy wire rod requires different technology and is a speciality of Rautomead™.

RAUTOMEAD STANDARD CuMg CASTING LINE

Rautomead offers a standard line of upwards vertical continuous casting equipment for production of a nominal 3,000 tonnes per year of CuMg wire rod. This line comprises an RS 3000/5 CuMg upwards vertical combined melting and casting machine, configured to produce five strands of trolley wire rod up to 30mm diameter and five heavy duty rod coilers. Wire rod for the single strand contact wire is cast at 28-30mm diameter. Wire rod for the stranded cable used for support wire and droppers is typically cast at 20mm diameter. Feedstock for the line is Grade A quality cathode with elemental magnesium additions. No separate melting furnace is used. Typical alloy compositions are CuMg0.1 to CuMg 0.6.

fig. 3 Rautomead RS 3000/5-CuMg Casting Machine

The Rautomead upwards vertical process is especially well-suited to CuMg rod production. Tensile strength and resistivity in the finished product are very sensitive to alloy composition. The totally enclosed nature of the process permits the user to control the level of magnesium within a tolerance better than +/- 0.05%.

PROPRIETARY TECHNOLOGY

Rautomead continuous casting technology is based on electric resistance heating, using a graphite crucible furnace and graphite heating elements protected in an inert gas atmosphere. By contrast, the majority of competing systems were originally designed for production of oxygen-free copper using electric channel-induction induction heating with rammed ceramic lined furnaces to melt, hold and cast the copper.

THE RAUTOMEAD SYSTEM

In the Rautomead system, the graphite crucible forms a twin-chamber still metal bath with no induced electro-magnetic stirring in the charge. Energy to melt the materials is applied by radiation and convection through the walls of the graphite crucible. The crucible itself forms part of the stored energy in the process. This is conducive to achieving steady casting temperature (normally within +/- 3deg. C), despite a relatively small molten metal bath (approx. 2,500 kg Cu). The process is largely automatic, with all key operating parameters monitored and alarmed.

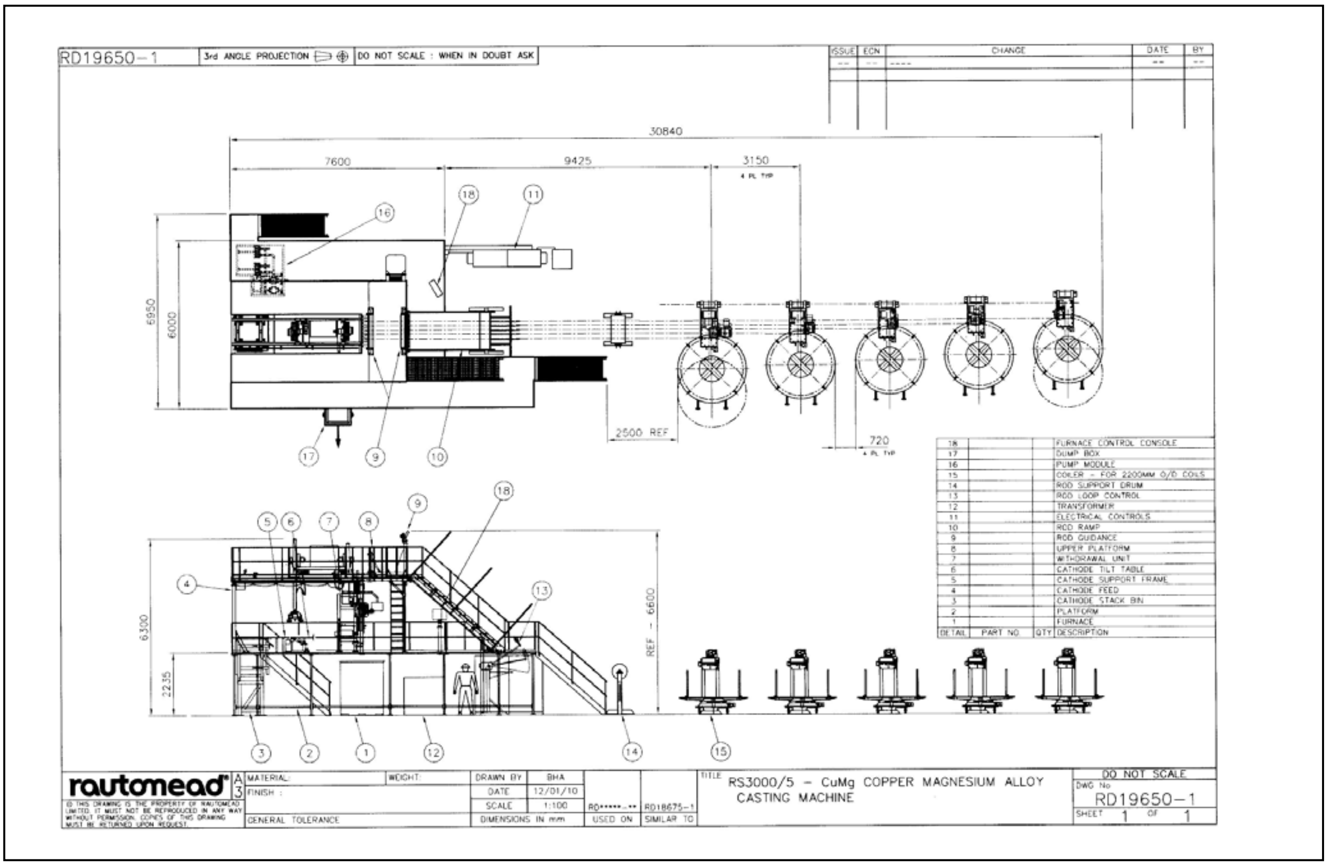

fig. 4 Rautomead RS 3000/5-Cu-Mg Casting Machine Layout

GRAPHITE CRUCIBLES
The Furnace crucible for CuMg applications is machined from a vibration-moulded solid block to form a homogenous containment vessel, with two inter-connecting chambers. Copper cathodes are automatically and progressively lowered into the melting chamber. The molten metal flows with gravitational force through ports in the base of the crucible to the separate casting chamber. Sacrificial linings are used to protect exposed surfaces from oxidation. The naturally reducing effect of the graphite material assists in ensuring the full de-oxidation of copper and avoids contact with and contamination of the melt by refractory particles.

fig.5 graphite crucible

GRAPHITE HEATING SYSTEM
The good electrical conductivity of graphite enables this material to be used as heating elements in a low voltage resistance furnace heating system. Secondary power is fed to water-cooled graphite busbars and to a chain of accurately rated heating elements which surround the crucible. Energy is fed to the metal in the crucible by radiation and convection and all at low voltage (typically 40 V). The arrangement is not only thermally efficient, but also very safe in operation. CuMg is prone to slag formation in processing, particularly in narrow induction channels or when exposed to atmosphere. These serious processing difficulties which can lead to significant non-productive time are avoided in the Rautomead.

fig. 6 graphite heating elements

PHYSICAL PROPERTIES OF GRAPHITE

Graphite is elemental carbon. Mechanical properties of graphite are similar to those of ceramic materials, while thermal conductivity and electrical resistivity correspond to those of metals. See table 3 below. It is this unique combination of refractory and metallic properties which makes graphite so well suited for use in electro-thermal processes at elevated temperatures.

		graphite crucible
Bulk density	g/cm3	1.83
Open porosity	%	9
Young's modulus	kN/mm2	10.8
Flexural strength	N/mm2	21.5
Resistivity	Ωμm	7.7
Thermal conductivity	Wm-1 K-1	165
Coefficient of thermal expansion	10-6 K-1	2.7

table 3

The change in electrical resistivity of carbon during the graphitization process is very marked. The material is transformed from being an insulator to a conductor. Thermal conductivity of graphite is at its maximum at about room temperature. Strength and Young's modulus both increase with temperature and peak at ca. 2500deg C., where values are 50-100% higher than at room temperature.

Above 1400deg C, the specific strength (strength/density) of graphite is greater than that of metals and most other refractory materials. Graphite used at higher temperatures is often exposed to sudden temperature changes or large temperature gradients, both introducing mechanical stresses. Table 4 shows the thermal stress resistance of graphite compared with some other refractory materials.

	W/m
Graphite	50,000
Titanium carbide	1,000
Magnesia	50
Alumina	1

table 4

OXYGEN REDUCTION
The graphite furnace naturally reduces oxygen to extremely low levels (normally less than 5ppm). Normal grade A cathode may be expected to have an oxygen content of 60-80ppm. In the case of the Rautomead integrated melting and casting system for CuMg production, there are five stages where the oxygen is reduced:

- graphite pellet metal cover over melting chamber
- graphite sacrificial lining of upper part of melting chamber
- graphite walls of crucible
- graphite sacrificial lining of casting chamber
- graphite flake cover over casting chamber

The graphite crucible in the model RS 3000CuMg machine has a capacity of approx. 2,500kg Cu. With an hourly output of 500 kg, the copper has a dwell time of approx. five hours, which has been shown to be well in excess of the time required to complete the oxygen reduction.

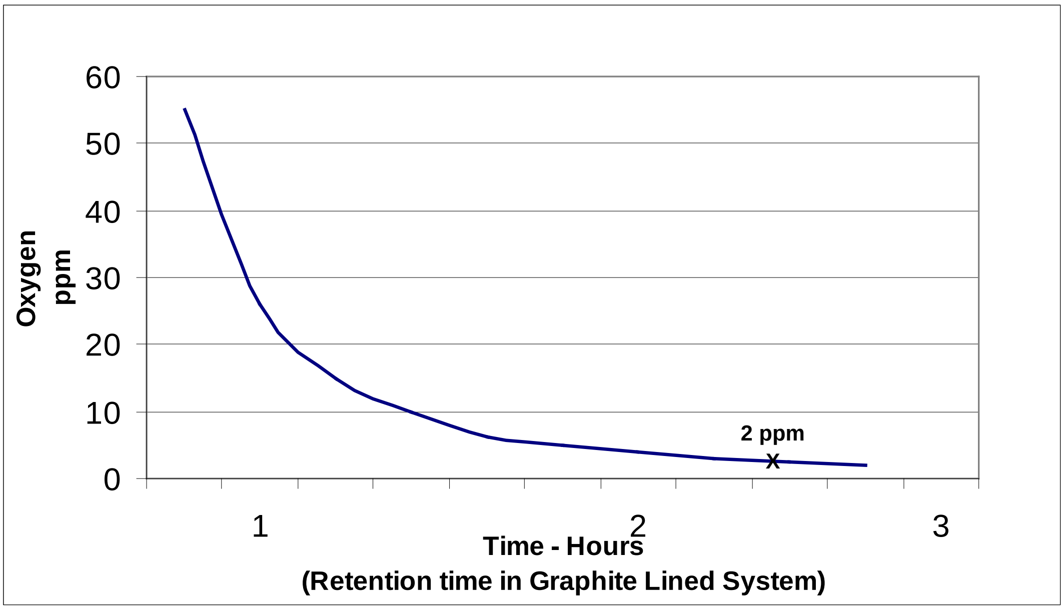

fig. 7 oxygen reduction in graphite lined system

Mg ALLOY ADDITION
A key aspect of the process is the method used to incorporating Mg as the alloying material. As shown in table 5, contrasts between the physical properties of copper and magnesium are significant. Magnesium, while imposing no health hazard, is a light and highly reactive element.

		Cu	Mg
Density at room temp	gm/cc	8.96	1.738
Density at melting temp	gm/cc	8.02	1.584
Melting temp	deg C	1085	650
Boiling temp	deg C	2567	1090

table 5

Three possible methods are used to introduce the magnesium. All include individual weighing of cathodes as these are fed automatically to the furnace. All of the feeding methods below have been successful in production of CuMg alloy wire rods to a consistent chemical specification within Mg +/- 0.05%.

Master Alloy

Master alloys with 10-50% Mg content are commercially available. Additions are made simultaneously with cathode feeding, to ensure the master alloy is effectively plunged into the melting chamber of the crucible.

Elemental Mg powder

Measured amounts of Mg powder wrapped to Cu foil is added in a similar way as feeding master alloy.

Cored Rod

The latest technique, through a joint development between Rautomead and Affival® of Solesmes, France is by controlled automatic feeding of a cored copper rod with magnesium powder as the core. The rate of feed is electronically adjusted to cathode weight data and the cored rod plunged beneath the surface of the melt. The technique is an the evaluation stage at present, but shows promises tighter alloy tolerances, reduced Mg losses and reduced slag formation on the surface of the melt.

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