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Progress in Net and Near Net Shape Manufacturing of Metallic Components using the Ohno Continuous Casting (OCC) Process

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Abstract

The OCC products have the potential to be used in many industries due to the versatility and low cost of the manufacturing process. The process produces single crystal/unidirectional net, and near net products with excellent surface quality, controlled microstructure and enhanced properties. This article is an overview of the progress in OCC process since its inception in manufacturing of metallic components. The process, product range, potential and limitations are outlined. The process is now commercialized; and products for electronics, medical, joining, hard facing, shape memory, etc., can be fabricated. However, according to expectations, its use is still limited and potential applications including fabrication of structural materials for aerospace and automobile applications, production of large size ingots, purification of alloys and silicon crystal growth remain to be explored.

Keywords: Continuous casting; Crystal; Directional; Heated mold

Introduction

Polycrystalline metals/alloys are always of either limited strength or ductility since strengthening is accompanied by loss of ductility in these materials [1-3]. The corrosion resistance and conductivity also decline with increase in strength [3,4]. In addition, the casting processes producing these polycrystalline materials cannot fabricate some brittle materials or small diameter wires due to friction between the mold and the cast component. These inferior properties are brought about by grain boundary imperfections in the microstructure [5,6]. To overcome these problems, bulk crystal growth processes such as the Bridgeman and Czochralski are now widely used to produce single crystals without any imperfection. Such crystals are of superior strength, ductility, conductivity, and corrosion resistance. However, these crystal growth processes cannot produce long crystals continuously because of the dimensional limitation of the apparatus [7]. Thus, the heated mold continuous casting process, called the Ohno Continuous Casting was developed in the mid-1980s at the Chiba Institute of Technology in Japan. The OCC process is a metal forming process, producing ingots of directional structure with infinite length without internal and shrinkage defects [8]. Such a continuous casting process is cheap and conveniently produces bulk ingots. To date, since its inception, numerous research studies have been conducted in developing and widening the application of this process. This includes casting of brittle metals and metal matrix composites (MMCs), casting of cored materials, casting of unidirectional ingots with fine grains in their microstructure, casting of thin wires, purification of metals, etc. These unidirectional or single crystal ingots are used for a variety of applications including electronic wires, thermal fuses, shape memory alloys, dental implants, soldering wires, etc. Research on the application of the OCC process and diversification of its products is still progressing. This work reviewed the progress of the OCC in terms of its development, products, potential and challenges since its inception in the 1980's up to today. Many products are now commercially available. However, there remain some opportunities because the OCC products are still limited. The use of the process to manufacture ingots of superior mechanical strength for structural, automotive and aerospace industries is one of the potential active research fields. Alloy and silicon purification are also areas worthy of investigation. There is still a need for researching OCC of a variety of alloy materials for many potential applications. Numerical models for predicting fluid flow, microstructures, segregation are still to be developed and applied in order to improve the process.

The OCC Process

The technique

The principle of the OCC process can be understood if it is compared with that of the conventional continuous casting as shown in Figure 1. The mold in the conventional continuous casting is cooled simultaneously with the entry of the melt inside the mold and heat is extracted from the melt by the cold mold [9]. The growth of crystals takes place radially from the mold walls towards the center of the ingot since nucleation starts from the surface of the mold. This mode of solidification produces strand-mold friction making it difficult or impossible to produce small cast products. This is opposite to the OCC process where the mold is heated and nucleation of crystals only starts outside the heated mold in the strand being cast. As a result, crystal growth occurs parallel to the casting direction. According to the separation theory [10], a cast with only columnar grains can be produced by preventing separation of the crystals from the cold mold walls. Ohno found that cooling an ingot only at one end could produce a cast with unidirectional columnar crystals and single crystals [10,11]. In the OCC process the use of a heated mold prevents separation of crystals and allows solidification to start at mold exit, so crystals are only initiated at the mold exit and grow in the casting direction.

Process description

The OCC process is a unique metal forming technique in which molten metal is introduced continuously into an externally heated mold, the temperature of which is held just above the solidification

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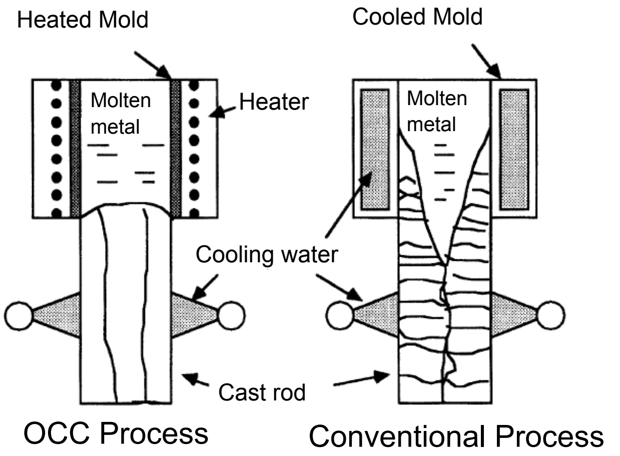

Figure 1: Schematic diagram comparing OCC process with conventional casting [11]. Copyright @2001, adapted with permission.

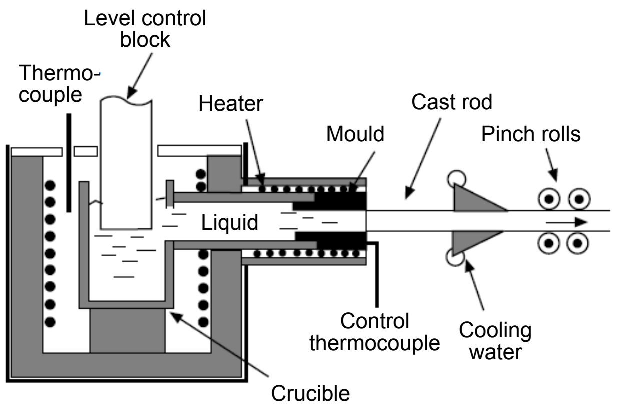

Figure 2: Schematic illustration of the melting and OCC equipment [18]. Copyright @1997, adapted with permission.

temperature of the metal to be cast, thus preventing the nucleation of crystals on the mold surface. Heat is extracted from the cast product by means of cooling water located near the mold exit, differentiating the direction of heat flow in the OCC process from that in the traditional continuous casting process. Consequently, friction between the mold surface and the cast product is eliminated, thereby facilitating casting of smaller diameter wires without breakage [12]. An axial temperature gradient exists between the heated mold and the separated cooler, and heat is extracted only through the ingots being cast. As a result, crystal growth occurs parallel to the casting direction and cast products are obtained with unidirectional morphology, thus the process integrates directional solidification with continuous casting [13]. Figure 2 shows a schematic diagram of the horizontal OCC system which consists of a melting furnace, a cylindrical displacer block for molten metal level control, a heated graphite mold, a water-cooling device and pinch rolls for withdrawal of the cast product. To start casting, the mold temperature is set at a target value, which is slightly above the melting point of the metal, and a starting bar is positioned at the mold exit. If many crystals are nucleated at the end of the dummy where the ingot begins to solidify, competitive grain growth and macroscopic interface curvature eliminates all grains except one having a direction of preferred growth. The OCC principle can be utilized in either vertical or horizontal casting configuration. Through precise control of temperature gradient and growth rate, a high degree of microstructural control is achieved. Furthermore, solidification shrinkage in OCC process is easily fed by liquid metal, producing ingot wires or rods without shrinkage holes or porosity. For large temperature gradients and low growth rate, a planar interface is usually achieved which allows a crystal to form with uniform composition [14]. The solid-liquid interface is flat or convex to liquid. Thus, the OCC process permits the generation of single-crystal materials, cored materials or cast products with a unidirectional structure [7].

In controlling the OCC system, it is conceivable that breakout will occur when the solid-liquid interface is located at the mold exit. Thus, in practice the location of the solidification front must be determined based on consideration of the metal density and diameter of the cast product. For example, during the casting of copper rods, the solidification front is kept slightly within the mold [15]. On the other hand, with lighter density materials such as aluminium, it is possible to cast products with the solidification front outside the mold. Products produced by the OCC process exhibit improved ductility [16,17].

Influence of Process Variables

During the OCC process, several process variables influence the ingot quality and should be properly controlled to get the required ingot properties [18,19]. The mold exit temperature, casting speed and cooling conditions are the three main key process variables affecting the OCC process [11,15,19,20]. These process conditions affect the position of the solid-liquid interface, which must be carefully controlled to obtain a quality ingot.

The influence of process parameters on the solid-liquid interface position and quality of ingots were studied by many investigators [11,15,19-25]. The results showed that process parameters affect surface quality by affecting the position of the solid-liquid interface. The casting speed and cooling intensity should be adjusted such that the solid-liquid interface will be just at the mold exit without breakout; depending on the material.

Mold exit temperature

As the temperature of the mold is increased, the solid-liquid interface will move from the inside to the outside of the mold [20]. This is because the extraction of heat will be now difficult if the same cooler is used. The mold exit temperature should not be too high as this will decrease the diameter of the produced ingots due to deformation resulting from failure to fully solidify during ingot pulling with pinch rollers. The mold exit temperature should be kept just above the melting point of the metal in order to prevent heterogeneous nucleation inside the mold. If breakout does not occur, then the surface quality of the produced ingot will improve as the mold exit temperature increases.

Casting speed

When the temperature of the mold is set, the interface will move from inside to outside of the mold as the casting speed increases and the opposite is true when the casting speed decreases as shown in Figure 3. Increased casting speed decreases effective cooling such that the heat created when the ingot is solidified increases resulting in an increase in the mold temperature. Thus, in order to keep the temperature of the mold at a certain value, the interface must move to the mold exit to counteract the increasing heat. Casting speeds should allow the ingot to completely solidify before pulling it off.

Cooling condition

The capability of cooling, which is determined by the mold exit-water cooling distance and flux intensity of the water cooling, is weak as the cooling distance increases or the cooling water flux intensity and area is reduced, and cooling is strong for the opposite effect. The solid-liquid interface will move to the mold exit with weak cooling and will move into the melt with strong cooling. Effective water cooling helps the growing crystal to sustain its diameter and prevent ingot deformation.

Interface Shape

The shape and morphology of the growth interface depends on the axial and radial temperature gradients on both sides of the interface [26]. Figure 4 shows that the convex interface with respect to the solid is created when the temperature gradient at the growth interface is low since heat extraction through the growth crystal becomes dominant whereas the concave interface towards the melt is formed since the temperature gradient is large because the heat is lost outside the mold. The shape of the solid-liquid interface is flat under conditions like low axial temperature gradients and high growth rates. If no free surface exists, the solid-liquid interface is vertical and straight, while with free surface (thermocapillary), the solid-liquid interface is inclined and curved in the growth direction. The lower the thermal conductivity, the less concave the interface will become [27]. The heat transfer coefficient is also very important in determining the shape of the interface. When the interface is convex towards the melt, grains of the preferred growth orientation can grow at the expense of others and when the interface is concave into the solid, disoriented crystallites that nucleate on the interface may propagate into the crystalline matrix [27].

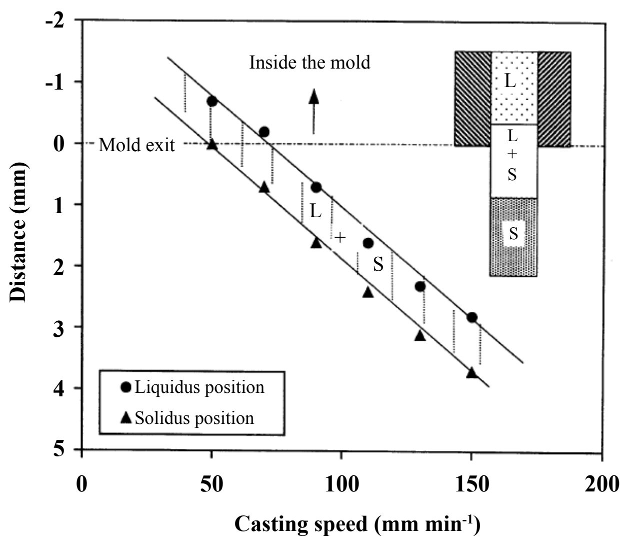

Figure 3: The location of liquid-solid (L-S) zone *vs* casting speed [11]. Copyright @2001, adapted with permission.

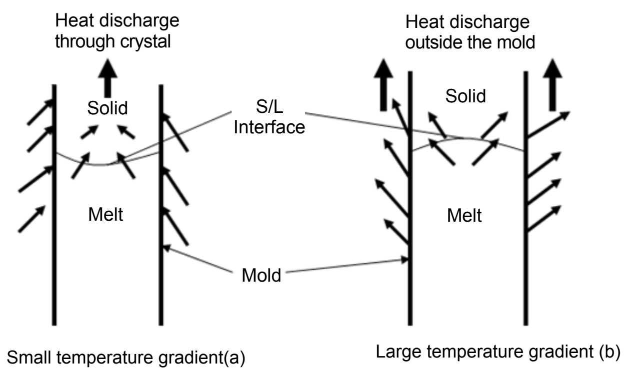

Figure 4: Effect of temperature gradient on the solid-liquid interface shape, (a) small temperature gradient, (b) large temperature gradient [27]. Copyright @1984, adapted with permission.

OCC Products

As was shown in previous section, the OCC process produces net shape or near net shape, unidirectional or single crystal ingots of unlimited length. The process is used to make low defect rate and high-quality ingots of almost any alloy and the largest diameter reported so far was 8 mm whilst the smallest diameter was 1.6 mm for some alloys. To date, various OCC ingots, such as Bi, Cu, Zn, Mg, Co and Al alloys have been fabricated by several researchers [8,9,11,16,28-35]. Here known OCC products according to their usage are presented.

Electronic cables

The wires produced by the OCC process are already available in the market for electronics applications like video and audio cables. These wires possess unique electronic, mechanical, optical and thermal properties [15,36,37]. For example, the resistivity of single-crystal copper wires is about 15% lower and the elongation rate is about 80.24% higher than those of common copper wires [38].

The wires/rods produced by OCC include:

1. Cu wires [29,39]
2. Ag rods [39]
3. Al-Cu cored rods [36]
4. Al wires [40,41]
5. Al wires with optical fibres/ceramics [40,41]
6. Al-Y [42]
7. Au [30]

Examples of copper and silver wire products, which are already in the market, are shown in Figure 5.

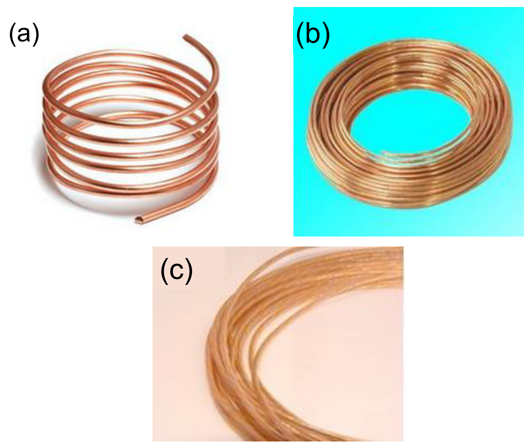

Figure 5: Some wires produced by OCC **(a)** Copper Tubes **(b)** copper wires and **(c)** silver mixed with fibers wire.

Soldering, hard facing, and thermal fuse wires

Bi containing lead free rods for soldering, metal matrix composites of hard phases in alloys rods for hard facing and Bi-Sn thin fuse wires were successfully developed by the OCC process and are now available in the market. Bi is brittle and easily segregates, but OCC was successful in fabricating good surface finish rods free of segregation.

Specific products in this category include:

1. Sn-Bi rods [29,43]
2. Sn-Bi-Ag-Cu rods [43]
3. Bi-In-Sn wires [16]
4. Al-Cu/Al-Si MMC hard facing rods [44-46]

Dental and medical materials

High quality ingots cast by the OCC process also find applications in the medical field including for dental uses. The products include Co-Cr-Mo-based alloy cylinders as dental implant materials [47] and ductile Cu-Al-Ni alloys for biomedical applications [48]. Many high quality materials with many geometries for other medical uses like drug delivery and implants are possible from the OCC process.

Structural applications

Light and high strength materials like Al alloys can be produced by the OCC process and have superior mechanical properties compared to conventionally cast materials. These alloys have potential applications for structural purposes like automotive and aerospace industries. Compared to single crystals produced using bulk growth processes, these OCC alloys are not yet commercially applicable for structural applications due to size limitations. The aluminium bronzes (Al-Cu) were much researched and showed superior mechanical properties like strength, high ductility, high corrosion and fatigue resistance [18,49,50]. These alloys can be used in sea water-related service, water supply, oil and petrochemical industries, specialized anti-corrosive applications and certain structural retrofit building applications [51].

Shape memory alloys

Single crystal shape memory alloys of low cost that are ductile can be produced from brittle materials by the OCC process. Ductile and high quality Cu-Al-Ni low cost shape memory alloy wires can be continuously cast by the OCC process [9,11]. These alloys are smart materials and are applicable as sensors and actuators for a variety of technologies.

Miscellaneous

The OCC products can also be used for other applications including:

1. Rare earth alloys for vapor deposition e.g. Al-Y, Al-Ce, Al-La [42,52,53]
2. Copper tubes for heat exchangers, induction coils and inserting optical fibers [54]
3. Stellite tubes of complex geometries [54]

Properties of OCC Products

The properties of the OCC products are different from those obtained by conventional casting due to differences brought about by change in microstructure. The unidirectional solidification in OCC mostly forms crystals with a preferred orientation of [55]. Metals are easily cast with this orientation as single crystals when compared to alloys due to the stability of the planer solid-liquid interface. The addition of grain refiners and modifiers like Ti and Sr was also found to enhance directionality and mechanical properties such that single crystals can be produced even at higher casting speeds [56,57]. Figure 6 compares the microstructures of OCC and gravity cast Al-Si alloys and clearly demonstrates an improvement in microstructure when using OCC process compared to static casting. Although other properties like electronic, thermal and optical properties are improved by the formation of single or directional ingot, in this section mechanical properties are particularly looked at since for many engineering applications, such information is crucial.

Mechanical properties

The biggest challenge of conventional cast alloys is the presence of defects such that the mechanical strength is reduced. The common defects include cracks, inclusions, blowholes and shrinkage porosity [49]. To reduce the numbers of cast defects, an attempt has been made in the past to use alternative casting technologies, e.g., squeezed casting [58], melt drag twin-roll casting [59], hot-chamber casting [60], semi-solid rheo-casting [61], thixoforming [62] and continuous casting technology [63]. Still, these processes produce polycrystalline materials with some casting defects. The OCC process as explained in previous sections produce alloys free from many casting defects. It was shown that the OCC materials exhibits the highest total elongation compared to those produced by chill casting or crystal growth processes. Conditions favouring formation of single crystals like low casting speed are desirable since they enhance the mechanical properties of the ingots [43].

The mechanical properties of OCC products have been examined by several researchers and was often incomplete [9,11,16]. Microstructure and mechanical properties were often not analysed simultaneously and the analysis on mechanical properties was not comprehensive. For structural applications, aluminium alloys were researched the most. The effects of microstructure on mechanical properties of ingots were comprehensively researched by several investigators [32,33,49,50,55,64,65]. Properties like ductility, strength, and fatigue were shown to be better in OCC compared to conventional casting. This was because of their unidirectional fine microstructure, low concentration of defects and uniformly oriented lattice structure. Figures 7 and 8 show the comparisons of yield strength, ultimate tensile strength, elongation and ductility of OCC versus statically cast Al-Cu and Bi-In-Sn alloys. There is significant improvement in mechanical properties when using OCC to produce these alloys when compared to conventional casting.

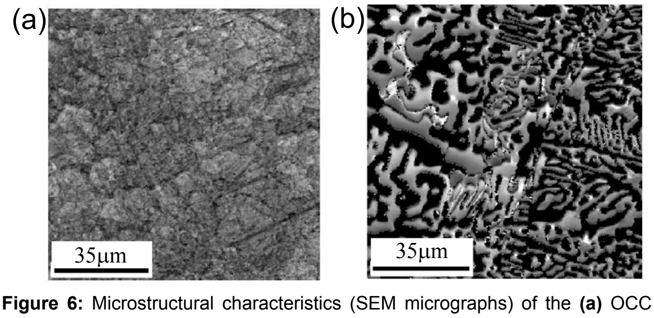

Figure 6: Microstructural characteristics (SEM micrographs) of the **(a)** OCC and **(b)** gravity cast Al-Cu alloys samples [49]. Copyright @2010, adapted with permission.

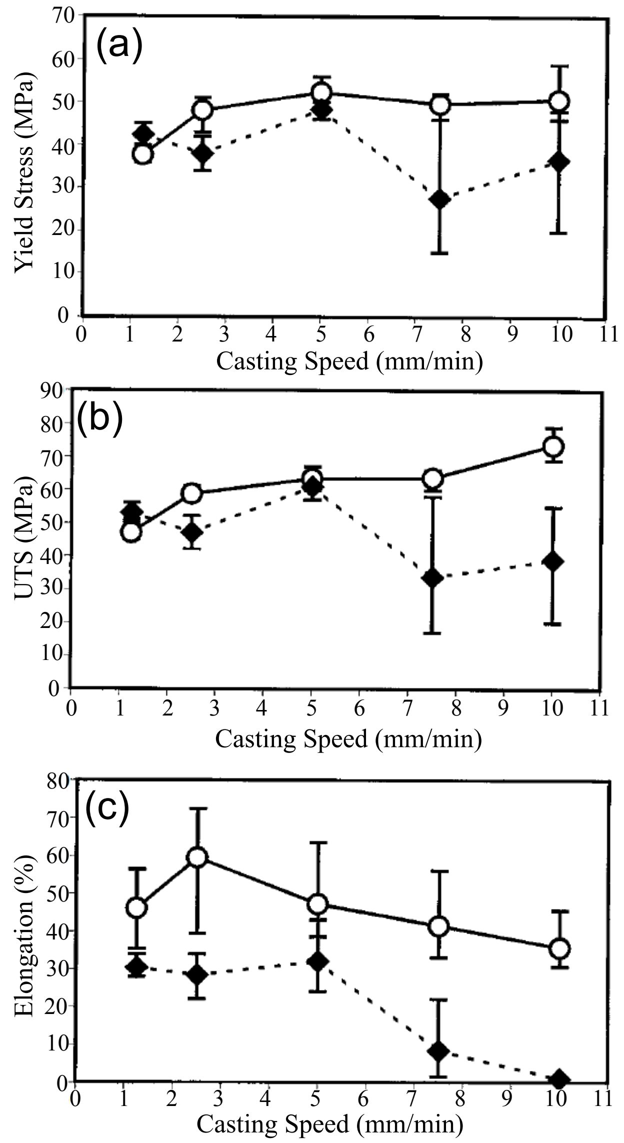

Figure 7: Change in values of yield stress, UTS and elongation with casting speed for OCC cast (○) and statically cast (♦) specimens [16]. Copyright @2002, adapted with permission.

Modelling of the OCC Process

To gain some insight into the OCC process and optimize working conditions, a couple of researchers used numerical modelling and computer simulation. Morman [66] used an asymptotic approach to model the OCC of Sn-Pb eutectic cored rods. The effects of process parameters on the shape of the cored rod system and temperature profiles were computed. Wang [2,67] developed a numerical model for simulating heat and fluid flow during crystal growth by the OCC process. A three dimensional model was developed and applied to simulate the position of the phase change region and melt flow patterns by Chabchoub [68] and the results were in excellent agreement with experimental measurements. Ni et al. [69] accessed the feasibility of a one dimensional heat transfer approach on important processing parameters. The temperature profile results were in agreement with experimental results. In our work [28,70,71], we used numerical modeling and computer simulation to determine the stirring

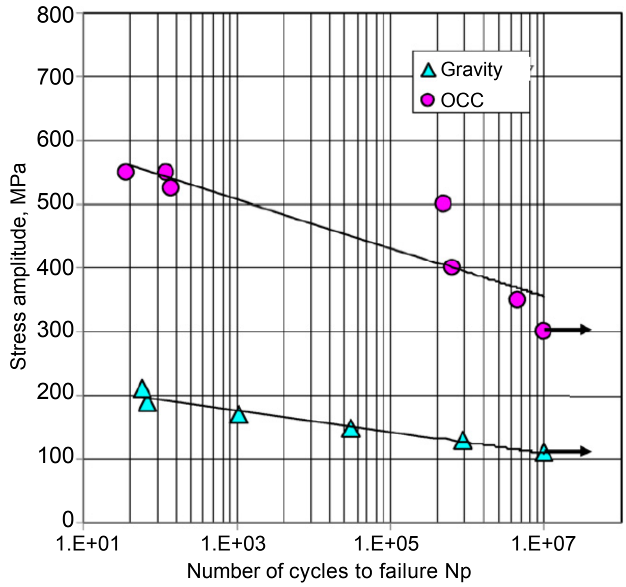

Figure 8: Stress amplitude *vs.* cycles to failure curves for the OCC and gravity samples [49]. Copyright @2010, adapted with permission.

conditions necessary for purification of contaminated industrial Al-Si alloys during the OCC process. The influence of stirring method and stirring direction on ingot purity was numerically analyzed. However, more work should be done in modeling and simulation of the fluid flow, microstructure and macrosegregation during the OCC process since research in this area is scarce. Such information will guide and assist in the development of the process for manufacturing various multicomponent alloys.

Challenges and Potential Developments

Challenges

1. The size of the castings from the OCC process is still limited for large size manufacturing of components. More research is still needed in increasing product size without compromising quality. Efficient methods of cooling the ingot as it exit the mold should be developed.

2. In some applications requiring anisotropic materials such as those structures exposed to anisotropic stresses, directional properties of directionally solidified OCC alloys may be a problem. To mitigate this, there is still a need of research on OCC process with either mixing in the mold to produce equiaxed microstructures or fabrication of a perfectly single crystalline structure with anisotropic properties.

Potential developments

There are still a variety of some potential developments in research and application of the OCC process and these include and are not limited to:

1. Development of ingots of large diameter to extend the use of cast products.

2. Casting of a variety of alloys e.g. Ni based super alloys, Ti Alloys, high entropy alloys.

3. Purification of ingots and silicon during casting using e.g., electromagnetic fields.

4. Modeling and simulation of microstructures and macrosegregation.

Conclusions

The OCC process for manufacturing metallic components is now established and commercialized for a number of applications. Products like audio and video cables, dental implants, lead-free solders and thermal fuse wires are now on the market. However, there remain some opportunities because the products from the OCC are apparently limited. The use of the process to manufacture ingots of superior mechanical strength for structural, automotive and aerospace industries is one of the active research fields. There is still a need for researching OCC of a variety of alloy materials and silicon purification for many potential applications. Numerical models for predicting microstructures, segregation and fluid flow during OCC are still to be developed and applied in order to improve the process.

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