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# Aluminium Countergravity Casting – Potentials and Challenges

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## 1. Introduction

Counter-gravity casting, also called vacuum casting, is a mould filling technique in which low pressure created inside a mould cavity, causes prevailing atmospheric pressure on the melt surface to bring about an upward or counter-gravity movement of the melt into the mould cavity. The process was patented in 1972 by Hitchiner Manufacturing (Lessiter & Kotzin, 2002) and different variants of the process had evolved over the years. Greanias & Mercer (1989) reported a novel valve system that could potentially increase throughput by allowing mould disengagement prior to solidification while Li *et al* (2007) have developed a multifunctional system aimed at aggregating different variations of the technology into a single equipment.

The unique mould filling approach of the countergravity casting technique confers on it a set of unique advantages related to casting economics, defects elimination and attainment of net-shape in cast products. Such desirous attributes has ensured the growing importance of the technology, especially in power and automotive applications. A testament to the rising profile of this casting technique is its adoption in the production of a range of parts such as compressor wheels for turbo-chargers (TurboTech, 2011), automotive exhaust manifolds (Chandley, 1999) and a high-volume production (130,000 units/day) automotive engine Rocker Arm (Lessiter, 2000).

The growing importance of this casting technique in some metal casting sectors notwithstanding, there is scant awareness and interest in many mainstream casting spheres. This chapter thus seeks to present a technology overview of the countergravity casting technique. The shortcomings of conventional processes are highlighted alongside the unique advantages of the countergravity technique. Challenges of the countergravity technique are also presented with discussion of efforts and prospects for their redemption.

## 2. Description of the countergravity casting process

The basic process steps for the vacuum casting process are presented as follows. In the diagram in figure 1, a preheated investment mould with an integrated down-sprue (fill pipe) is positioned in the moulding flask.

The sprue, with a conical-shaped intersection point with the rest of the mould, pokes through and sits in the conical depression of the lock-nut. The “square” fit of the two, depicted in figure 2, ensures a sealing of the flask interior from the external environment.

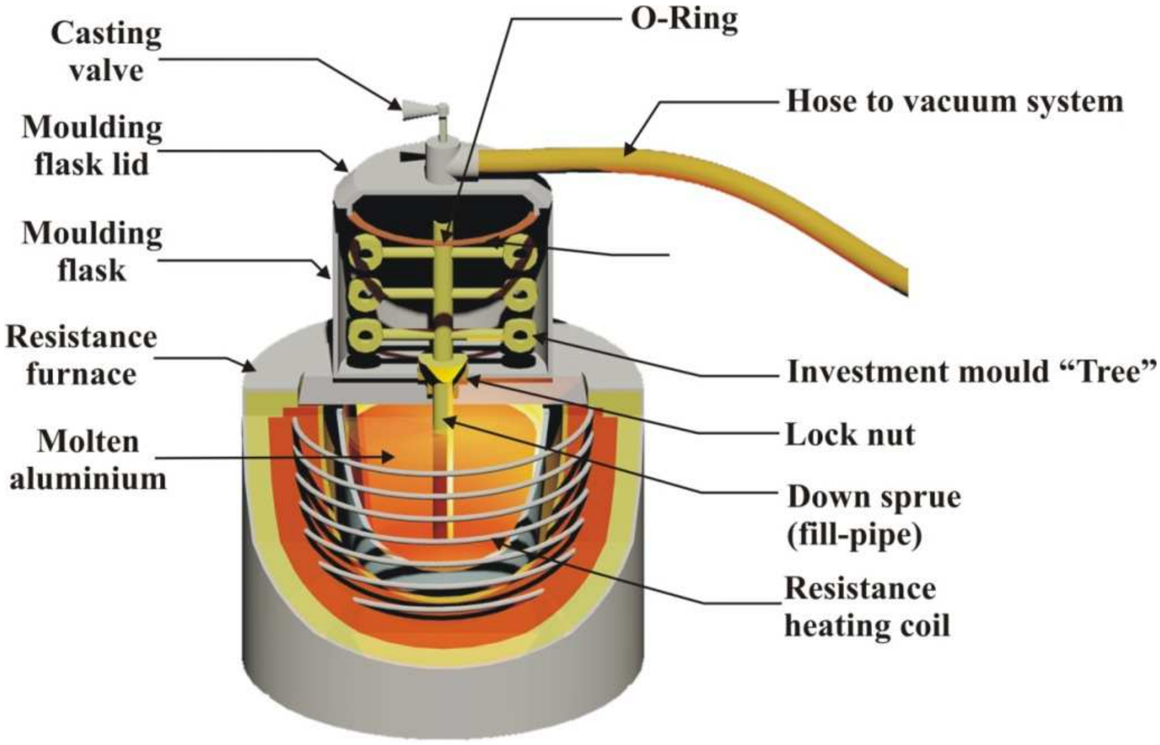



Fig. 1. Typical setup of the countergravity casting process

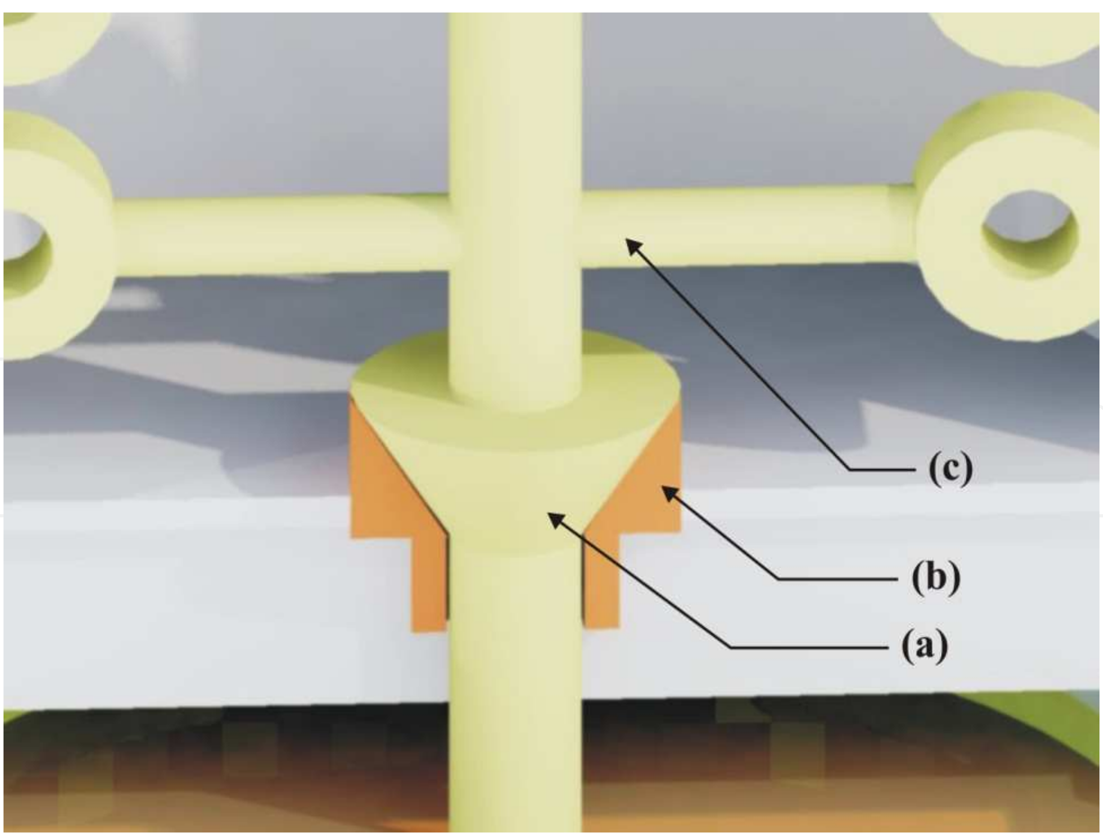



Fig. 2. Down sprue, with conical base (a) is integrated with the rest of the investment mould "tree" (c). The assemble rests inside the conical depression of the lock-nut (b)

The otherwise solid investment mould is made permeable by a single opening at its apex. This opening effectively connects the mould cavity with the interior space of the moulding flask, making it an extension of the moulding flask and enabling its evacuation along with the rest of the flask. The flask lid hosts the casting valve, a connecting hose to the vacuum system and lid locking mechanism. The electrical resistance furnace melts the aluminium charge, usually by a superheat of about 40 °C above the melting temperature (660 °C) of aluminium to reduce melt viscosity and ease melt up-flow into the mould. During countergravity casting, the moulding flask with the mould assembly inside, is placed on the furnace lid with the down-sprue poking through a hole in the furnace lid.
The vacuum system evacuates the moulding flask and the ensuing low pressure thus created causes ambient atmospheric pressure on the melt to push up the molten metal, up inside the mould. See figure 3.

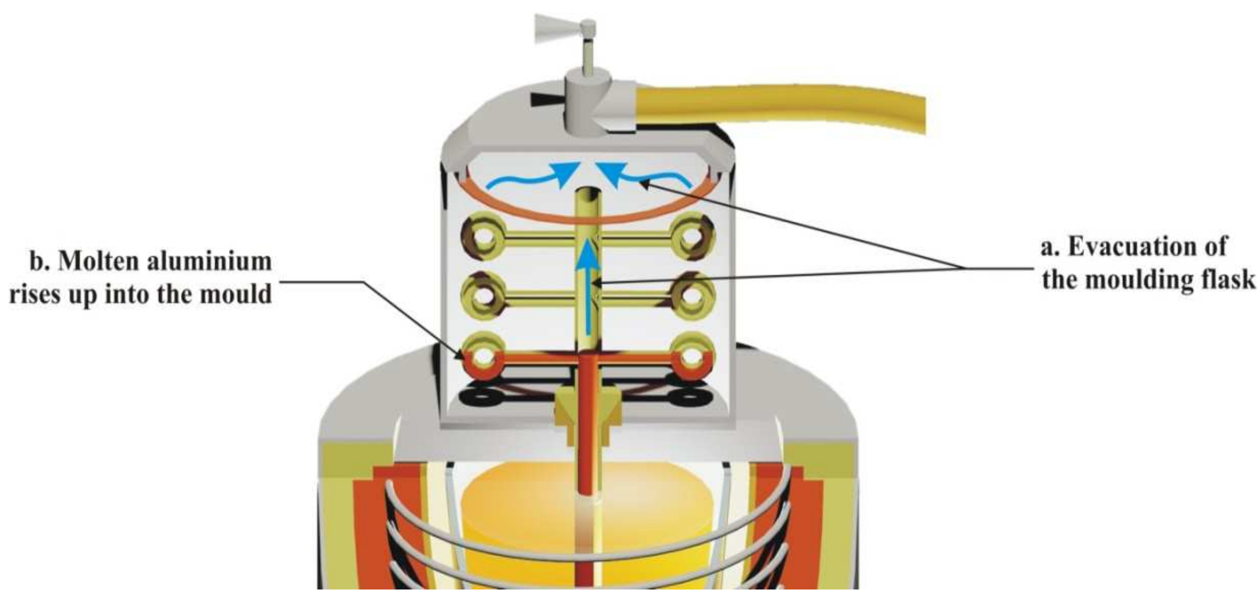



Fig. 3. The evacuation of the moulding flask (a) also evacuates the investment mould cavity. This causes molten aluminium to rise up into the mould cavity (b)

Apart from investment material, the mould could be a metal mould or a ceramic mould. The vacuum system is calibrated so that just the right volume of melt flows inside the mould for a period long enough for the melt to solidify. The vacuum is released after allowing enough time for melt solidification in the mould cavity. This allows un-solidified melt along the sprue length to be flow back into the furnace. The illustration in figure 4 shows the vacuum being maintained until the cavity is completely filled. Vacuum pressure is then released causing un-solidified melt in the sprue to flow back into the furnace

## 3. Conventional techniques and casting defects

Conventional gravity- or pressure-assisted aluminium metal casting techniques like sand casting, investment casting and die casting are fraught with problems. These include gas defects, melt oxidation, shrinkage defects and pouring defects. Defects are naturally undesirable because they can result in low strength, poor surface finish and high number of rejects in a batch of cast products.

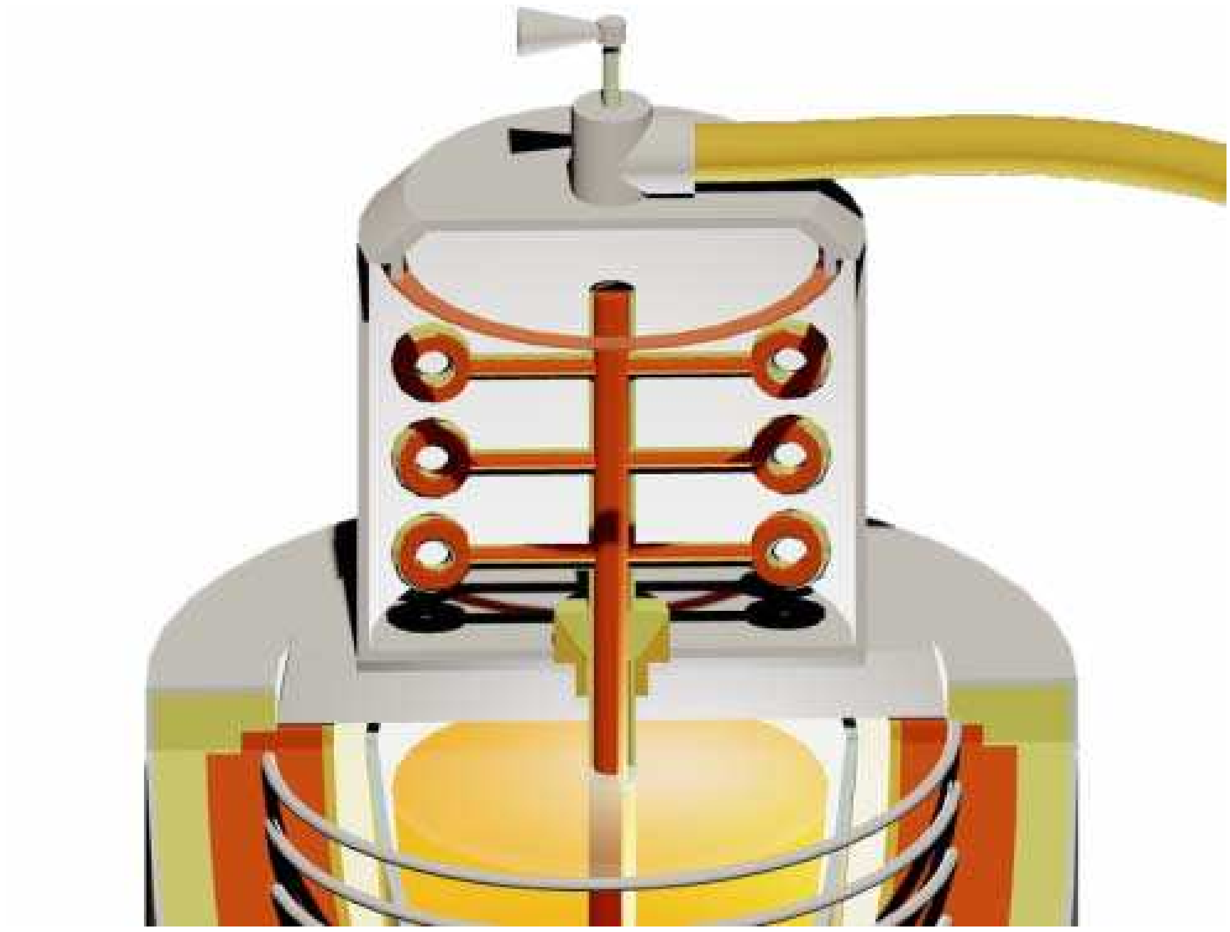


Fig. 4. The vacuum is maintained until the cavity is completely filled. Vacuum pressure is released causing un-solidified melt to flow back into the furnace

### 3.1 Gas defects

Molten aluminium is particularly susceptible to adsorbing significant quantities of hydrogen gas from atmospheric moisture, which leads to a high concentration of dissolved hydrogen in the melt. This may be further exacerbated by alloying element like magnesium which may form oxidation reaction products that offer reduced resistance to hydrogen diffusion into the melt (Key to Metals, 2010). This causes blow holes and gas porosity which combine to reduce strength of the cast part. The micrograph in figure 5 shows a blow hole defect, it can appear at any region of the cast microstructure and is exacerbated by damp mould materials which give off steam during casting. Figure 6 shows gas porosity defects in an aluminium casting, these are much smaller than blow holes and tend to form in clusters around the region of the grain boundaries.

### 3.2 Melt oxidation

Oxidation of the melt is another severe defect suffered by aluminium alloy castings. The elevated melt temperature promotes easy oxidation of the aluminium by ambient oxygen. The aluminium oxide thus formed is an undesirable non-metallic inclusion. Considerable efforts, through the use of in-mould filters, protected atmosphere, or alloying additions are often needed to reduce oxide formation and entrainment in the mould.

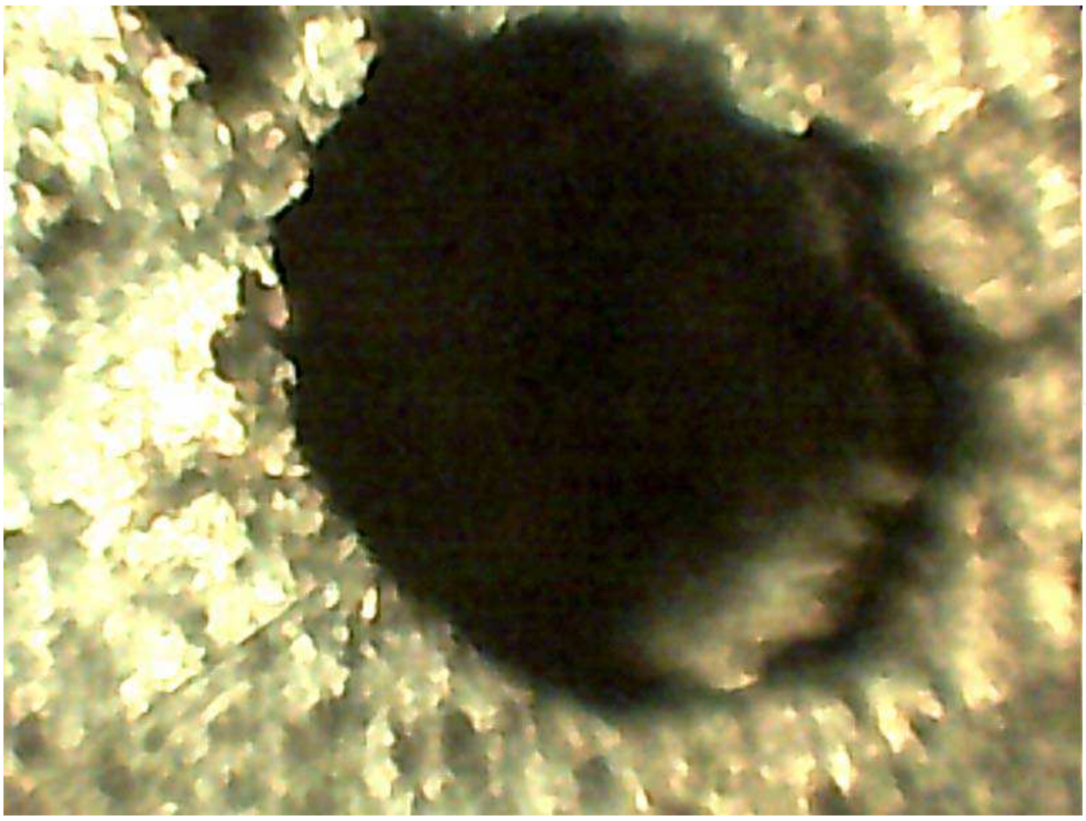


Fig. 5. A Blow hole defect in an aluminum casting at 100× magnification

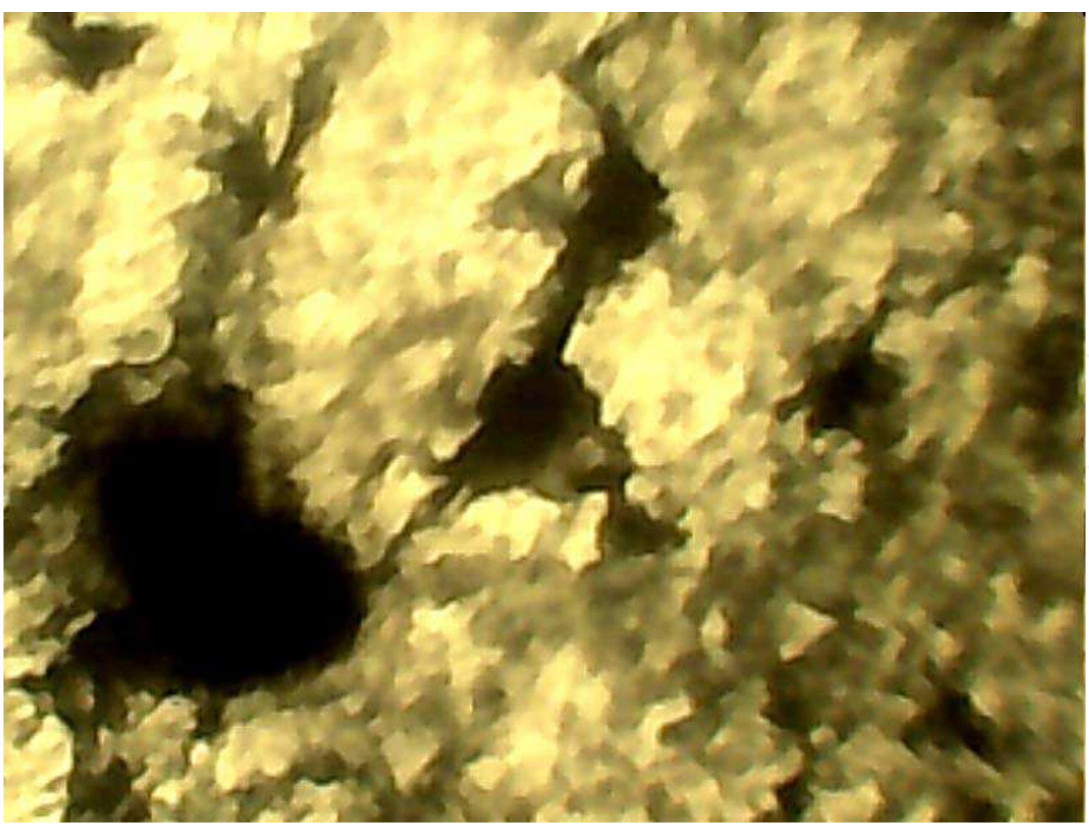


Fig. 6. Gas porosity in aluminium casting at 1000× magnification

### 3.3 Shrinkage

Shrinkage is the natural consequence of liquid to solid transformation of the melt during cooling and is common in most metals. Shrinkage is particularly severe in aluminium alloys. In aluminium alloys, the volumetric shrinkage ranges from 3.5% to 8% (Kaufman and Rooy, 2004). This manifests as shrinkage cavities in larger portions of the casting.
This is often counteracted by strategic placement of risers. Figure 7 shows the typical appearance of volumetric shrinkage defect in an aluminium section.

Fig. 7. Typical appearance of volumetric shrinkage defect in an aluminium section

### 3.4 Pouring defects

During pouring of the melt, there is considerable splashing and sloshing about of the melt. This entrains significant quantities of air and non-metallic inclusions in the mould. Such entrained material degrades casting quality. This problem is often mitigated by incorporation of complex gating systems designed using advanced Computational Fluid Dynamics (CFD) modules. Such casting simulation software is able to predict and avoid bubble streams in metals castings (Waterman, 2010).
Some of the problems outlined above have been resolved by advancements in pressure die casting, improved investment casting techniques and centrifugal casting. These techniques individually solve some, but often not all of the problems with gravity-assisted pour of an air-melt. For instance, in conventional die casting, melt is sprayed at high velocity into the die and cavity-atmosphere tends to be admixed and entrapped in castings during the

turbulent cavity-fill (Jorstad, 2003). The process of air melting and pouring also inevitably introduces oxides, formed during melting, into the cast product. Significant inclusions segregation at grain boundaries are thus very common with gravity assisted sand casting.

## 4. Advantages of the countergravity casting technique

Numerous advantages for metal casters are endemic to the countergravity casting technique. These may be broadly categorized into defect reduction and elimination and casting economics.

### 4.1 Cleaner melt

For aluminium alloys, metal oxides formed and aggregated on the melt surface can be by-passed by taking clean melt from below the surface. The practice of de-slagging using a hand ladle or metal rod to scoop the slag layer off the melt surface unavoidably leaves pieces of slag in the melt which ultimately flows into the mould during casting. Countergravity casting also results in improved melt cleanliness, due to reduced turbulence during mould filling (Druschitz and Fitzgerald, 2000).

### 4.2 Elimination of shrinkage defect

Shrinkage is virtually eliminated in the countergravity casting technique. This is because a constant supply of fresh melt is maintained in the mould during casting. Hence, as portions of the mould begin to solidify, the down-sprue is the last to start solidifying. The reservoir of molten melt in the crucible acts as a riser, ensuring a steady supply of melt into the mould during solidification. This effectively eliminates the need for risering. Figure 8 shows the cross-section of a countergravity cast rod. The absence of volumetric shrinkage defect is evident from the convex meniscus at the top of the rod section.

### 4.3 Simplified gating system

In the countergravity technique, the gating system is considerably simplified as is depicted in figure 9. It consists merely of branches of flow channels emanating from the central sprue. This simplicity is possible because the interior of the mould is actually an extension of the vacuum system. The high pressure differential between the mould interior and the atmospheric pressure ensures that the molten metal will completely permeate every cavity in the mould. Complex in-gates, depending on gravity flow of melt are thus not needed. This considerably simplifies the mould design.

### 4.4 Economical

Countergravity technique significantly decreases the amount of gates that must be re-melted (Flemings et al, 1997). This was actually one of the original goals of the countergravity technique at its inception. Fettling time and costs are reduced while high quality melt is judiciously used.

## 5. Potentials and applications of the countergravity casting technique

The countergravity technique has numerous potentials, derivable from its advanatges over the conventional metal casting techniques. As such it is gradually making in-roads into traditional investment casting applications and also in novel materials production.

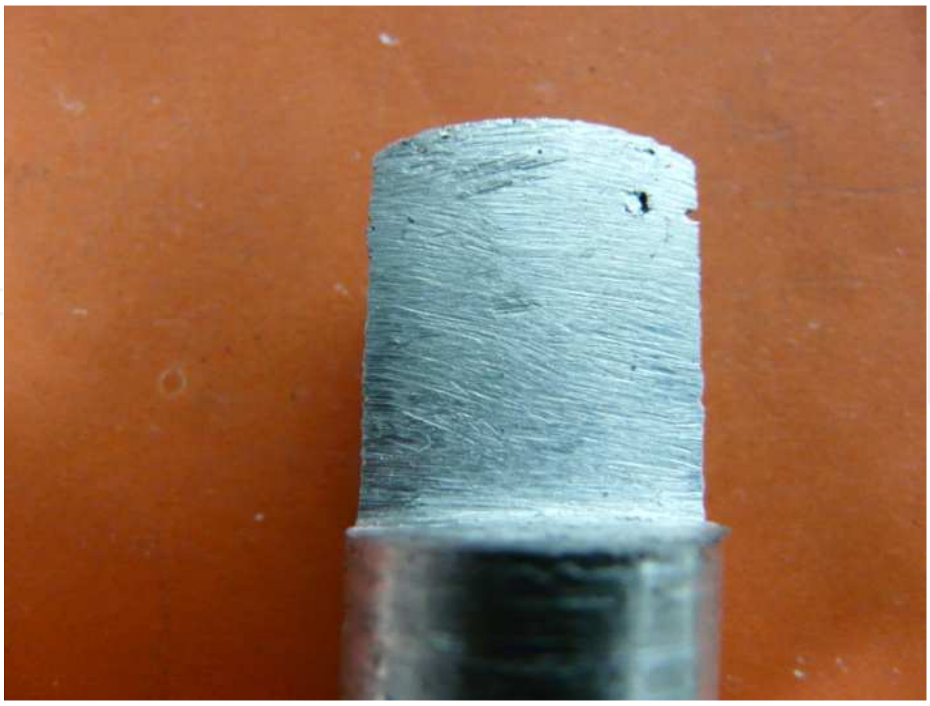


Fig. 8. Cross-section of a countergravity cast rod showing the absence of volumetric shrinkage defect as evident from the convex meniscus at the top of the rod

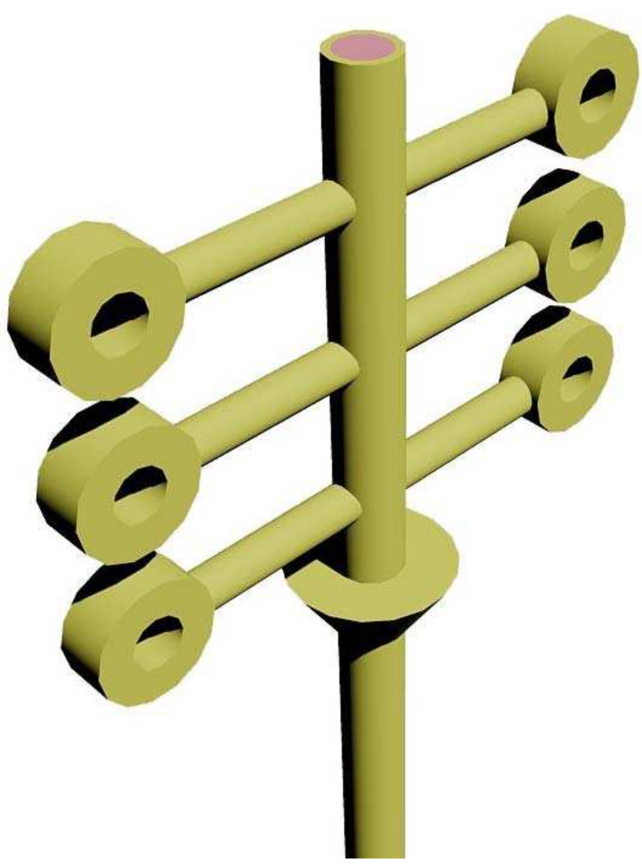


Fig. 9. An investment mould “tree“, simplified structure is characteristic of the countergravity technique

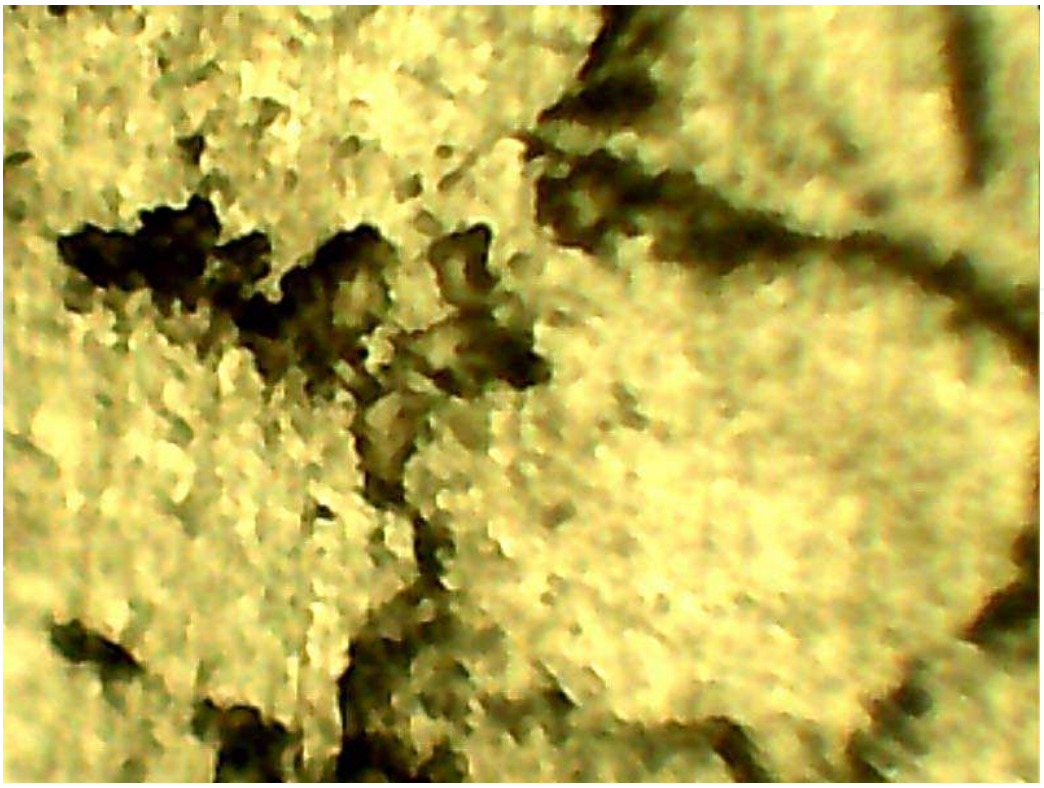


Fig. 10. Ceramic mould at 400× magnification shows heavy segregation of impurities at the grain boundaries

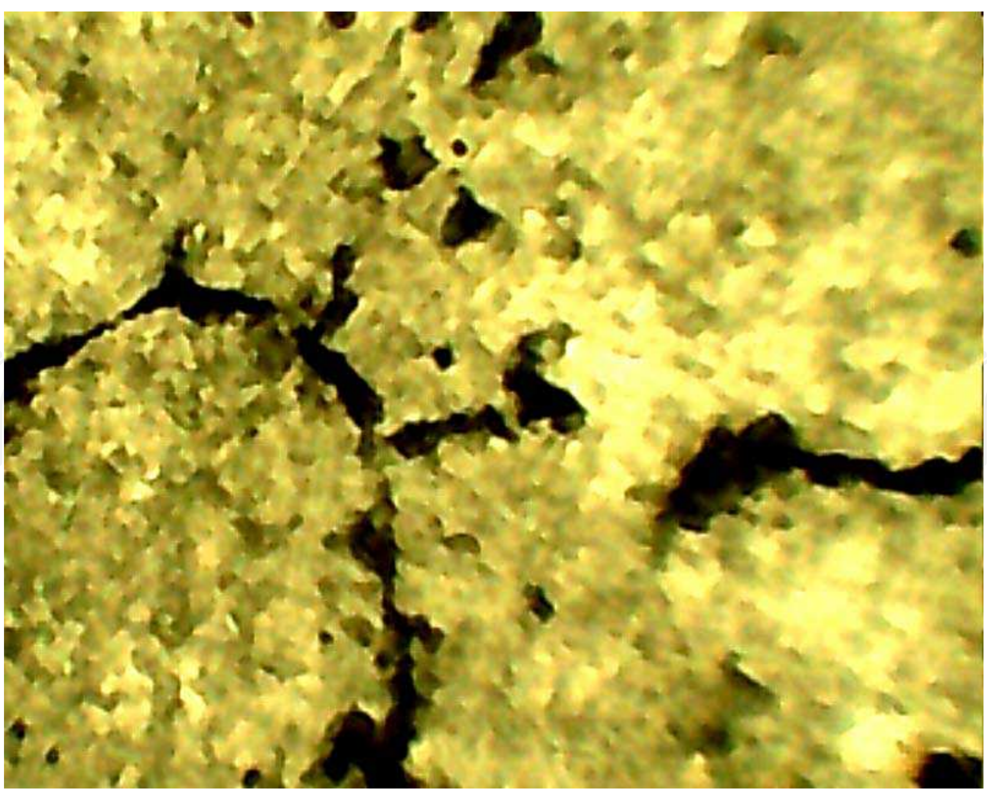


Fig. 11. Countergravity cast specimen at 400× magnification. Significant reduction of impurities at the gain boundaries indicates lesser intake of impurities from the melt

### 5.1 Scrap reduction and scrap usage

Due to the intrinsic ability of the casting technique to produce cleaner castings, it is more adaptable to the use of scraps and foundry returns. These types of foundry feedstock contain significant admixed impurities like moulding sand and oxide inclusions. Such scrap metals produce significant slag which float on the melt surface.

The process of taking the melt can actually be used to pump clean metal below the melt surface. Figures 10 and 11 respectively show the micrographs of gravity-pour ceramic mould cast samples and countergravity cast samples of scraps of aluminium foundry returns. The microstructure shows more segregation of melt impurities in the gravity-pour ceramic mould, while the vacuum cast specimen shows significant reduction in impurities.

### 5.2 Net-shape casting

The countergravity technique is well suited for producing net-shape cast products. It is especially suited for thin-walled sections and intricate details due to its excellent mould filling. This is possible due to the virtual elimination of shrinkage defects in the countergravity casting technique. Near net-shape castings of even higher temperature alloys, such as steels are possible. Such has been reported by Chandely *et al* (1997) in the production of thin-walled steel exhaust manifolds.

### 5.3 Improved strength

Countergravity cast products have improved strength over green sand and ceramic mould specimens. The technique may be thus deployed in the production of high strength parts hitherto produced by forging. High Counter-Pressure Moulding, a proprietary variant, has been reported to exhibit the same strength characteristics as forging in alloy wheel production, at little more than the price of cast wheel (Alexander, 2002). Countergravity techniques are increasingly becoming the preferred choice for the production of alloy wheels because of the added advantage of design flexibility over forging processes. Furthermore, the Cosworth process, which achieves countergravity melt flow by means of an electromagnetic pump, has been successfully used for high strength structural components for air frames, gun cradles, and air tanker re-fuelling manifolds (Bray, 1989).

Griffiths *et al* (2007) observed that countergravity filling method produced higher values of the Weibull modulus than conventional gravity mould filling methods. This is a pointer to the reduced variability of strength achievable in the countergravity technique.

### 5.4 Economical use of melt

There are often considerable wastages of melt in more conventional casting techniques due to provisions made for risering and complicated in-gates.

This also results in considerable fettling time and costs. Such wastages are virtually eliminated in countergravity casting since there is no need for risers and complex in-gates are not necessary.

### 5.5 Production of metal matrix composites

Use of the countergravity casting technique is gradually branching into novel materials production. An emerging field of application is the production cast Metal Matrix

Composites (MMC) which can be cast into complex, intricate geometries. These materials have found applications in diverse fields, from high quality reflective mirrors to optical and laser equipment (O'Fallon Casting, 2009). There has been increased interest in the use of cast aluminium/silicon carbide MMC for optoelectronics packaging due to its compatible coefficient of thermal expansion, high thermal conductivity, and potential to produce parts at low cost (Berenberg, 2003). In ring laser gyros, these MMCs are displacing traditional favourites like beryllium and stainless steel in the production of dimensionally stable mirrors that can withstand extreme thermal cycling (Mohn and Vukobratovich, 1988).

## 6. Challenges and limitations of countergravity casting

The afore-mentioned advantages notwithstanding, the process has some challenges militating against its wide-spread deployment.

### 6.1 Equipment cost

Spada (1998) reported the cost of countergravity mould and handling equipment to be typically between $50,000 to $1.25 million depending on complexity. Present day prices would naturally be much higher. This is so because the proper utilisation of a countergravity casting equipment requires an ecosystem of support facilities. These include high-temperature mould pre-heating ovens, mould and moulding flask positioning units, and sophisticated vacuum control systems. These added facilities add to the cost of setting up and operation of the technique. In some instances, licensing fees may also apply, further raising up the cost.

### 6.2 Size restriction of products

Countergravity casting is typically restricted to smaller sized components, usually less than 50 kg. This is because the moulding flask tend to be small, to allow for proper operation of the vacuum system. Larger flasks are more difficult to evacuate and maintain at desired partial vacuum.

### 6.3 Mould and sprue pre-heat temperature

It is essential for the mould and the sprue to be adequately heated prior to carrying out countergravity casting. The pre-heat prevents chilling of the melt as it flows up from the crucible. Improperly pre-heated sprue and mould will cause increased melt viscosity and a tendency for the melt to get stuck in the sprue or incomplete mould filling. Figure 12 shows premature solidification of melt inside the sprue due to inadequate pre-heat of the mould and sprue assembly.

### 6.4 Vacuum control

Proper control of vacuum pressure is paramount in countergravity casting. Too much vacuum will result in splatter of melt inside the moulding flask due to over-filling of the mould cavity. Loss of vacuum during casting is also a real problem for countergravity technique. This may be caused by improperly closed lid, damage to or cracks in the moulding flask, or a poor seal between the recess of the lock-nut and the conical connection point of the sprue on the mould. These non-ideal, but very real instances may require a more interactive vacuum system, wherein pressure feedback is used to constantly adjust the flask vacuum pressure.

### 6.5 Melt contamination by reusable sprue

An effort to bring down overall system costs have led to the use of re-usable sprues. These are usually in the form of metallic pipes. Re-usable sprues must however be used with caution because of the tendency of accumulated impurities in the sprue channel to contaminate the melt.

Fig. 12. Premature solidification of melt inside the sprue due to inadequate pre-heat

## 7. Benefits of countergravity casting

Some of the advantages highlighted for the countergravity casting technique may be achievable in other, more conventional processes. However, the countergravity technique provides a more complete solution. The process easily lends itself to automation for large scale production; while at the same time can be scaled down for small-scale and jobbing applications.

The possibility of more economical use of the melt is good for the bottom line of foundry operation and was actually the original goal of the countergravity technique. This has motivated a growing list of companies and industrial sector to adopt the technology.

The combination of precision near net shape and strength has resulted in countergravity die casting being used to produce parts formerly made of steel that required a significant amount of secondary machining (Aurora Metals LLC, 2009).

Net shape casting, particularly for thin sections is easily achievable in countergravity casting. Countergravity cast part may have walls as thin as 0.5 mm (National Institute of Industrial Research, 2005).

In order to make the benefits of this casting technique more accessible, low-cost countergravity equipment have been developed. A low-cost design developed by the authors is presented in figure 13.

The design utilizes a simplified vacuum control system and manual positioning of mould and moulding flask. Such low cost alternatives would be invaluable for small scale operations.

Fig. 13. A low-cost machine for countergravity casting

Size restrictions have been tackled by many recent designs. Jie *et al* (2009) reported a system using compressed air to assist the up-flow of melt for large-sized castings. The Check Valve (CV) process is has been developed Hitchiner for larger sized casting. This allows for portions of the melt in the down sprue to be returned to the furnace whilst keeping the portion delimited by the valve in the moulding flask.

Vacuum control in countergravity casting has benefited significantly from advances in control technology and instrumentation. Li et al (2008) demonstrated a pressure control system based on fuzzy-PID control and a digital valve system and achieved pressure error of less than 0.3 KPa. Other workers such as Khader et al (2008) have carried out extensive system modelling of the countergravity casting machine with the goal of developing an automatic controller for control of machine operation.

## 8. Conclusion

Metal casting is several millennia old, and yet it continues to evolve both in areas of applications and in the technologies of implementation. The increasing relevance of aluminium alloys in modern technology, from power applications to consumer products, makes it imperative to seek better, more cost-effective production routes.

The countergravity casting technique is an ingenious method for production of aluminium parts. The numerous permutations and mutations of this technique over the last four decades is a testament to its feasibility and flexibility; and a recognition of its inherent advantages. Aluminium alloy castings stand to benefit immensely from the unique attributes of the countergravity technique because the goals of net-shape casting and superior mechanical properties are truly achievable via this method.

## 9. References

Alexander, D. (2002). High-Performance Handling Handbook. MotorBooks International, ISBN 978-0760309483, Osceola, Wisconsin

Aurora Metals. (2009). Vacuum Cast Impellers. March $12^{th}$ 2011, Available from: < http://www.aurorametals.com/vc.htm>

Berenberg, B. (2003). Metal Matrix Composites Advance Optoelectronics Package Design. In: *High Performance Composites*, $20^{th}$ May, 2011, Available from: < http://www.compositesworld.com/articles/metal-matrix-composites-advance-optoelectronics-package-design>

Bray, R. (1989). Aluminium casting process finds new applications; developments in the Cosworth Process have spread its application to such fields as the aerospace and defence industries. *Modern Casting*, $20^{th}$ May 2011, Available from; < http://www.highbeam.com/doc/1G1-8230613.html>

Chandley, G.D.; Redemske, J.A.; Johnson, J.N.; Shah, R.C. & Mikkola, P.H.(1997). Counter-Gravity Casting Process for Making Thinwall Steel Exhaust Manifolds *Society of Automotive Engineers (SAE), Technical Papers,* March $3^{rd}$ 2011., Available from: < http://papers.sae.org/970920/>

Chandley, G.D. (1999). Use of vacuum for counter-gravity casting of metals. *Materials Research Innovations*, Vol. 1999, No. 3, pp 14-23.

Druschitz, A.P & Fitzgerald, D.C. (2000). Lightweight Iron and Steel Castings for Automotive Applications. *Proceedings of Society of Automotive Engineers (SAE) 2000 World Congress*, ISSN 0148-7191, Detroit Michigan, March, 2000

Flemings, M.; Apelian, D.; Bertram, D.; Hayden, W.; Mikkola, P. & Piwonka, T.S. (1997). *World Technology Evaluation Centre Report on Advanced Casting Technologies in Japan and Europe*. American Foundrymen's Society (AFS), ISBN 1-883712-45-9

Greanias, A.C. & Mercer, J.B. (1989). Vacuum countergravity casting apparatus and method with backflow valve, In: *United States Patent 4862945*, March 3rd 2011, Available from :< http://www.freepatentsonline.com/4862945.html>

Griffiths, W.D.; Cox, M.; Campbell, J & Scholl, G. (2007). Influence of counter gravity mould filling on the reproducibility of mechanical properties of a low alloy steel. *Materials Science and Technology*, Vol. 23, No. 2, pp 137-144, ISSN 0267-0836

Jie, W.Q.; Li, X.L. & Hao, Q.T. (2009). Counter-Gravity Casting Equipment and Technologies for Thin-Walled Al-Alloy Parts in Resin Sand Moulds. *Materials Science Forum*. Vols. 618-619 (2009), pp 585-589

Jorstad, J.L. (2003). High Integrity Die casting Process Variations, *Proceedings of International Conference on Structural Aluminium Casting,* Orlando Florida, November, 2003

Kaufman, G.J. & Rooy, E.L. (2004). *Aluminium Alloy Castings Properties, Processes, and Applications*. ASM International, ISBN 0-87170-803-5, Ohio.

Key to Metals (2010). Aluminium and Aluminium Alloys Casting Problems. March 6th 2011, Available from: < http://www.keytometals.com/Article83.htm>

Khader, A. M.; Abdelrahman, M. A.; Carnal, C.C. & Deabes, W. A. (2008). Modelling and Control of a Counter-Gravity Casting Machine. *Proceedings of 2008 American Control Conference*, Seattle Washington, June 2008

Lessiter, M.J. & Kotzin, E.L. (2002). Timeline of Casting Technology. *Engineered Casting Solutions*, Summer 2002, pp 76-80.

Lessiter, M.J. (2000). Engineered Cast Solutions for the Automotive Industry. *Engineered Casting Solutions*, Fall 2000, pp 37-40.

Li, X.; Hao, Q.; Jie, W. & Zhou, Y. (2008). Development of pressure control system in counter gravity casting for large thin-walled A357 aluminium alloy components. *Transactions of Nonferrous Metals Society of China*, Vol. 18, No. 4, pp 847-851

Li, X.; Hao, Q.; Li, Q. & Jie, W. (2007). Study on Technology of Multifunction Counter Gravity Casting Equipment. *Foundry Technology*, Vol. 07, No. 014,

Mohn, W.R. & Vukobratovich, D. 1988. Recent applications of metal matrix composites in precision instruments and optical systems. *Optical Engineering*, Vol. 27, No. 2, pp 90-98

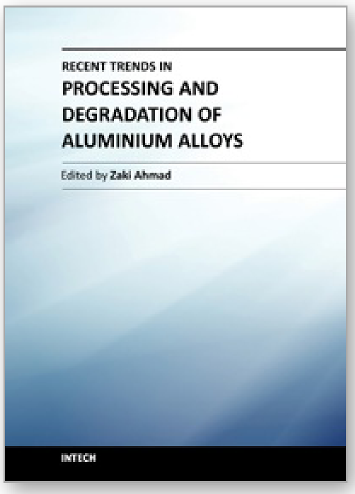
National Institute of Industrial Research (NIIR) Board of Consultants & Engineers. (2005). The Complete Book on Ferrous, Non-Ferrous Metals with Casting and Forging Technology. National Institute of Industrial Research, ISBN: 8186623949, New Delhi

O'Fallon Casting. (2009). Silicon Carbide Metal Matrix Composite Alloys (SiC MMC), March 12th 2011, Available from:
< http://www.ofalloncasting.com/MetalMatrix.html>

Spada, A.T. (1998). Hitchiner Manufacturing Co. – Turning the Casting World Upside Down. *Modern Casting*, Vol. 88, No. 7, pp 39-43

TurboTech Precision Products Ltd. (2011). Aluminium Compressor Wheel Castings for Turbochargers, March 3rd 2011, Available from:
< http://www.turbotech.co.uk/manufacturing-process.htm>

Waterman, P.J. (2010). Understanding Core-Gas Defects Flow-3D software helps trace, predict and avoid bubble streams in metal castings. In: *Desktop Engineering, Design Engineering and Technology Magazine*, March 6th 2011, Available from:
< http://www.deskeng.com/articles/aaaype.htm>




**Recent Trends in Processing and Degradation of Aluminium Alloys**
Edited by Prof. Zaki Ahmad

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