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NETCAST™ SHAPE CASTING TECHNOLOGY: A TECHNOLOGICAL BREAKTHROUGH THAT ENHANCES THE COST EFFECTIVENESS OF ALUMINUM FORGINGS

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Abstract

A new Direct Chill (DC) casting process is introduced to semi-continuous casting where near net shaped ingots are solidified. This process is currently being used at Alcan Engineered Cast Products (ECP) facility in Jonquiere, Canada, sectioned, then forged at Alcoa Automotive, Kentucky Casting Center (KCC). Finished forgings are machined and assembled into the Ford D/EW98 platform as suspension components. A brief description of the process and the implications on the forging process are presented.

Introduction

In the competitive arena of material supply and semi-fabricated component manufacture, innovation is a well-recognized key to sustaining market share and positioning for future growth. As a leader in aluminum solidification technologies, innovation is at the core of the Wagstaff business. This paper will introduce the latest such technology, which is currently being commercialized for automotive forgings. NetCast™ is a near net shape, semi-continuous, vertical direct chill shape casting technology with the potential to dramatically reduce forged component cost making them attractive for wider adoption for automotive and other applications.

Aluminum and the Automotive Industry

The aluminum industry continues to grow with Western World Primary Aluminum consumption growing continuously since 1982, apart from a brief lull in 1998. In 1999 total consumption of aluminum grew by 3.9% to 27.1 Mt.

Transportation, the largest and fastest growing market for aluminum, increased by 9% to 7.9 Mt, or 29% of the western world aluminum market. The increase is due in large part to the growing automotive sector, particularly in North America.

U.S. Aluminum Shipments for Passenger Cars and Light Trucks increased by 200% in the last 10 years reaching 2.3 Mt in 1999. North American Shipments for passenger cars and light truck are forecast to grow by 0.800 Mt between 1999-2005, a CAGR of 6.4%.

Automotive weight reduction is driven in part by the OEM's need to improve the fuel efficiency of their cars and light trucks. This coupled with the demonstrated safety and performance advantages of aluminum components will continue to provide incentive for the switch from heavier, traditional materials.

The growth in automotive aluminum usage can be largely credited to the penetration of cast aluminum components that are both lightweight and inexpensive to manufacture. With weight savings from these castings already designed into the vehicles, the OEMs are moving to next generation weight reduction opportunities. The largest growth opportunities for aluminum are in chassis and suspension components, engine blocks, closure panels and body structures.

Many of the suspension components require superior and predictable properties. Forgings meet the property needs of chassis/suspension components, but the higher cost of aluminum forgings has – up until now - been a barrier to fully capturing and growing the market for these applications. With the technological breakthrough of near net shaped forge stock, aluminum forged suspension components can become cost competitive in the marketplace.

The current forging processes are well known through the industry and documented in the published literature and hence we will not go into depth with our explanation of the process. We will cover some components in summary only because it provides the necessary background required to normalize our abbreviated comments and show the pertinent process steps and document the critical process inputs and outputs.

The Existing Process

Referring to Figure 1, we notice the incoming metal as a liquid, to be alloyed, processed and then solidified. After solidification, the metal is homogenized, pre-heated and extruded to the final slug diameter prior to stretching or cutting to length. Once the slug has diameter and length, it is pre-heated, bent, blocked, trimmed and allowed to cool. The rough preform is then once again pre-heated, blocked, finished and trimmed before aging and inspection. This cycle can be shorter or longer depending upon the complexity of the part.

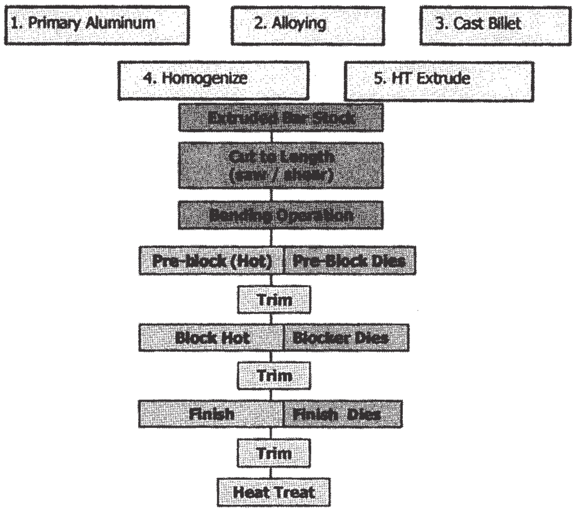

Figure 1. Current forging process from extruded stock to finished forging.

The New Process

Figure 2 compares conventional to near net shape ingot produced forging stock once the molten metal has been alloyed and solidified. After solidification, we section the ingot to the desired thickness, pre-heat the preform, block, finish, trim, age and inspect the final forging.

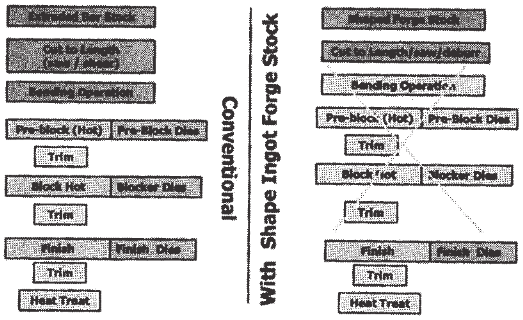

Figure 2. The proposed forging process from near net shape produced ingot.

The Solidification Process

The Direct Chill (DC) casting process was started by Bill Ennor (1) in 1930. At that point, shape perspectives included both round and square configurations. A few years later, on the other side of the world in the USSR, Stepanov (2) introduced a process whereby irregular shaped ingots could be solidified from a chilled seed, similar in nature to the production of single crystals for the semiconductor industry today. Ohno (3) brought us closer to shaped continuous castings on a small scale with a deviation to the DC process when he used a heated mold to produce small cross-sectioned, irregular shaped ingots. The most recent work, included casting by Fukugaito (4), where complex shaped ingots were produced with the DC casting process, sectioned and forged. Unfortunately his work never reached the market, as the finished forging preform contained a coarse chilled and segregated region around the periphery of the cast shape. This had to be removed, either prior to forging or during the forging process, as taught by Sugimoto (5).

Wagstaff Inc. introduced the AirSlip™ Air Casting Process into the marketplace in the early 1980's. This technology provided a cast product with minimal chill and segregated regions at the cast surface. The technology has its heart in the use of a porous graphite ring and a strong direct quench through which heat is extracted from the cast article. The graphite-casting ring acts as a container for the metal in the molten and semi-solid state. The introduction of gas and oil to the ring helps minimize primary cooling while providing an extremely low-friction surface for solidification. See Figure 3.

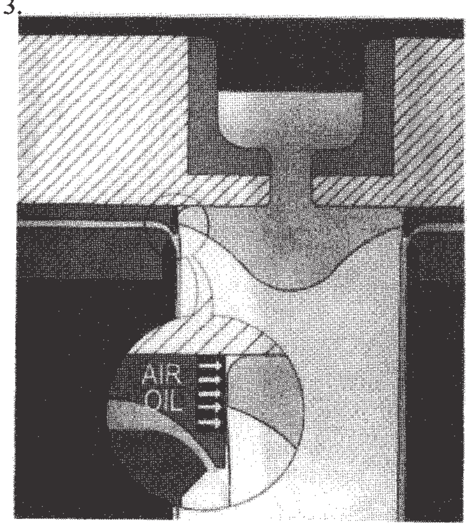

Figure 3. AirSlip™ schematic diagram.

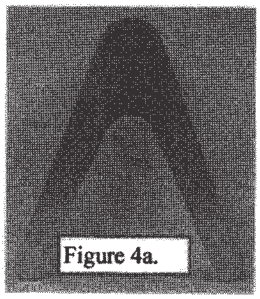

Figure 4a.

Work with complex shapes began at Wagstaff Inc. in the mid 1990's with a fairly straightforward "V" shaped cross section (Figure 4a) for Alcoa Automotive Castings (KCC).
While this shape had no direct commercial uses, it served as an excellent platform to verify theories surrounding heat transfer, solidification, fluid dynamics and lubrication. While there were other shapes after that, commercial realization came with the Ford D/EW98 platform cast at Alcoa Lafayette and forged at Alcoa Automotive Castings (KCC) in early 1999. Figure 4b.

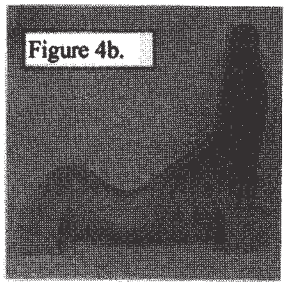

Figure 4b.

This near net shaped ingot is currently being cast at Alcan's ECP facility in Jonquiere, Canada.

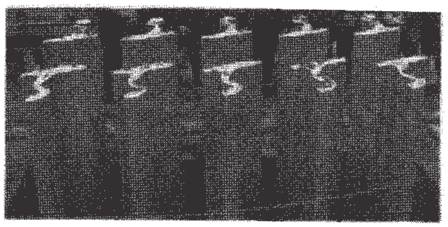

Figure 5. Ten NetCast™ Shape Cast Technology produced ingots at 6m lengths.

Technological Challenges

In our development cycle we experienced many of the same challenges common to practitioners of the process today. We found that the fill and hold sequence needed to be controlled to levels common to that encountered when casting 100mm diameter sizes. Flashing, the result of an improper starting head to mold gap or elevation could, like rolling slab ingot, contribute to cracking at the start of the cast.

Many of the challenges we encountered were defects which, when solved added insight into some common defects found in round and rectangular shaped ingot production. For example, a common defect with round ingot production is the center crack. Center cracks in round ingot production occur as the exterior surface, (solidified and cold) restrains the center regions ability to contract. This generates a tensile stress that yields if the differential stress or cooling rate between the surface (in compression) and the center (in tension) exceeds the strength of the solidifying alloy. With shaped ingots, we have not encountered center cracks in the classical definition described above. We did go through extensive numerical analysis to find a solution where center cracks could be mitigated by allowing outwardly extending appendages to be solidified at one rate so that the integrating regions of each appendage had identical cooling rates. In practice, we found that this could be easily done by varying the per unit volume or mass of water discharging from the mold around the periphery and balancing it with the appropriate latent heat rejected from the solidifying metal. See Figure 6.

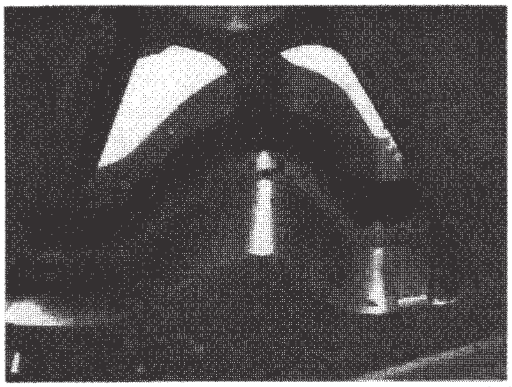

Figure 6. Shaped section with varying water exit holes.

By far, the most difficult challenge associated with the casting of shaped ingots occurs far before the water actually contacts the ingot, well above the air gap region where the meniscus first begins to oxidize and solidify. In round ingot production, the oxide formed at the meniscus plays a critical role in the formation of the surface of the ingot. It is the oxide that begins to define the outer shape of the ingot at the meniscus. Once the oxide is formed, there is a shell or protective layer, which surrounds the curvilinear geometry of the meniscus as the pure aluminum immediately adjacent to the oxide layer begins to solidify. As the shape of meniscus moves from being curvilinear in nature to linear at the mold wall interface, the oxide layer, with the solidifying pure aluminum, is stretched from a disk shaped geometry to a torroidal shape at the meniscus and finally a cylindrical shape that thereafter defines the round ingot geometry. See Figure 7 and Figure 8. In the case of a round ingot, the surface generation rates are generally consistent around the periphery of the meniscus and cylindrical regions of the ingot.

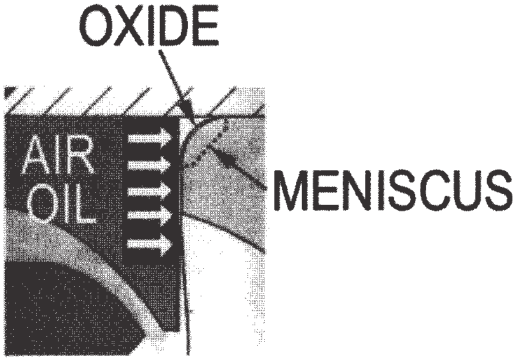

Figure 7. Oxide at the meniscus

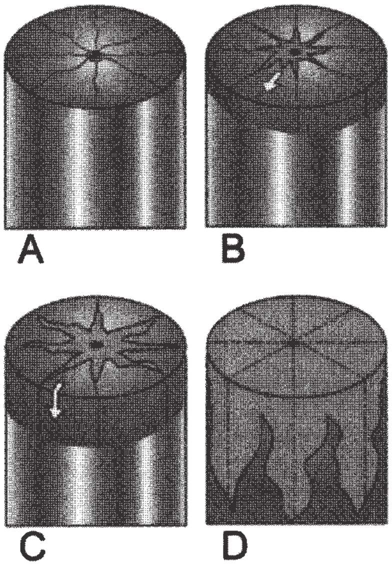

Figure 8. Oxide rollover

Because the cross section of shaped ingots are non-uniform, being both convex and concave in varying degrees, oxide and surface generation rates associated with the shaped ingots are not consistent around the periphery. They are in fact non-linear and generally complex in the manner they proceed from the meniscus to the linear orientation of the finished ingot. Some areas of circular orientation stretch and others compress the oxide. Stretching the oxide like we see in round ingot production helps the success of the cast.

Oxides in compression typically buckle and will crack if enough stress is present at the solidifying interface. See Figure 9.

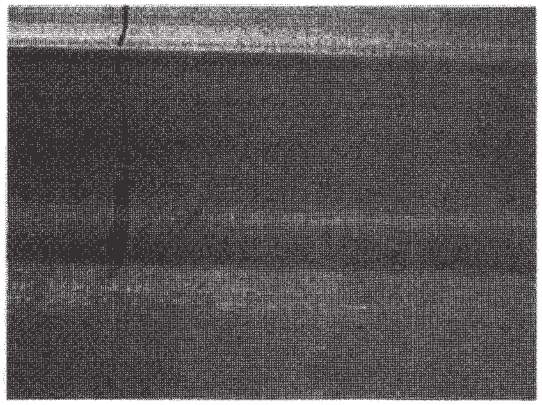

Figure 9. Typical oxide crack with vertical fold.

While we did not expect to encounter a problem with the 6xxx series and this type of defect, we found that strict control of alkali and alkali earth forming salts helped in preventing the formation of such oxides. We also found, that by controlling the oxidation rate and varying the mold to metal interface friction we could negate the occurrence of these types of defects. See Figure 10.

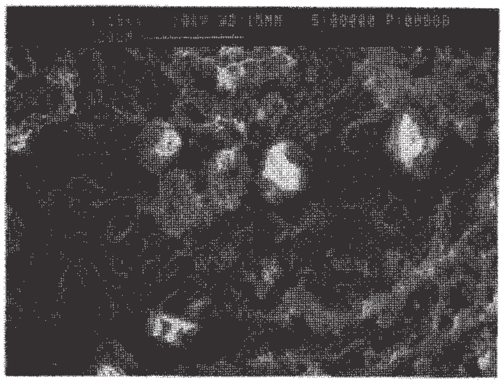

Figure 10. Salt containing oxide film.

Results

Our experience with the new process has been exemplary. The casting technology has been transferred to the production facility and we have achieved the production consistency and quality required to meet automotive component requirements.

Segregation and chill zone, a problem with Fukugaito, is not an issue of concern with this technology. See Figure 11.

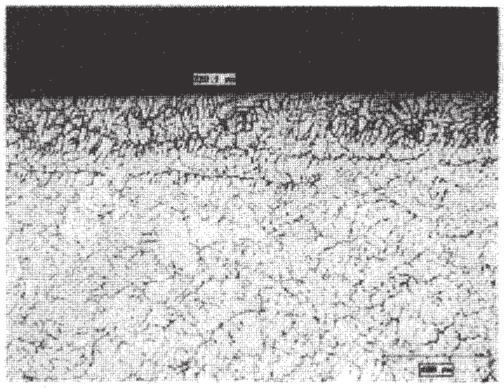

Figure 11. Typical surface segregation of near net shape ingot that shows a typical segregated zone (enriched and depleted) is consistently less than 200 micron around the perimeter of the shape.

The surface to center grain size distribution is shown in Figure 12a & 12b.

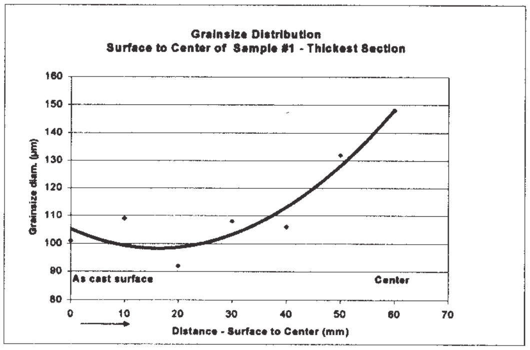

Figure 12a. Grain size distribution.

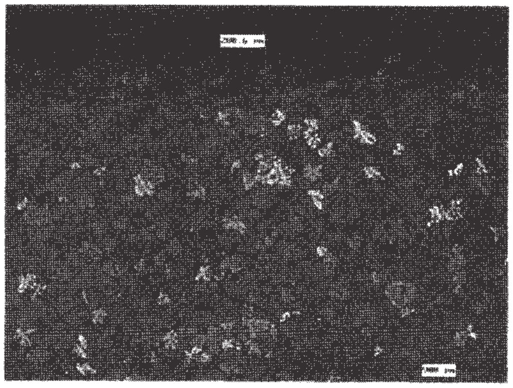

Figure 12b. Polished and etched microstructure.

The data and photos of Figures 11 & 12 are consistent with samples from several thousand metric tones of cast product. We have demonstrated excellent control over macro segregation and floating crystals that could reduce the material properties in the cast and forged product.

The castings and forgings produced with the NetCast™ Shape Casting Technology have excellent material properties, i.e., yield strength (YTS), ultimate tensile strength (UTS), and elongation. Material properties values speak for themselves and are presented in the two following tables. See Table 1 and Table 2.

Figure 13 are photographs of similar forged components of similar chemical composition (Mn, Cr, Zr), showing a typical recrystallized structure (extruded forge preform) and the absence of any recrystallized structure in the near net cast shape preform. See Figure 13.

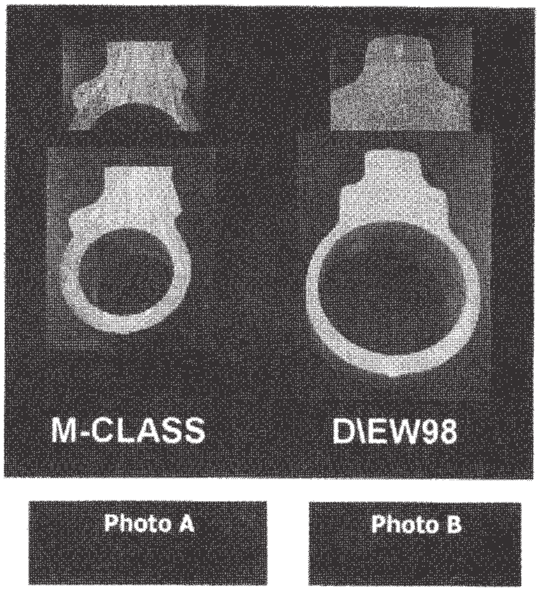

Photo A: Forged control arm using conventional bar stock and multiple press heats exhibits extensive recrystallization.

Photo B: Forged control arm using shaped ingot forge stock with a single block/finish heat shows no recrystallization.

Figure 13. Recrystallization.

Competitive Advantage

As important as the technological breakthrough of casting a shaped ingot is, the commercial implications are equally significant. As mentioned in the introduction, suspension components have been targeted for conversion to aluminum by automakers and their suppliers. Aluminum forged suspension components are attractive because of their net shape, lightweight, and corrosion resistance along with high strength, increased elongation, and improved fatigue properties. However, the cost of forgings produced with conventional round forge stock can often be a barrier to selection for these components. NetCast™ Shape Casting Technology can significantly lower the cost of forged components by reducing press operations, handling costs and improving material recovery. A typical recovery for conventional extrusion forge stock to final product has a range of 35 to 45% depending upon the complexity of the final part. It has been demonstrated that near net shape cast preforms can achieve 65% overall metal unit recovery. This represents a significant raw material savings in the overall cost structure.

Further, when designed for the improved properties offered by the NetCast™ Shape Casting Technology, automotive designers can achieve additional weight savings as shown in Table 3 below. In the past, design engineers looked at the strength and elongation properties of all different types of castings and forgings. Most of the properties reported showed very little difference in values. Because of this, there was little reason to change a design to take advantage of the properties. Forgings made with aluminum solidified by this process, bring an order of magnitude improvement to the basic properties of permanent mold produced component. Even if designed to only 75% of the elongation, Table 3 illustrates quite clearly the potential for improved weight and cost savings. Components designed for these material properties allow the aluminum forging option to financially compete against castings.

TABLE 1
MATERIAL PROPERTIES FROM THE NEAR NET SHAPE CAST PREFORM

Chemistry							
wt%	Si	Fe	Cu	Mn	Mg	Cr	Ti
12494-A-1	0.58	0.21	0.2	0.06	0.93	0.13	0.09

As Cast Properties	Part ID	Direction	YTS		UTS		Elongation
			ksi	MPa	ksi	MPa	%
May 2000 Samples	12494-A-1	Transverse	15.0	103	30.2	208	26.5
	12494-A-1	Longitudinal	14.3	99	30.4	210	27.0

TABLE 2
MECHANICAL FORGED PROPERTIES*

Product	YTS		UTS		Elongation
	ksi	MPa	ksi	MPa	%
Preforms produced by NetCast™ Technology (6061-T6)	45.8	316	50.4	347	19.0
Conventional Extrusion & Forging (6061-T6)	40.3	277	45.3	312	15.5

*parts shown in Figure 13

TABLE 3
DESIGNING PARTS TO MINIMUM MECHANICAL PROPERTIES

Process	Perm Mold	SSM	Conv. Extrusion & Forging	NetCast Forging
Actual Elongation	5%	10%	15%	20%
Design to Minimum Elongation	3%	5%	10%	15%
Theoretical Designed Part Weight (lbs)	14.5	14	10	8.5
Weight Saved from Perm. Mold	0	3%	31%	41%
Metal Cost Difference in US$ (assuming $.75/lb)	$10.87	$10.50	$7.50	$6.38

Conclusions

NetCast™ Shape Casting Technology is a technological breakthrough developed by Wagstaff, Inc. and commercialized by Alcan (ingot casting) and Alcoa (forging).

The automotive needs to replace steel and cast iron with aluminum components continues to grow. Current targets for conversions include suspension components such as control arms, knuckles, etc. Many of the suspension components require superior, predictable properties that can be assured part to part. While forging can easily meet these requirements, up until now their cost has been a barrier to widespread adoption.

The ability to cast input forge stock in complex geometries offers the potential to significantly reduce the manufacturing and handling costs associated with forging, while improving the material recovery.

In addition, forgings produced with aluminum solidified by the NetCast™ Shape Casting Technology have properties that are superior to forgings from conventional extrusion based preforms. This enables designers the freedom to capture additional weight savings while maintaining component strength requirements.

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3. U.S. Patent #4,616,204, May 7, 1985.

4. J.P. Patent #2179336A2, July 12, 1990.

5. J.P. Patent #3023028A2, January 31, 1991.

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