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Austempered Ductile Iron (ADI) - A Green Alternative

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ABSTRACT

In discussions of sustainable or “green” design, the topic of weight reduction is often the first consideration. Immediately, engineers of structural components turn to materials with low density such as aluminum and magnesium. However, when strength and stiffness are taken into consideration, a low density material does not always result in a lower mass component or assembly. Further, in the search to propel devices using less fuel energy, engineers can often lose sight of the total life-cycle energy of the material/process combination they have chosen in their design.

High strength steels have made great advances, allowing their designs to compete with “lightweight” metals. The steel manufacturers have done a good job communicating “new steel” to the design community. However, the design community is largely unfamiliar with the light weight and low energy properties of Austempered Ductile Iron (ADI). The lure of low specific gravity can lock design engineers into an improper material/process combination early in the design process to the exclusion of other, more efficient material/process combinations. This paper will familiarize the reader with the concept of embodied energy and some of the environmental advantages of converting from a conventional material/process combination to an ADI casting solution.

INTRODUCTION

The sustainability or “green-ness” of a product or device can be measured by its use of energy and its effect on the ambient (radiation, emissions, etc.) during its life. The net energy and ambient affect is mitigated by the recyclability of all of the components of an engineering device.

The life-cycle energy of a component or assembly is based on the total energy used to create the materials, to assemble them into a useful design, and to operate them. The life-cycle energy is reduced if the materials can be recycled at a lower energy than if virgin materials were used.

The life-cycle effect of an assembly or device on ambient is the sum of its effects on the environment around it. As with energy, the total life cycle affect can be mitigated to the extent that waste can be reduced during the manufacture of the components or if the components can be recycled.

The architectural community employs the term “embodied energy” to define the total energy resident in a manufactured component. That concept can be useful in inventorying and quantifying the energy content in an assembly or device. For example, the embodied energy in the manufacture of the components and assembly of a light vehicle can constitute about 20% of the life-cycle energy of that vehicle. (The balance of the life-cycle energy of a light vehicle is its operation and the fuels, fluids and replacement parts it consumes during its life^{1,2,3}). The aforementioned life-cycle energy cost does not include the cost of recycling all the components at the end of the vehicle’s life.

Much talk in the engineering community has centered on mass reduction as the only path to sustainability. Sustainability is much more dependent on waste reduction. Engineers and designers are often surprised when life-cycle energy comparisons are made that show ferrous metals to be more sustainable than many polymers or other “light materials”. Today, for example, ferrous materials (steel and iron) make up approximately 62% of the total mass of a light vehicle^{1,2} and 64% of the mass of a Class 8 truck tractor and trailer³ largely because of their low cost and recyclability.

This paper will discuss the sustainability of Austempered Ductile Iron (ADI) castings and demonstrate through case studies how engineers can design and produce ADI components with less waste, and at lower life-cycle energy, than comparable designs in steel, aluminum or magnesium.

BACKGROUND

Austempered Ductile Iron (ADI) is a ferrous cast material (ductile iron) heat treated by the Austempering process

resulting in a new material that is strong and tough with a high strength-to-weight ratio. Ductile iron can be produced from many casting methods including; green sand, bonded sand, lost foam, lost wax, continuous casting, centrifugal casting and even permanent mold. The development of Ductile Iron (or Spheroidal Graphite Iron) was announced jointly in 1948 by the International Nickel Company (US) and the British Cast Iron Research Association. ADI has only been commercially available since 1972. Thus, in the entire spectrum of engineering materials, both ductile iron and ADI are relatively young.

Consider the capping of the Washington Monument with a 2.8kg aluminum casting on 06 December 1884. It was the largest aluminum casting of its day. The Wright brothers employed an aluminum engine block, (radical for its time), in their “first flight” in 1903 and the widespread commercial application of aluminum came only with World War II. It has taken over 100 years for aluminum to reach its current maturity as an engineering material, today comprising approximately 9% of the mass of a light vehicle.^{1,2}

Magnesium’s commercial beginnings as an engineering metal alloy go back to German use of the alloy they called “Elektron” in aircraft in World War I. A 1957 Chevrolet Corvette built for racing employed magnesium alloy sheet and structural members. Today, magnesium makes up a tiny (but growing) fraction of an average light vehicle’s mass.

Steel remains the most widely used metallic engineering material and has been in commercial use for hundreds of years. In recent decades, specially alloyed and formulated steels have increased the strength of the material. With its superior stiffness, steel remains competitive in specific-strength with materials commonly referred to as “light metals” (principally aluminum and magnesium alloys) and other, not so common, materials such as titanium and even many polymers.

Together, aluminum, iron, magnesium and titanium make up 16% of the earth’s crust. Scarcity is not a long-term issue, particularly because all of these metallic materials can be, to a greater or lesser extent, recycled.

The scope of this paper does not allow the author to compare all materials with respect to sustainability. Some advances, like the emergence of Compacted Graphite Iron (CGI) to replace gray iron, merit discussion in another venue. Discussion of titanium alloys and carbon fiber composites also merit investigation, but their price precludes them from practical consideration in most engineering designs. (For example, per unit of mass, titanium alloys cost roughly twenty times that of

carbon steel). Plastics, although low in density and inexpensive per unit volume, exhibit stiffness (Young’s Modulus 2-4 GPa) that is up to two orders of magnitude less than that of steel (210 GPa) making them unsuitable for most dynamically loaded components. Polymers also use as much as 2-5 times more energy per kilogram to produce than ferrous materials.

Neither does this paper offer the opportunity to address other vital engineering properties like fatigue strength, wear resistance, corrosion resistance, etc. The case for sustainability in this discussion is built around strength, stiffness, mass and the energy used to create and operate the component.

Developments in the Ductile Iron casting process and the ADI process in recent decades have made ADI a sustainable alternative material. This is demonstrated by the successful material/process conversion case studies detailed in this paper.

ADI AND SUSTAINABILITY

Consideration of “sustainability” requires us to consider the energy content and the ambient affect of material/process combinations in components and assemblies. ADI is a material/process combination with much to offer in sustainable engineering designs. Metal casting is the lowest energy path from earthen raw materials to finished product. The metal casting process produces less waste, has fewer process steps and consumes less energy than hot or cold forming, extruding or welding. Metal casting is a near-net shape process.

ADI starts as a ductile iron casting. ADI is created by applying the Austempering process to ductile iron (spheroidal graphite or SG iron) castings. Unlike magnesium and aluminum alloys, ductile iron of any grade can be cast with nearly 100% recycled materials; steel scrap (ie. punchings, trimmings and bundled turnings) and ductile iron returns (gates and risers discarded from the casting process). The ductile iron process is very sustainable which is represented in its low embodied energy value.

By comparison, high-performance aluminum components are produced largely with virgin materials as the additive affects of oxygen and hydrogen exposure reduce the properties of recycled aluminum. Those marvelous thin-walled, seamless aluminum beer and soda cans are only produced with virgin materials. The recycled cans cannot be used to make new cans and are used to make other, less demanding products.

Any comparison of material/process combinations must begin with the engineering properties of the materials under consideration. **Figure 1** compares the strength and ductility of ADI to that of other, selected engineering materials.

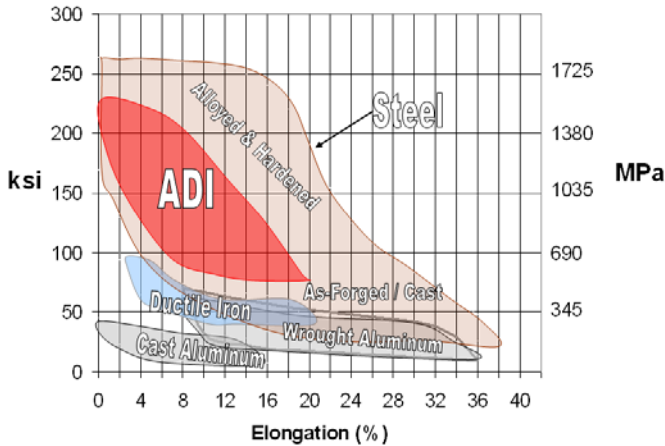


Figure 1: A comparison of the yield (proof) strength of ADI to that of several engineering materials.

As one can see from **Figure 1**, ADI is competitive with steel in strength for a given level of ductility. What that figure does not show is the relative density of the materials in the comparison. Ductile iron and ADI are 8-10% lower in specific gravity than wrought steel. (This is due to the presence of graphite in the cast iron matrix). Therefore, if the component stiffness is sufficient and a steel part can be replaced with an ADI component of the exact same configuration, the part will weigh 8-10% less. ADI is typically lower in cost (per unit of mass) than steel. One implementing a same-configuration steel-to-ADI conversion will not only buy less material (mass), they will pay less for the material (per unit of mass).

The difficulty for the designer in the choice of ADI is the lack of available engineering information. While one may find the typical strength, stiffness, density, etc. of ductile iron in common textbooks such as the "Machinery's Handbook",⁴ no reference is even made to ADI. For such information, a few informative specifications are ASTM A897/A 897M-06 Standard Specification for Austempered Ductile Iron Castings,⁵ ISO 17804:2005 Founding Ausferritic Spheroidal Graphite Cast Irons – Classification,⁶ and SAE J2477:2004 Automotive Austempered Ductile (Nodular) Iron Castings (ADI),⁷. Other resources such as AGMA 939-A07 Austempered Ductile Iron for Gears⁸, Ductile Iron Data for Design Engineers⁹ and the AFS Strain-Life Fatigue Properties Database for Cast Iron¹⁰ include informative charts, tables, appendices and FEA coefficients and exponents to assist the designer.

Table 1 Compares the density (specific gravity) of several engineering materials. One can see why aluminum and magnesium are commonly termed "light metals".

Table 1: Specific gravity of several engineering materials.

Material	Specific Gravity (gm/cm ³)
Carbon Steel	7.8
Ductile Iron / ADI	7.2
Titanium Alloys	4.5
Aluminum Alloys	3.0
Carbon Fiber Composite	2.3
Magnesium Alloys	1.7
Polymers	.95-2.0

From the information in **Figure 1** and **Table 1**, one can see that aluminum and magnesium have relatively high strength-to-weight ratios compared to steel. So why can't one make everything from those materials?

The Young's Modulus (E or stiffness) quantifies the deflection that will result from a given input load. **Figure 2** compares the stiffness of several engineering materials.

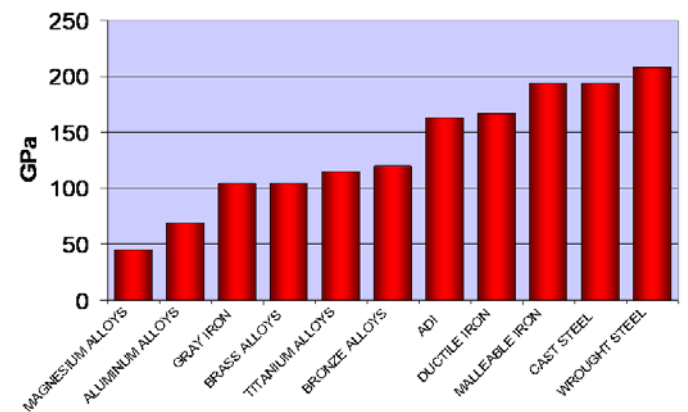


Figure 2: Young's Modulus (stiffness) of various materials.

The density of ADI is 2.4 times that of aluminum alloys (7.2 vs. 3.0), but so is the stiffness (168 GPa vs. 70 GPa). One can see from **Figure 1** that the allowable yield stress for ADI is about 3-5 times that of cast aluminum and 2-3 times that of forged aluminum. Therefore, a properly designed ADI component can replace an aluminum component at equal (or lower) mass, provided that a (commercially available) minimum wall thickness of about 3mm is acceptable.

Table 2 shows the relative (average) energy required to produce various materials from their raw materials. The numbers utilize the "typical" processes from ore

extraction to heat treatment. Where not specified, the numbers assume average levels of commercial recycling within a process. The architectural community employs a useful term “embodied energy” to describe this material feature.

Table 2: Embodied energy in selected engineering materials expressed in Megajoules per kilogram (MJ/kg).^{1,2,3,11,12,13,14}

Material	MJ/kg
Wrought Aluminum (Primary, average)	255
Copper (average)	151
Structural Polymers (Primary, average)	84
Magnesium (average)	80
Stainless Steels (average)	79
Rubber (average)	70
Cast Aluminum (Primary, average)	58
Plain Carbon and Low Alloy Steels (average)	51
Structural Polymers (secondary, average)	42
Malleable Iron (average)	35
Glass (Primary, average)	30
Austempered Ductile Iron (ADI) (average)	30
Ductile Iron / CG Iron (average)	26
Cast Aluminum (secondary, average)	23
Gray Iron (average)	23

Table 2 brings into perspective the various material/process combinations. For example, extracting aluminum from Bauxite ore uses an energy intensive electro-chemical winning process that uses large amounts of electricity and produces vast amounts of CO₂. More efficient processes are being researched, but the tabular numbers represent the current (average) reality.

Note the large difference in embodied energy between wrought, primary aluminum and cast, secondary aluminum. In most engineering applications, wrought aluminum parts use virgin materials. In cast aluminum designs requiring significant toughness and fatigue strength, the alloys utilized are typically all (or nearly all) virgin materials; increasing their embodied energy. This stands in contrast to the production of cast irons, which can utilize up to 100% recycled materials in all applications.

Cambridge University’s Materials Engineering Department has developed a clever visual for comparing the energy content vs. cost for various engineering material/process combinations (**Figure 3**)¹⁴.

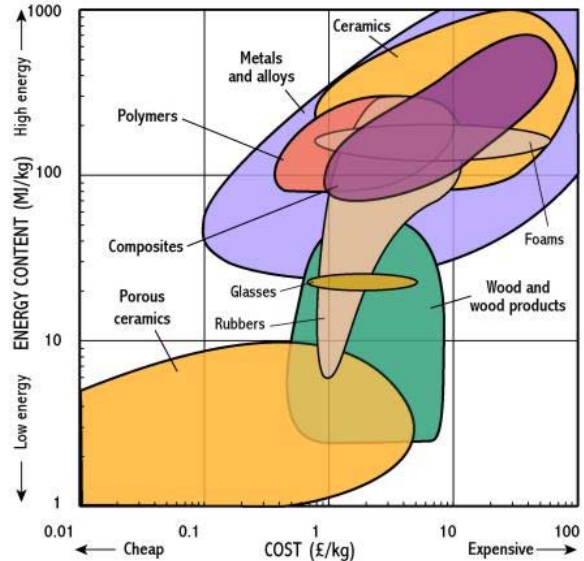


Figure 3: Energy content (embodied energy) vs. cost (£UK) for various metallic and non-metallic materials.¹⁴

Figure 3 shows a roughly proportional relationship between embodied energy and cost. This relationship is significant in the consideration to convert from one material/process combination to another one. **Figure 4** is also from Cambridge University. It takes a closer look at the metals subset of materials in the analysis.

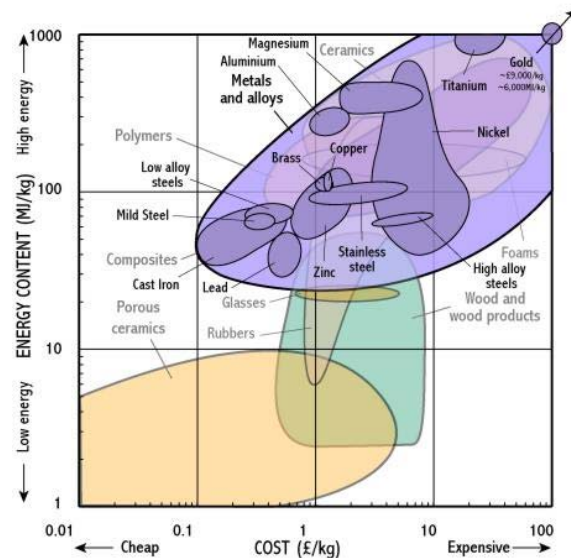


Figure 4: Energy content (embodied energy) vs. cost (£UK) for various metallic materials.¹⁴

One can see that cast irons (including ductile iron) are at the lower energy/cost end of the distribution while titanium is at the higher energy/cost end of the metals spectrum. This comparison is useful to us in evaluating the embodied energy in a conversion.

If one is building a mechanical device and wishes to define its dynamic vibrational performance in service, one must look to stiffness; but at what cost? **Table 3** integrates the stiffness, specific gravity and embodied energy of several materials. In other words, for a given input load, how much would the various cross sections (or section moduli) have to be increased to result in the same deflection; thus affecting the mass of the component. The resultant number is the embodied energy necessary to produce a component of equivalent stiffness (compared to a 1kg steel part).

Table 3: Embodied energy in a component designed to achieve an equivalent vibrational response.

Material	Relative Mass for Equivalent Stiffness (kg)	Relative Volume for Equivalent Stiffness (cm ³)	Embodied Energy for Equivalent Stiffness (MJ)
Wrought Carbon Steel	1.00	128	51
ADI	1.25	174	38
Primary Aluminum			
-Forged	3.00	1,000	765
-Cast	3.00	1,000	174
Magnesium	4.70	2,765	376

In designs where stiffness is not a primary issue, the “specific strength” can be used to compare various materials for their suitability. **Figure 5** compares the specific strength (mass (weight) per unit of yield strength) of several engineering materials.

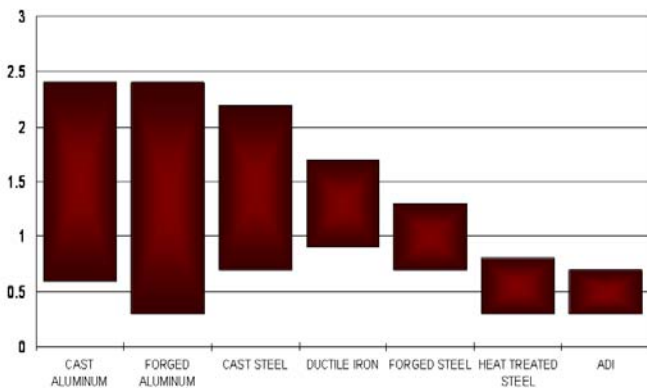


Figure 5: Relative mass per unit of yield strength for various materials. (Forged carbon steel centered on unity).

Figure 5 implies that with proper design, ADI can replace aluminum at equal mass. Extrapolating that to embodied energy leads to the conclusion that a thin-walled ADI part that is of equal weight to its larger/thicker cast aluminum counterpart embodies 48% less energy, (30MJ/kg for ADI vs. 58MJ/kg for cast primary aluminum). This is reflected in the market price and ADI components are typically priced at 25-50% less than the aluminum components they replace.

ADI will not replace a 3mm wall aluminum die casting at equal mass. However, leading-edge metal casting techniques can produce 3mm wall ADI components that will replace 8-10mm wall aluminum components¹⁵ at a significantly lower price. **Figure 6** shows a prototype ADI bracket with a (typical) 3mm wall.



Figure 6: An ADI prototype bracket with a continuous 3mm wall.

A European automaker had experienced a noise problem with an aluminum alloy component produced with a squeeze casting process. That bracket is shown in **Figure 7**. A conservative ADI design produced by the green sand casting process was proposed to replace the existing aluminum design. The aluminum bracket was 370 cm³ in volume, weighing one kilogram with an embodied energy of approximately 58 MJ. The thin-walled ADI design was 160 cm³ in volume weighing 1.1 kg and embodying 33 MJ, over 40% less energy. The ADI, with its higher damping coefficient, also proved to be a cost effective, low energy, solution to the noise problem.



Figure 7: The ADI bracket (right) replaced the aluminum bracket (left) to solve a specific NVH problem.

Wrought steel bars and plates can be purchased for very low per-kg prices. For example, merchant steel bar prices in 2009 averaged about 0.77 \$US/kg; but, 25%-75% of the material is generally removed during the machining process. Taking low-cost shapes (bars and plates) and forging (or forming) them adds energy, but reduces the material to a nearer net shape. Certain features, like through holes and hollows, cannot be formed into wrought parts. The end-connector link shown in **Figure 8** is a steel forging weighing 1.81kg with an embodied energy of approximately 92 MJ. Finish machining removed 0.82kg of chips resulting in a machined part weighing 0.99kg.

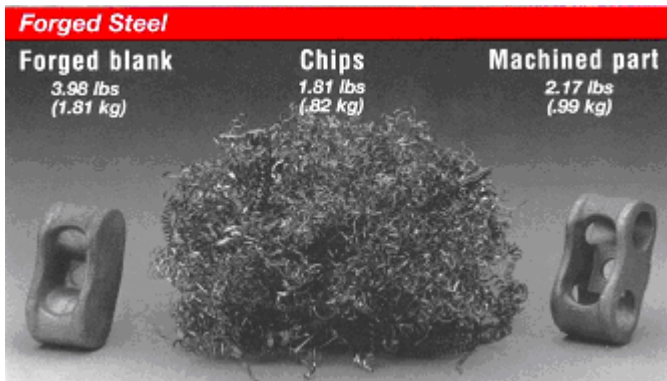


Figure 8: A 0.99kg steel end connector is produced from a 1.81kg forging.

Figure 9 shows an ADI solution to the end connector depicted in **Figure 8**; a 1.09kg ADI casting produced by the green sand process. This finished ADI end connector weighed 0.93kg with a total embodied energy of 33MJ; a 65% reduction compared to the steel forging (92MJ).

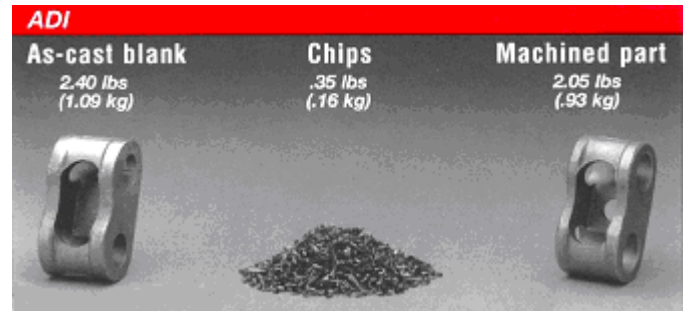


Figure 9: The finished, 0.93kg ADI end connector was produced from a 1.09kg green sand casting.

When considering a conversion from a weldment to an ADI casting, one must consider the added energy cost of welding. Welding is, in fact, the remelting of metal. A typical, triangular weld of nickel-alloyed steel (0.6cm on a side) is estimated to embody 9MJ/m of weld. **Figure 10** shows a rangeland seeder boot made from welded steel. The part weighed 6.9 kg and contained roughly one meter of weld for an entire embodied energy estimated to be 361 MJ.



Figure 10: A rangeland seeder boot fabricated from cut, formed, punched and welded steel blanks.

The producer of the seeder boot sought to reduce the cost and improve the performance of the boot and designed an ADI conversion (**Figure 11**).

The ADI seeder boot (**Figure 11**) weighs 5.9kg, or 15% less than the incumbent steel part that it replaced. Furthermore, the embodied energy of the ADI component at 177 MJ is 50% less than the welded steel counterpart. The lower energy embodied in the ADI component is reflected in the price; 65% less than the weldment.



Figure 11: An ADI rangeland seeder boot produced from a green sand ductile iron casting and machined in the as-cast condition.

In the heavy transport industry, vehicle weight is critical for a very different reason than fuel efficiency because each additional kilogram of vehicle mass is one less kilogram of goods that can be legally transported. As a result, commercial trucking firms buy light-weight trailers to maximize the weight of goods that can be loaded in each trailer.

Aluminum wheel hubs have proven to be desirable over traditional ductile iron hubs for their lower weight. However, for over a decade, light-weight ADI hubs have been commercially available. **Figure 12** shows an ADI Dura-Light® hub (left) and the traditional light-weight aluminum hub (right). Because of the high strength-to-weight ratio of ADI, the ADI hub is actually 2% lighter than the aluminum hub that it replaces. When you consider the embodied energy in the aluminum hub (58MJ/kg) vs. the ADI (30 MJ/kg), the ADI hub has embodied energy that is 50% less than the permanent mold cast aluminum hub.

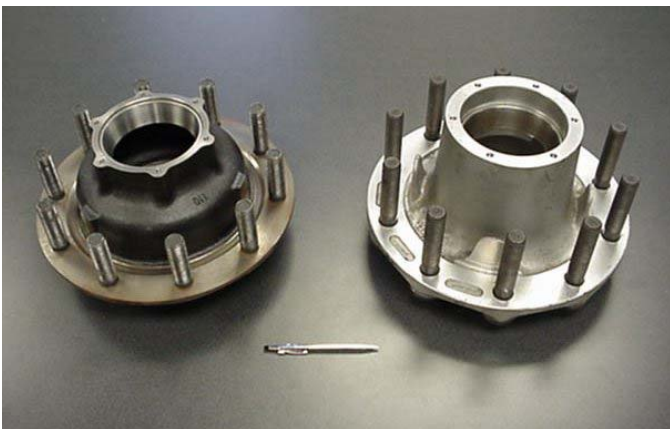


Figure 12: The ADI Dura-Light® hub on the left replaced the permanent mold cast aluminum hub on the right with a 50% savings in embodied energy and a 2% weight reduction.

Steel stamping technology has improved with the development of improved stamping equipment and steel alloys that allow deeper drawing. One OEM producer of light and medium duty trucks considered stamped steel and ADI designs for a suspension upper control arm (**Figure 13**).

The stamped steel arm weighed 15kg and embodied energy of approximately 900MJ (including production and welding of the separate ring). The one-piece, cast ADI arm weighed 14kg and embodies 420MJ of energy to produce, an energy savings of over 50%.



Figure 13: The ADI control arm (right) exceeded testing requirements and replaced the stamped steel component (left) at a 6% weight savings.

In a gasoline powered vehicle, the fuel energy consumption in mega-joules per kilometer (MJ/km) is decreased with decreased vehicle mass. A one kilogram vehicle mass reduction results in a typical energy decrease of 0.003 MJ/km (an increase in the fuel efficiency of 0.03 miles/gallon)¹⁶. Converting two control arms reduces vehicle mass by 2kg. For a vehicle life of 300,000km, the life-cycle fuel savings is estimated at 1800MJ (approximately 47 liters of fuel). If you include the energy savings in manufacturing and the lifetime fuel savings, the ADI conversion saves 2,760 MJ compared to using stamped steel control arms.

SUMMARY

The concept of embodied energy can be a useful tool for quantifying the sustainability of a certain design. When embodied energy calculations are used to compare various material/process combinations, a rough proportionality can be drawn between embodied energy and the component's cost.

Low material density does not necessarily extrapolate into a lower weight, more efficient or lower embodied energy component. ADI's high strength-to-weight ratio and stiffness allow it to replace materials like aluminum or magnesium at equal mass in sections over 3mm.

Furthermore, its low embodied energy and recyclability give it superior sustainability compared to steel, aluminum or magnesium.

Properly designed ADI components can replace steel, aluminum and magnesium components at lower life-cycle energy. Designers should consider total life-cycle energy consumption in their designs and not be focused solely on fuel efficiency or light weight. It seems that the component with the lowest embodied energy capable of performing the component function may likely be the lowest cost solution.

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