



International Conference on Systems, Science, Control, Communication, Engineering and Technology 2016 [ICSSCCET 2016]

ISBN	978-81-929866-6-1
Website	icsscet.org
Received	25 – February – 2016
Article ID	ICSSCCET106

VOL	02
eMail	icsscet@asdf.res.in
Accepted	10 - March – 2016
eAID	ICSSCCET.2016.106

Production of Carbidic Austempered Ductile Iron [CADI]

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Abstract: Carbidic austempered ductile iron is produced with carbides by selecting proper composition of materials by melting route. The base materials are melted in a medium frequency induction furnace and molded. The specimens are subsequently austempered. The resulting microstructure consists of carbides in an ausferrite matrix. The amount of carbides present is depending upon the end use and it may range from 10% to 30%. This material exhibits excellent wear resistance with adequate toughness. Abrasion wear resistance test and impact test were conducted on the samples and the results were compared with that of the material may replace. The results shows better wear resistance and impact resistance. In a number of applications, it can compete favorably with high chromium abrasion resistant irons in addition to providing improved toughness.

Keywords: Carbides, Nodulising, Austempering, and wear resistance.

INTRODUCTION

Industry has discovered various materials/processes combinations that exhibit surprisingly good wear resistance materials. CADI (carbidic austempered ductile iron), which was developed to improve the wear durability of conventional ADI. Carbides are the known strong wear resistance compounds compare to other materials and are produced easily. But these carbides are not directly used due to their higher brittleness. They are combined with tough materials. The ductile iron which is tougher and extensively used in industrial applications. But it lacks in wear resistance. This is increased by introducing carbides in the ductile iron. The present work explains preparation of ductile iron with carbides. In this the carbides are formed in the ductile iron matrix (Ausferrite) by adjusting the composition and proper cooling rate. They are subsequently heat treated by the Austempering process. Strength improvements in combination with excellent toughness can be realized by this process. In fact, the only necessary ingredient for the production of CADI is high quality ductile iron with the appropriate alloy content with carbide forming elements such as manganese, chromium and molybdenum. This paper will review the austempering heat treat process and the foundry requirements that are necessary for the production of ADI.

Carbidic Austempered Ductile Iron

Carbidic Austempered Ductile iron describes a family of ductile cast irons, with desired amount of carbides that are subsequently austempered to exhibit adequate toughness. Carbides are produced by using carbide stabilizing materials at melting and are sometimes thermally or mechanically induced, that is subsequently Austempered to produce an Ausferritic matrix. The toughness is due to the Ausferrite matrix and it is produced by the austempering process.

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Cite this article as: P Dhanapal, A Sayith Ibrahim. "Production of Carbidic Austempered Ductile Iron [CADI]". *International Conference on Systems, Science, Control, Communication, Engineering and Technology 2016*: 527-535. Print.

As-Cast Carbides

This paper explains the production of ductile iron with suitable carbide forming elements. Iron created as ductile iron and treated with magnesium to result in spheroidal graphite. The same irons can be induced to form a carbidic microstructure with carbide stabilizers. These include alloying with carbide stabilizers such as chromium, molybdenum, titanium and controlling the cooling during shakeout or adjusting the carbon equivalent to produce a hypo-eutectic iron chemistry. The carbides produced from this technique can be “dissolved” to a controlled extent by subsequent Austempering heat treatment. Ductile irons are treated with magnesium and/or rare earths to produce spheroidal graphite.

Experimental Work

Foundry Considerations for the Production of CADI

Aimed Chemical Composition

The chemical composition for a CADI should initially be established in the foundry. The amount of alloy (if needed) will be a function of the alloy in the foundry's base metal, the part configuration (section size and shape) and the austempering equipment that is used. Suggested chemical targets along with typical control ranges are listed in the table.1.

Once the chemical composition ranges have been established, it is important for the foundry to produce ductile iron with established ranges. Variation in chemical composition can lead to variations in the pearlite / ferrite ratio in the as-cast ductile iron as need to adjust the heat treatment parameters. The response or growth during austempering is a function of the prior microstructure and austempering parameters.

Table 1: Suggested Targets for the Production of CADI

Element	Suggested Target
Carbon – C	3.6%
Silicon – Si	2.5%
Phosphorus – P	0.04% maximum
Magnesium – Mg	(%S x 0.76)+0.025%
Sulfur – S	0.02% maximum
Manganese – Mn	
Max section > 13 mm	0.35% maximum
Max section < 13 mm	0.60% maximum
Copper – Cu	0.80% maximum
Nickel – Ni	2.00% maximum
Molybdenum - Mo	0.10% maximum
Tin - Sn	0.02% maximum
Antimony – Sb	0.002% maximum
Oxygen – O	50 ppm maximum
Chromium – Cr	0.10% maximum
Titanium – Ti	0.040% maximum
Vanadium – V	0.10% maximum

Casting Quality

Austempering Castings should be free of non-metallic inclusions, carbides, shrink and porosity. In order to achieve the property minimums in Table 1, the following levels should be maintained.

Carbides + Nonmetallic inclusions - maximum 0.5%
Porosity and/or Microshrinkage – maximum 1%

Carbon Equivalent

The Carbon Equivalent (CE = %C + 1/3 %(Si+P)) should be controlled to produce sound castings. General Guidelines are provided in Table 2.

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Table 2: Carbon Equivalent Guidelines for the Production of CADI

Section Size	CE Range
0 – 0.5 inches (0 – 13 mm)	4.4 – 4.6
0.5 – 2 inches (13 – 51 mm)	4.3 – 4.6
Over 2 inches (51 mm)	4.3 – 4.5

When austempering cast irons, careful control of parameters is essential to achieve optimal material properties and consistency. The solution can be found in purpose-designed furnaces supported by process know how.

Nodule Count and Nodularity

The recommended minimums for nodule count and nodularity for ductile iron to be austempered are as follows:

Nodule Count -100/mm² (with a uniform distribution)
 Nodularity - 85%

Nodule count is especially important when alloy additions are made. Low nodule counts lead to larger spacing between the graphite nodules and larger regions of segregation. In the worst case, these regions can become so heavily segregated that they do not fully transform during austempering, resulting in the formation of low carbon austenite or even martensite. Segregation regions that did not transform during austempering. Higher nodule counts will break up the segregated regions

Base Metal Melting

The base composition of ductile cast irons usually is hypereutectic, where the carbon and silicon contents are typically 3.7 and 2.5 respectively (CE = 4.5). Thus the first constituents to appear during solidification are graphite nodules, which nucleate and grow, first without any austenite, but eventually with austenite enclosing the graphite nodule.

The processing scheme utilized in the production of ductile iron using a magnesium ferrosilicon alloy (MgFeSi) involves the following steps:

1. Build a charge from scrap steel, returns (risers, gates, etc.) and pig iron.
2. Melt charge and superheat to 1540°C.
3. Pour into treatment vessel, covering MgFeSi and reacting Mg.
4. Transfer into pouring ladle, inoculating with ferrosilicon.
5. Pour castings.

An Electric induction furnace is used for the melting of base metal. The basic melting process operations are furnace operations, including charging, melting, and back charging; refining, during which the chemical composition is adjusted to meet composition specification, and slag removal. The raw materials, metallic, and fluxes are added to the melting furnaces directly. Slag is removed from furnaces through a tapping hole or door. The molten metal is tapped by tilting and pouring through a hole in the side of the vessels.

Magnesium Treatment

It is critical in making ductile iron that the amount of magnesium present in the melt during solidification is in the range 0.03 to 0.05 weight percent. Magnesium contents less than this amount will result in graphite flakes, and amounts more than this results in the appearance of so called exploded graphite. Either type contributes to degradation in the ductility of the cast iron produced.

The large amount of Si present in the treatment alloy, a fact which requires that the Si content in the base charge be kept quite low, ~1.4 wt%, or about 1 wt % lower than the Si content in the final casting. This necessarily means that the charge will have to contain a significant component with a low Si content.

Figure.1 shows the design of a ladle suitable for the treatment. The use of a refractory dividing wall to form an alloy pocket in the bottom of the ladle gives improved Mg recovery. The diameter of the filling hole is chosen to minimise the generation of fume while allowing the ladle to be filled quickly without excessive temperature loss. It is essential that the MgFeSi alloy is not exposed to the liquid iron until quite late in the filling procedure, so the filling hole is positioned to introduce liquid iron away from the alloy pocket in the ladle bottom. The Mg alloy in the alloy pocket is covered with steel turnings or FeSi pieces of size 25 × 6 mm, then when the

level in the ladle reaches the dividing wall, iron flows over and forms a semi-solid mass with the cover material allowing the ladle to be almost filled before the reaction starts, thus ensuring good recovery of Mg.

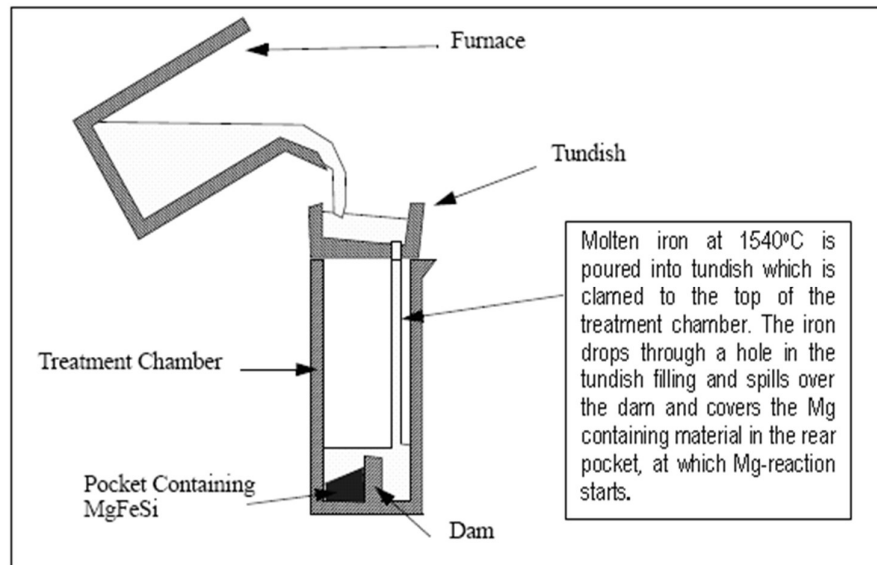


Figure 1 Magnesium Treatment process

In order to minimise temperature losses during treatment, the ladle and cover should be separately heated with gas burners before assembly. Immediately before use, the ladle should be filled with base iron from the melting furnace and allowed to soak for a few minutes before returning the iron to the furnace. The prescribed weight of MgFeSi alloy is charged through the alloy charging tube which is plugged after removal of the charging funnel. A common magnesium treatment (MgFeSi) master alloy approximately 5 wt % Mg, about 45 wt % Si, with the balance Fe is used. About twice as much Mg to be added during treatment than is required in the casting (this represents a 50 % recovery) because of the losses from oxidation during the violent treatment reaction.

During this time the Mg reaction involves the production of bubbles of magnesium vapor which proceed to rise up through the molten iron bath which is now covering the pockets in the chamber. Successful treatment results when a significant portion of the magnesium is dissolved into the molten iron, so that the correct conditions for graphite nodule formation are met in the solidifying melt. Typical "recoveries" of magnesium for the Tundish treatment facility shown are in the range 50 - 60 percent. Successful nodularization requires a composition of about 0.03 to 0.05 weight percent elemental magnesium in the iron. It is necessary that sulfur content be kept below 0.01% for successful treatment, because of the ability of the sulfur to react with the Mg (forming Mg_2S) and remove elemental Mg from the melt. Often times the melt needs to be desulfurized before treatment can progress, a process which usually involves additions of Ca (calcium) to combine with the sulfur. The calcium sulfide will then rise to the slag layer and be skimmed. This is done primarily to reduce the violence of the reaction that occurs when the molten iron contacts the magnesium. The pouring operation during treatment takes about 30 seconds to one minute to complete.

Tapping time is usually around 40 seconds. The temperature loss during treatment is around 50°C, so the tapping temperature must be adjusted accordingly; treatment temperatures of around 1530°C are commonly used. After treatment, the tundish cover is removed; the metal transferred to a pouring ladle where inoculation may take place, then it is cast. The castings must be poured within a short time after treatment, usually less than 10 minutes.

Inoculation and Fading

Immediately after treatment, the iron must be inoculated. From 0.5–0.75% of a graphitising inoculant such as INOCULIN 25 should be used. Inoculation treatment is not permanent; the effect begins to fade from the time the inoculant is added. Significant fading occurs within five minutes of inoculation. As the inoculating effect fades, the number of nodules formed decreases and the tendency to produce chill and mottle increases. In addition the quality of the graphite nodules deteriorates and quasi-flake nodules occur.

The Austempering Process

Austempering is a high performance isothermal heat treatment that imparts superior performance to ferrous metals. The Austempering process begins similarly with austenitization followed by rapid cooling to avoid the formation of Pearlite. In the

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Austempering process the quenching media is held at a temperature above the Martensite start temperature. This results in the FCC austenite cooling to the quench temperature. The quenched material is then held at that temperature for a time necessary to produce the desired acicular structure. In steels, that structure is bainite, a structure of acicular ferrite and carbide. In cast irons, with their higher silicon content, an intermediate structure called Ausferrite results. Ausferrite consists of acicular ferrite and carbon stabilized Austenite. This isothermal transformation results in uniform transformation of the structure throughout the part.

In Austempered cast iron, this Ausferrite has very good abrasive wear properties because of its tendency to “strain transform” on the abraded surface. Austempered Ductile Iron (ADI) can compete with much harder materials. However, even ADI can be bested by materials containing carbides. But, carbide irons tend to be very brittle.

Figure 2 contains a schematic of the austempering process.

The steps followed for the austempering process are

1. Heating to the Austenitizing Temperature (A to B)
2. Austenitizing (B to C)
3. Cooling to the Austempering temperature (C to D)
4. Isothermal heat treatment at the Austempering temperature (D to E)
5. Cooling to room temperature (E to F)

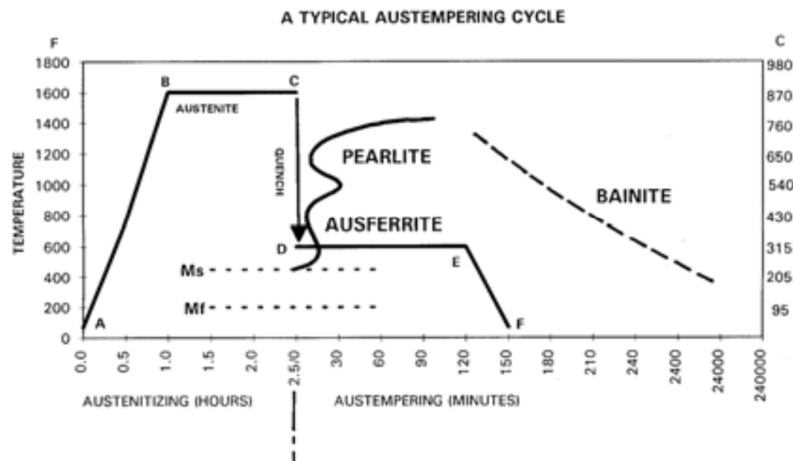


Figure 2 A schematic of the Austempering process

Heat Treatment Furnace and Process

The furnace system used for CADI Treatment is shown in fig.3. It has a controlled atmosphere austenitising batch furnace (A) with integral re-circulating roof fans and radiant tubes to ensure rapid heat up of heavy loads and high uniformity. An intermediate purge transfer chamber (B) and an enclosed vestibule (C) continue to protect the work from oxidation as it is transferred to a salt quenching station (D). The vestibule also isolates the furnace from salt ingress.

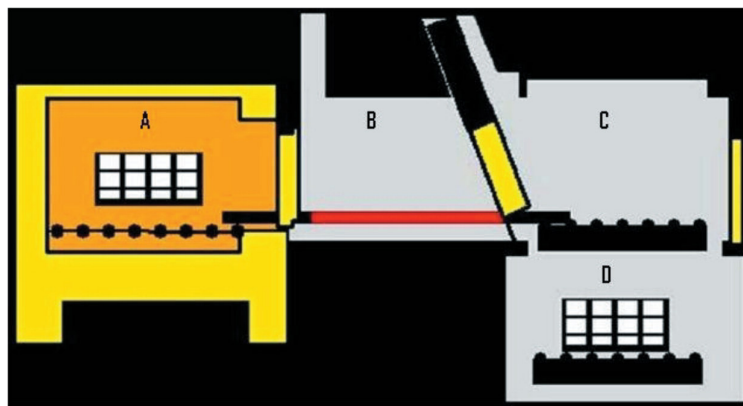


Figure 3. Heat Treatment Furnace

Flexibility in the furnace and controller configurations allows the austempering process to be tailored to the part. The controlled atmosphere features eliminate oxide scale formation, while the austempering process introduces minimal distortion and stresses.

Furnace system and process are driven via a state-of-the-art Human Machine Interface, which also provides access to the heat treatment programmes. Fig.3 illustrates a typical two-stage thermal process carried out at ADI Treatments on carbide irons. The first stage austenitisation cycle is followed by a controlled quench and an austemper of typically one to two hours duration.

The choice of austenizing temperature is depend on the chemical composition of the ductile iron. The time at the austenitizing temperature is equally as important as the choice of temperature. The ductile iron components should be held for a time sufficient to create an austenite matrix that is saturated with carbon. This time is additionally affected by the alloy content of the ductile iron with heavily alloyed material taking longer to austenitize. For this study, the samples were austenitised at 900°C for a time period of 1.5 hours and then austempered.

Cooling to the Austempering Temperature Cooling from the austenitizing temperature to the austempering temperature (as shown from C to D in Figure 2) must be completed rapidly enough to avoid the formation of pearlite. If pearlite is formed, the strength, elongation and toughness will be reduced.

The formation of pearlite can be caused by several things, most notably a lack of quench severity or a low hardenability for the effective section size. It is possible to increase the quench severity of molten salt quench bathes by making water additions. Oil quench equipment is limited to the production CADI.

The quench medium is a nitrate mix that is held at temperature of 340°C. The range of the autempering temperature for the production of CADI is 240 to 400°C. The higher grades are produced at lower quench temperatures. To ensure the homogeneity of the process and final material properties, the salt is forcibly circulated through the load. By inoculating the salt bath with water, quenching rates are enhanced to allow treatment of larger section parts without adjustment of cast composition. The salt is managed and recycled to obviate environmental damage.

The traditional quench media, oil and water, are not used so that the load does not reach the Ms temperature and brittle martensite cannot develop.

The components are held for a sufficient time at temperature for ausferrite to form. Ausferrite consists of ferrite in a high carbon, stabilized austenite. If held for long time periods, the high carbon austenite will eventually undergo a transformation to bainite, the two phase ferrite and carbide ($\alpha + \text{Fe}_3\text{C}$). In order for this transformation to occur, longer periods of time are typically needed – much longer than would be economically feasible for the production of CADI.

Once the ausferrite has been produced, the components are cooled to room temperature. The cooling rate will not affect the final microstructure as the carbon content of the austenite is high enough to lower the martensite start temperature to a temperature significantly below room temperature.

Instead the microstructure is transformed to an ausferritic matrix with controlled carbide dispersion (fig. 4), an arrangement that confers excellent wear-resistance with adequate toughness. Parts may be designed to account for dimensional changes during the heat treatment so that little or no finishing is required. In the following case study,

Figure 4 shows the linear dimensional change as a function of austempering temperature for CADI with prior microstructures of ferrite, pearlite and a ferrite/pearlite mix.

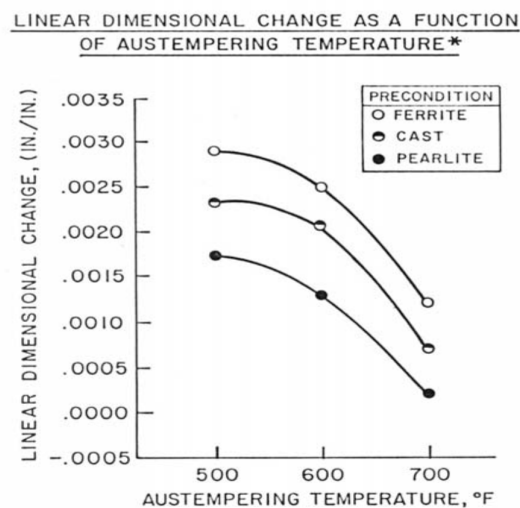


Figure 4: Linear Dimensional Change as a function of Austempering Temperature

Results and Discussion

A. Microstructure

Microstructure analysis was taken on the specimens using a metallurgical microscope. Figure. 5. shows the microstructure of CADI material. The microphotograph contains ausferrite matrix with controlled carbide dispersion and graphite in the form of nodules. The graphite nodules are very soft with respect to the matrix. This carbide morphology is found in all places of the treated iron casting. The combination of ausferrite matrix, carbides and the graphite nodules conform a high wear resistance and adequate toughness material.

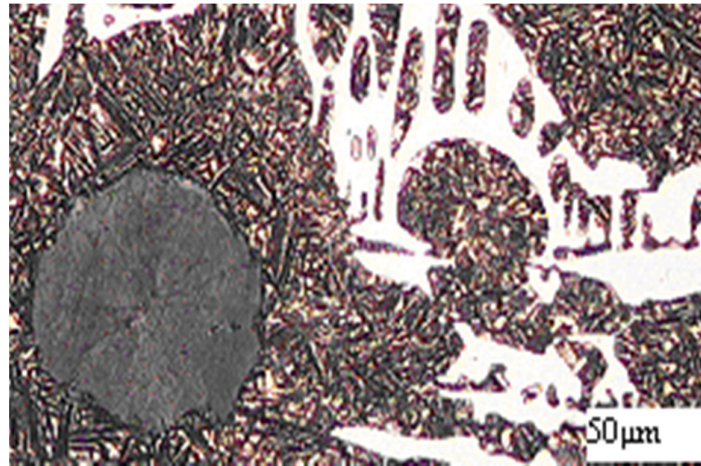


Figure. 5. CADI microstructure Austempered at 340°C

B. Wear Test

A schematic drawing of the main portion of the pin on disc abrasion wear testing machine is illustrated in the Fig. 6. The specimen is pushed on to the disc with a load of 10 N on to the disc. This test is carried out to a distance of ----(Velocity of the machine)m on the specimen. Volume losses on the specimens were measured and compared with other materials.

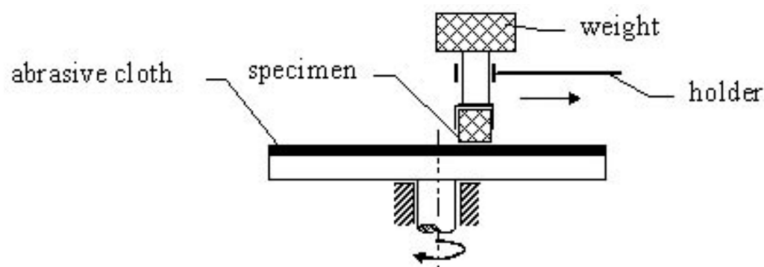


Figure. 6. Schematic of PIN-ON-DISC wear test machine.

Material	Weight loss (mg)
CADI	43.7
ADI Grade 1	100
ADI Grade 2	76.7
ADI Grade 4	70.3
ADI Grade 5	62.8
ASTM A514-T1A steel	134

Table. 3. Compilation of Abrasion data.

Table 3. Shows the quantitative weight loss data of different reference metals, they are used in the high wear rate applications. The data indicates that CADI offers significantly greater wear resistance than other ADI materials. The wear resistance of CADI is 128%

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higher compared to ADI grade 1 and 43.7% higher than ADI grade 5. CADI's wear performance may be increased by increasing the volume fraction of carbides in it.

C. Impact Test

The results obtained by un-notched Charpy Impact energy of the CADI is listed in the table 4 with some reference materials. CADI is 300% tougher than ADI5.

Material	Impact energy (J)
CADI	13
Carburized 8620 Steel	17
Grade 5 ADI	52
Grade 4 ADI	35
Grade 3 ADI	91
Grade 2 ADI	80
Grade 1 ADI	117
4512 Ductile Iron	123

Table 4. Un-notched Charpy impact Values.

CADI is a ductile cast iron containing carbides, which may be manufactured in other methods also, that are either thermally or mechanically carbides are induced. The following are the other methods for carbide iron preparation. That is subsequently Austempered to produce an Ausferritic matrix with an engineered amount of carbides.

Methods of carbide introduction include:

1. As-Cast Carbides
 - 1.1 Internal (chemical or inverse) chill
 - 1.2 Surface chill (limited depth, directional)
2. Mechanically Introduced Carbides
 - 2.1 Cast-in, crushed MxCy carbides
 - 2.2 Cast-in, engineered carbides (shapes)
3. Welded
 - 3.1 Hardface weldment
 - 3.2 Weldment with MxCy grains

Conclusion

The production of CADI is not a highly complicated process. Any foundry that works in conjunction with a heat treater can conceivably make CADI. However, there are important considerations in order to be successful. High quality ductile iron with the proper alloy content is the necessary ingredient.

Trials were performed on the CADI parts. Over the lifecycle the CADI proved to be more energy efficient and wear-resistant.

The data indicates that CADI offers significantly greater wear resistance than standard ADI materials, some wear resistant steels and martensitic ductile iron, CADI's wear performance increases with increasing carbide volume. This is accompanied by a corresponding reduction in impact properties.

Unnotched Charpy test data for a typical CADI alloy containing 30-45% carbide and a range of traditional materials are compared in table 4.

Carbide austempered ductile iron offers cost savings and a useful mix of properties that position the material alongside established wear resistant steels and irons.

Furnace capability is key to achieving component performance and batch to batch consistency. No capital investment is required for the metal caster to add this new product line.

CADI is less expensive and tougher than 18% chrome white iron.

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Expected Applications of CADI

CADI's properties present some intriguing market opportunities, potential applications in vehicles including camshafts and cam followers. Agricultural applications may include rippers, teeth, plough points, wear plates and harvester, picker and baler components. In construction and mining, potential applications include digger teeth and scarifiers, cutters, mill hammers, flails, guards, covers, chutes, plates, housings, transport tubes and elbows, rollers and crusher rollers.

General industrial applications could include pump components, wear housings and plates, conveyor wear parts, skids and skid rails, rollers Crankshafts, steering knuckles, differential carriers, brake callipers, hubs, brackets, valves, water pipes, pipe fittings and blast parts. Market entry is eased because no capital investment is required for the ductile iron producer to add the material as a new product line.

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