The 2008 Keith Millis Symposium on Ductile Cast Iron cosponsored by DIS and AFS was held at the Orleans Hotel & Casino in Las Vegas on October 20 – 22, 2008. Approximately 200 attendees from the international community attended 2 ½ days of presentation related to ductile iron (DI), austempered ductile iron (ADI) and compacted graphite iron (CGI).

The conference began with a day of presentations concerned with markets for ductile iron as well as applications. Day 2 of the conference began with the keynote address, “Modified Graphitic Iron – Now What Do We Do With This Stuff?” by Dr. Preston Scarber. Presentations on production, processing and properties of DI were also delivered.

SUMMARY OF DAY 1

Alfred Spada (AFS), Patricio Gil (Blackhawk de Mexico) and Chandra Rajan (FOSECO) summarized how the US ductile iron industry is competing in a global market. 2008 and 2009 are forecasted to be low production years; however, steady growth is expected across the industry starting in 2010 and to continue for at least 7 years. Argentina, Brazil and Mexico were cited as good and growing manufacturing options for North America with Mexico having a 20% lower manufacturing cost. Figure 1 summarizes imports to the US by country in 2008.

**Figure 1:** Pie chart showing the countries of origin for importing castings into the U.S.

Kerui Li (China Foundry Institute) provided information about the history and status of production of ductile iron in China. China is the current world leader in tonnage produced of ductile iron. The wind power generation industry is growing at a rapid pace and demands for large, heavy section castings are increasing. Producers in China are working diligently to solve the challenges associated with producing high quality ductile iron that meets the stringent requirements for wind power applications.

Papers describing the historical development of CGI and ADI were presented by Dr. Steve Dawson (SinterCast) and John Keough (Applied Process Inc.), respectively. Both presentations included information about applications of these materials along with the potential for the future of CGI and ADI.

Additional papers on applications of ADI were presented by Dr. Arron Rimmer (ADI Treatments), Eugene Muratore (Rio Tinto), Xia Yong (AP Suzhou) and Enrico Veneri (Zanardi Fonderie). Among the applications featured were a cross-link for a rear end suspension system, a wind turbine planetary gear carrier, rack & pinion gears, pattern tooling and crankshafts for four-cylinder diesel engines.
Enrico Veneri described a new microstructure that has been developed by Zanardi Fonderie – perfeccritic isothermal ductile iron. This patent pending material is an intermediate grade between pearlitic ductile iron and ADI.

Dr. Roberto Boeri (INTEMA) described ongoing research to understand the embrittlement of ADI and high strength ductile iron when exposed to liquids. He noted that this only happens when 3 conditions are simultaneously met: presence of a liquid, applied stress near yield and a slow strain rate. Recent work has focused on painting and coating to provide a barrier to contact with liquids. Preliminary results have shown that it is difficult to maintain the integrity of the coating during deformation.

Chantal Labrecque (Rio Tinto) presented a comprehensive literature survey on the status of thin wall ductile iron casting technology. State of the art practices for production of ductile iron can now produce high quality castings with a 2 mm wall thickness.

**SUMMARY OF DAY 2**

Dr. Preston Scarber’s (University of Alabama-Birmingham) keynote address featured, “Modified Graphitic Iron – Now What Do We Do With This Stuff?” This presentation demonstrated how simulation and real-time x-ray can be used to better understand the processing variables that affect casting quality. Ductile iron and CGI can be used in many high stress applications without needing to be twice as thick as other ferrous castings.

Dr. Alan Druschitz (University of Alabama-Birmingham) described preliminary efforts to investigate low carbon equivalent ductile iron. Cees van Eldijk presented information on applications of thin wall ductile iron (TDI) with a section thickness just under 2 mm. Figure 3 illustrates a TDI design for a shock absorber bracket.

**SUMMARY OF DAY 3**

Information about production/processing of ductile iron was presented by Hans Roedter (Rio Tinto), Dr. Rudolf Sillen (NovaCast Technologies AB), Christof Heisser (Magma Foundry Technologies), Dr. Jorge Sikora (INTEMA), Al Alagarsamy (Consultant) and Noberto Rizzo (Dana Corporation). Topics covered included: gating & risering, relating the true eutectic point to process control of ductile iron, autonomous optimization of ductile iron castings, solidification macrostructure of free graphite cast iron, reheating ductile iron and how nodule density is related to casting yield in ductile iron.

Compacted graphite iron was featured in 2 papers. Frans Mampaey (Sirris) described the use of oxygen activity measurements to determine graphite structure. David Poerschke (Case Western University) presented preliminary results from his graduate studies that are concerned with the effects of cooling rate on the microstructure, mechanical properties and machinability of CGI.
Robert O’Rourke (Wells Manufacturing – Dura Bar Division) discussed dry sliding wear characteristics of ductile irons. This data is of use when DI rubs against other metal parts with low interfacial pressures as would happen in hydraulic and other machine assemblies.

Gwendolyn Baker (TK-Waupaca) described how the application of poka yoke or mistake-proofing measures to detect and eventually prevent errors and failures in the ductile iron conversion process were implemented in a production foundry. The impact of implementing this methodology has resulted in a dramatic decrease in the amount of ductile iron from suspect conversions being poured into molds.

Dr. Richard Larker (Indexator AB) discussed ferritic ductile iron that has been solution strengthened by silicon. Misconceptions about the role of Si in ductile iron were presented. The results of the author’s investigations suggest that the loss of toughness in ductile iron may be related to Mn content rather than Si. Figure 4 shows a swivel housing that was converted to solution strengthened JS/500-10 in 2005.

Ian Lee (Graham Campbell Ferrum) and Chris Samuel (University of Alabama-Tuscaloosa) discussed topics related to heat treatment of ductile iron. Topics covered included criteria for heat treatment of ductile iron gears and the use of gleeble dilatometry for the determination of CCT curves.

The conference concluded with a discussion of machinability of ductile iron by Dr. Robert Voigt (Penn State University). The influence of casting dimensional variability on tool life variation was presented.

Figure 4: An ISO 1083/JS/500-10 swivel housing. Use of this grade of high Si ductile iron results in consistent properties and 20 µm tolerances.

FURTHER INFORMATION

Copies of the conference proceedings are available for purchase from the American Foundry Society at www.afsinc.org.

ACKNOWLEDGMENTS

The DIS would like to acknowledge the following individuals who volunteered their time to make the 2008 Keith Millis Symposium on Ductile Cast Iron a success:

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Applied Process, Inc.

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American Foundry Society

Eugene Muratore
Rio Tinto Iron & Titanium

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Rio Tinto Iron & Titanium

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Hickman Williams & Co

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Scott Gledhill Appointed Ductile Iron Society Vice President

Scott Gledhill

Scott graduated from the University of Alabama with a B.S. in Metallurgical Engineering. While at school he co-oped at Stockham Valves and Fittings in Birmingham spending time in the Bronze, Grey Iron, Malleable Iron and metallurgical areas.

In 1985, Scott started at GM Central Foundry in Defiance Ohio. There he held several positions in production, metallurgy, quality and engineering in both the Grey Iron and Ductile Iron production areas.

In 1992 Scott joined Thyssenkrupp Waupaca at their Marinette plant as Plant Metallurgist. During Scott’s 16 years with Thyssenkrupp he has held various positions including metallurgist, quality manager, plant manager, manager of research and is currently Director of Program Management and New Product Development.

Scott has been involved in various AFS and DIS committees including molten metal processing, mold-metal interface, DIS research and is currently a board member of the DIS.
ABSTRACT

Farmers, component designers, agricultural equipment manufacturers and after-market agricultural component suppliers have all found unique, cost-effective uses for Austempered components. Austempered Ductile Iron (ADI), Austempered Gray Iron (AGI), and Carbidic ADI (CADI) have all found applications in agricultural equipment and component applications. This paper will give the reader an overview of the processes, the salient properties of those processes, developments in the manufacture of said components, and specific case studies of their application.

INTRODUCTION

In 2002 Hayrynen and Brandenberg published the paper “Agricultural Applications of Austempered Ductile Iron”. The paper reviewed the properties exhibited by Austempered Ductile Iron (ADI) and its application agricultural components. That paper has been widely distributed and has lead users to other Austemper-based material/process applications in the agricultural equipment and component industry.

Many developments have occurred in the past few years that merit an updated review of Austempering applications in the agricultural industry. This paper is an overview that includes ADI, Austempered Gray Iron (AGI), and Carbidic ADI (CADI). The authors will attempt to familiarize the readers with each of the processes and the engineering, manufacturing and economic advantages of the aforementioned material/process combinations.

BACKGROUND

Austempering is an isothermal heat treating process that can be applied to ferrous materials to increase their strength and wear resistance without sacrificing toughness. Austempering consists of heating a ferrous material above the critical temperature (red hot), soaking at that temperature for a time sufficient to result in a uniform temperature and microstructure, cooling rapidly enough to avoid the formation of pearlite to a temperature above where Martensite forms (Ms) and then holding (Austempering) for a time sufficient to produce the desired matrix structure. In steel the resultant microstructure is a combination of acicular ferrite and fine, complex carbides. This multi-phased structure, named after its discoverer, Edgar Bain, is called “Bainite”. In cast irons, with excessive carbon in the form of graphite, and higher silicon contents, the resultant matrix consists of a mix of acicular ferrite and carbon stabilized austenite, collectively called “Ausferrite”. Figures 1 and 2 show example isothermal transformation diagrams for the Austempering of steel and cast iron respectively.

The strength level in Austempered steels and irons will (largely) be determined by the Austempering temperature. A higher Austempering temperature will produce a material with a lower strength and hardness, but greater toughness and ductility. A lower Austempering temperature will produce a higher strength and hardness material that has somewhat lower toughness and ductility. The “grade” or “hardness” of the material/process combination selected will be determined by the engineering, performance and economic factors defined by the end user and producer.
Because Austempering is an isothermal process, it offers several advantages over conventional quenching and tempering and other methods of martensitic hardening. Martensitic transformation takes place when the local material temperature drops below the Martensite Start (Ms) temperature. Therefore, the transformation (by definition) takes place at different times in sections of differing section modulus. This can result in inconsistent dimensional response, micro-, and even macro-cracking. Since the formation of Bainite and Ausferrite occur uniformly throughout the part, over many minutes or hours, Austempered components exhibit very consistent dimensional response and no cracking (either micro or macro).

ADI, AGI and CADI are generally lower cost replacements for steel and aluminum castings, forgings and weldments.

**AUSTEMPERED DUCTILE IRON (ADI)**

ADI is produced by austempering a ductile iron (spheroidal graphite iron) material to produce an ausferritic matrix. The spheroidal graphite “nodules” in ductile iron allow us to fully exploit the high strength and toughness of ausferrite as they do not reduce the toughness of the iron as do graphite flakes or large carbides. Figure 3 shows the properties of the ADI grades specified in ASTM A897/A897M-06. Furthermore, ADI is about 10% less dense than steel due to the presence of these graphite nodules.

Engineers and designers have learned that ductile iron can be easily cast into complex shapes. By subsequently austempering these castings they can exhibit a strength-to-weight ratio comparable to heat treated steel or aluminum. This allows designers to create one-piece designs that were previously assembled from multiple forgings, castings, extrusions, weldments or stampings.

ADI’s microstructure (Ausferrite) contains carbon stabilized austenite which is thermally stable but, when acted upon by a high, normal force, transforms locally to untempered martensite nested in a ferritic matrix. This dramatically increases the surface microhardness giving ADI an abrasive wear resistance that exceeds that implied by its bulk hardness.

In certain angular and rocky soils, ADI plow points, boots and plow shins have been reported by farmers to out-wear hard-face welded and high-chrome, wear resistant irons. In other, less aggressive soils, ADI does not perform as well. In those applications, CADI is generally chosen and will be discussed later in this paper.

The same “strain transformation” phenomenon that increases surface hardness also induces compressive surface stress which, in turn, increases allowable bending stress. The result is an increase in the fatigue strength of both structural and powertrain components which can benefit greatly from shot peening, grinding or fillet rolling after austempering.
<table>
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<th>Tensile Strength (MPa / ksi)</th>
<th>Yield Strength (MPa / ksi)</th>
<th>Elongation (%)</th>
<th>Typical Hardness HbW</th>
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<tr>
<td>1600 / 230</td>
<td>1300 / 185</td>
<td>1</td>
<td>402 – 512</td>
</tr>
</tbody>
</table>

Figure 3- Summary of the minimum properties of the six grades of ADI specified in ASTM A897/A897M-06.

There is much more technical information available on ADI’s fatigue behavior, machinability and other important design and manufacturing characteristics but the scope of the entire body of information exceeds the scope of this paper. Additional sources can be found within the reference section.

Ground engaging applications are considered by many to be some of the most difficult to engineer due to the abrasiveness of environments on the equipment. The Truax Company’s Rangeland Planter Boot is one where exceptional wear resistance, coupled with a detailed casting design, was required for a very specific and tough application; the replanting of arid, wilderness grasslands. The incumbent steel weldment (Figure 4a) used for the application was not holding up to the environmental and functional design needs of their seed planter. They teamed up with Smith Foundry Company and Applied Process for an exceptional material solution in ADI (Figure 4b).

The steel fabrication did not hold up to the rigors of the harsh, wilderness terrain in either wear resistance, or strict seed flow-through parameters. The steel weldment wore through after only 500 acres of planting necessitating an expensive and time consuming field replacement. The welded design also lacked the smooth, internal transitions needed for precise seed flow.

The redesigned ADI casting (shown installed on the planter in Figure 5) meets Truax’s difficult requirements while posting a 15% reduction in part weight, cutting the manufacturing lead time in half (from six weeks to three weeks), better than doubling the life of the boot, and reducing the part cost by more than 65%. This conversion won Smith Foundry and Truax the 2007 Engineered Casting Solutions / American Foundry Society Casting of the Year Award.

Sometimes ADI is simply chosen for its low cost to manufacture. That is the case with the small ADI lever arm shown in Figure 6. This arm is an alternative to forged steel. It is cast in ferritic/pearlitic ductile iron, machined completely and then Austempered giving the end user the low product cost and durability that they need.
Figure 6- Small, ADI actuating lever for a European agricultural application.

Many types of wheeled agricultural and construction equipment are being converted to rubber tracks for increased versatility, lower weight, cost and soil compaction. In one application, the Toro Dingo® TX 413 (Figure 7b), the main drive wheel consisted of an 84-piece welded and bolted steel assembly. Engineers at Toro and Smith Foundry collaborated to create a one-piece ADI design (Figure 7) that proved to be lower in cost and more durable. Because 84 pieces of steel were replaced with one, green sand, ADI casting, the wheel reliability was improved by eliminating the inherent variabilities in cutting, stamping, drilling, bolting and welding the components together.

Figure 7 – a) Toro Dingo TX drive system, b) Toro Dingo TX c) The one-piece ADI main drive wheel replaced an 82-piece steel welded and assembled component. (Courtesy of Toro and Smith Foundry).

Figure 8 shows a typical ADI plow point.

Of course, the earliest agricultural applications of ADI were simple aftermarket plow points and wear shins. Figure 8 shows a typical ADI plow point that has been in production for more than 15 years. These through-hardened ADI ground engaging parts replace hardened and hard-faced welded steel components at a competitive price.

Figure 8 shows a typical ADI plow point.

Australian farmers have utilized the prize-winning MitchTip design since the 1990’s (Figure 9). This clever, proprietary ADI design utilizes impacted soil to extend the life of the tip. An “engineered CADI” version with a brazed on carbide tip and a durable ADI body is also available. MitchTips have proven equal to the task of ripping abrasive Australian soils.

Figure 9- ADI Mitch Tips from Australia.
Harvesting machines present their own set of challenges to the designer. The advent of the highly efficient rotary designs has created new opportunities for castings. Many grain rasps, deflectors and other parts used to separate and convey the grain within the harvester have been converted to ADI and CADI. **Figure 10** shows an ADI grain deflector for a harvester. This complex shape would be nearly impossible to produce by any other method than casting. The wear resistance offered by ADI allows it to stand up to abrasive grain flow.

![Figure 10- An ADI Grain Deflector for a harvesting combine.](image)

A small, Iowa manufacturing company named Bergman Manufacturing has patented the rugged, simple to use, Agri-Speed Hitch (**Figure 11**) that consists of two main components with five ductile iron sub-components, of which, four are ADI. It allows the operator of a tractor to safely back up and hook, or unhook a wagon without leaving the tractor. Ductile iron, and ADI replaced steel in this application to reduce the cost and improve the durability of the hitch. This device was awarded a “Best in Class” in the 2008 Engineered Casting Solutions / American Foundry Society casting competition.

![Figure 11- The Agri-Speed hitch uses four ADI components.](image)

ADI is also used in powertrain and sprocket driven applications. **Figure 12** shows an ADI adjuster sprocket on a John Deere harvester. The ADI casting is a cost effective alternative to a steel sprocket machined from bar stock.

![Figure 12- This ADI adjuster sprocket is a durable alternative to steel.](image)

Agricultural components must often withstand impact loading and the abrasive wear characteristics of sandy and/or wet grass, stalks and organic material. The ADI flail shown in **Figure 13** is an elegant, cost effective design that puts the rotating mass where it is needed.
AUSTEMPERED GRAY IRON (AGI)

AGI provides the same excellent wear resistance as its ausferritic cousin, ADI. AGI exhibits much higher strength than as-cast gray iron. Figure 14 shows the tensile strength array of Class 20, 30, and 40 gray iron as-cast and austempered at 371°C (700°F), 316°C (600°F) and 260°C (500°F). Its most salient feature is its ability to damp noise due to the combination of an ausferritic matrix and large graphite flakes. Note that Figure 15 shows that as the austempering temperature is decreased, the strength of the AGI increases, as does the damping coefficient. Those graphite flakes also limit the strength of AGI, acting as angular voids in the metal matrix and allowing maximum strengths no higher than around 450 MPa.

The advantages of AGI are its low cost and excellent castability. This makes it a good candidate material/process combination for applications that require low cost, a complex shape, good strength and wear resistance where impact and cyclic stresses are not significant.

The most ubiquitous application of AGI is in cylinder liners for diesel engines. In that application the cylinder liners offer good wear resistance and noise damping as well as improved burst strength over as-cast gray iron liners.

The complex harvester machine cam in Figure 16 demonstrates the excellent manufacturability of AGI components. The gray iron has good castability and is easily machined. The critical shape of the cam is maintained during the austempering process. The ausferrite matrix provides good wear resistance for cam durability and good noise damping.
CARBIDIC AUSTEMPERED DUCTILE IRON (CADI)

CADI is produced by the introduction of carbides into the cast iron matrix during the casting process. The iron is subsequently Austempered in a manner that produces a controlled percentage of carbides in an ausferritic matrix. CADI was introduced in 1991 to produce components with better wear resistance than ADI at a price (and performance) competitive with abrasion resistant irons, but with a modicum of impact strength. Figure 17 shows the abrasive wear resistance of CADI vs. an array of other engineering materials.

CADI may also be produced by mechanically introducing carbides into a casting cavity prior to the introduction of molten metal. The subsequent austempering of the component does not affect the cast-in carbides. Another version of CADI can be produced by casting a part as ductile iron, hard-face welding a locality on the part and then subsequently austempering it, leaving the carbidic hard-face weld unaltered, while producing a base matrix of Ausferrite.

The first commercial application of CADI occurred in 1991. A small, agricultural implement manufacturer then using ADI needed “a little more wear resistance” on a certain fully-supported plow point (Figure 18). Keough and Kovacs worked with the manufacturer, Carroll Agricultural, and G&C Foundry to develop a casting process to produce an as-cast iron matrix containing mixed spheroidal graphite and carbides. The carbides were subsequently partially dissolved during austenitizing. The material was then austempered. The resulting wear resistance was suitable for the customer’s application and the parts exhibited adequate toughness to survive initial dropping of the plow and impacts with stones.

Figure 18- The first, commercial CADI application (circa 1991) was this small plow point for Carroll Agricultural.

Figure 19 shows the John Deere LaserRip™ ripper points that utilize CADI for good wear resistance and toughness highly abrasive, rocky soil. They provide better wear resistance than standard steel points and better impact resistance than high-chrome, abrasion resistant steels and irons. Many of the John Deere CADI components are produced using a special, patented method for the production of CADI developed by ThyssenKrupp Waupaca specifically for John Deere components.

Figure 19- John Deere LaserRip™ CADI ripper points. (Courtesy of John Deere and ThyssenKrupp Waupaca)

Harvesting machines pose interesting challenges to design engineers. If the handling and thrashing components are too soft, they will wear out, causing downtime at critical harvest times. If those same components are too brittle, they may break, causing the machine to be off-line at a critical time. Engineers have
found that CADI rasps, thrashing tines, flights and buckets can withstand the impacts sustained in grain harvesting and provide sufficient wear for a full season and more. Figure 20 shows several CADI components used in harvesting machine applications.

Figure 20 shows several CADI harvester applications. a) bucket, b) thrashing tine, c) flight, d) scraper blade.

SUMMARY

Austempering offers manufacturers numerous opportunities to make their iron components tougher, stronger, lighter, quieter and more wear resistant.

ADI is a cost effective, durable alternative to steel and aluminum castings, forgings, weldments and assemblies.

AGI combines good wear resistance and noise damping at a total manufacturing cost less than ADI, steel or aluminum.

CADI offers extreme wear resistance with a modicum of toughness that gives it performance and cost advantages over conventional abrasion resistant iron components.

ACKNOWLEDGMENTS

The authors would also like to thank the customers of Applied Process companies (and their licensees) for their collaboration on the various case studies, and their patronage. It is the customers that allow us to continue to “grow the pie” for Austempering.

REFERENCES


ADDITIONAL RESOURCES

Here the authors list additional sources of information that the reader may choose to review.

+ Applied Process Inc. internal research
+www.appliedprocess.com
+www.metalcastingdesign.com
+www.mitchtip.com
Keith Millis Ductile Iron Symposium Speaker Bios
Monday, October 20 Session

Alfred Spada

Alfred Spada is Editor/Publisher of Modern Casting and Engineered Casting Solutions magazines and AFS Director of Marketing, Communications and Public Relations. Alfred is a graduate of Northwestern University and has a MBA from the University of Colorado.

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Patricio Gil

Patricio Gil is currently the CEO of Blackhawk de Mexico. Previously he worked for 5 years as the CEO of Teknik and previously to that, 15 years at Cifunsa Foundry in different manufacturing positions. Patricio has his Industrial Engineering and MBA from Monterrey Tech, Foundry Specialist from the Saltillo Tech and Operations Management from the University of Western
Li Kerui

Li Kerui is currently a professor at the Zhengzhou Research Institute of Mechanical Engineering. He is also the Director of the Investment Casting Department. Li graduated from Hefei University of Technology in 1983, post graduated from China Academy of Machinery Science and Technology in 1986.

Dr. Steve Dawson

Steve Dawson is currently the President & CEO of SinterCast. Steve holds a Bachelor of Engineering (Metallurgy) degree from McGill University in Montreal, Canada and Masters of Applied Science and Doctor of Philosophy degree from the University of Toronto, Canada.

John R. (Chip) Keough

John Keough is currently the CEO and owner of Applied Process Inc. which now has locations world-wide. John graduated from the University of Michigan in 1977 with Bachelor’s Degrees in both Mechanical and Materials/Metallurgical Engineering. In 1980 he became a Registered Professional Engineer.

Dr. Arron Rimmer
Dr. Arron Rimmer is Development Director of ADI Treatments Ltd and is based at the company’s factory in Birmingham, England. Arron studied Metallurgy at the University of Manchester Materials Science Centre, which was the contemporary UK leader in ADI material investigations. On graduating he began a Masters degree in Austempered Ductile Iron before completing his Ph.D.

**Eugene C. (Gene) Muratore**

Gene Muratore is currently the Senior Foundry Metallurgist for Rio Tinto Iron and Titanium America. As such, Gene is responsible for technical service to the United States, Canada, Mexico, Japan, South Korea, and Taiwan. Gene graduated from Case Western Reserve University in Cleveland, Ohio in 1970 earning a B.S. in Metallurgy. Gene was an FEF scholar under Prof Jack Wallace.

**Xia Yong**

Xia Yong joined AP Suzhou at its launch in 2006, where he started as the Production Manager, later adding the additional role of Sales Manager to his responsibilities. Xia is a 1988 graduate of Nantong TV University in Jiangsu Province, China. Xia is presenting the paper on behalf of Liu Guanghua, a professor at the Nanjing University of Science and Technology, who was unable to attend. This paper is a collaboration of Liu Guanghua, Wang Shouhe and Xia Yong.

**Enrico Veneri**
Enrico Veneri is currently the Project Manager of ADI and Product Development for Zanardi Fonderie Spa. Enrico received his degree in Mechanical Engineering from the University of Padova in 1999. Enrico then joined Zanardi Fonderie in 2000.

Roberto Boeri

Roberto Boeri is currently a professor at the National University of Mar del Plata. Roberto received his Bachelor of Mechanical Engineering from the National University of Mar del Plata in 1983. He then received his Ph.D. from the University of British Columbia, Canada in 1990 where his thesis was titled, “The Solidification of Ductile Cast Iron”.

Chantal Labrecque

Chantal Labrecque is currently employed at Rio Tinto Iron & Titanium as a Research Engineer. She is responsible for research projects related to Ductile Iron Development. Chantal received her Bachelor of Science in Physics Engineering in 1991 and her Master’s of Science in Metallurgical Engineering in 1993 from the University of Laval in Quebec City, Quebec, Canada.
Keith Millis Ductile Iron Symposium Speaker Bios
Wednesday, October 22 Session

Robert O'Rourke

Robert O’Rourke is the Product Engineering Manager for Dura-Bar Division of Wells Manufacturing Company. Bob presented the paper on behalf of the author PR Gangasani. PR Gangasani is currently the Technical Director of Dura Bar, a Division of Wells Manufacturing Company. PR received his Bachelor of Science in Engineering from Osmania University in India. He then received his Master’s of Technology from IIT Kharagpur in India and then his Ph.D. in Metal Casting from the Indian Institute of Technology (ITT) Bombay, India.

Gwen Baker

Gwen Baker joined Waupaca Foundry in 1999 as part of the start up team for the Etowah, Tennessee plant, and has served with them for 9 years as Metallurgist and Six Sigma Black Belt. Gwen received her Bachelor of Science degree in Metallurgical Engineering from Michigan Technology in 1991.

Dr. Richard Larker
Dr, Richard Larker is the R&D Manager at the Swedish company Indexator AB. Dr. Larker has a Masters degree in Mechanical Engineering and a Ph.D. degree in Engineering Materials from Lulea University of Technology in Sweden. He was appointed Associate Professor in Engineering Materials at the same University in 1998.

Ian Lee

Ian Lee is currently the Technical Manager at Graham Campbell Ferrum in Australia. Ian started his foundry career back in 1978 when he joined Graham Campbell Ferrum. In 1998 he joined Steele & Lincoln Foundry as Technical Manager. In 2004 he was promoted to General Manager. In 2005 he returned to Graham Campbell at his current position.

Chris Samuel

Chris Samuel received his Master's in Metallurgical Engineering from the University of Alabama in Tuscaloosa, FL. Chris is currently pursuing his Ph.D. at the same university. His Master's research involved the use of Gleeble dilatometry for the prediction of ferrite-pearlite ratios in an unalloyed ductile iron.

Dr. Robert C. Voigt
Dr. Robert Voigt is currently the professor of Industrial & Manufacturing Engineering Department at Penn State University and Co-Director of Quality & Manufacturing Management Program. Robert received his Bachelor of Science in 1976 in Mechanical Engineering, his Master's in Metallurgical Engineering in 1978 and his Ph.D. in Metallurgical Engineering in 1981 from the University of Wisconsin.
Keith Millis Ductile Iron Symposium Speaker Bios
Tuesday, October 21 Session

Dr. Preston Scarber, Jr.

Dr. Preston Scarber, Jr. is currently the Director of Computer Simulations in the Casting Engineering Laboratory at the University of Alabama. Preston received his Bachelor's degree in Materials Engineering in 1992, his Master's degree in Materials Engineering in 1995 and his Ph.D. in 1998 from the University of Alabama at Birmingham.

Dr. Alan P. Druschitz

Dr. Alan Druschitz is a new professor of the Metals Casting Group at the University of Alabama at Birmingham. Alan worked also as a Research Engineer at GM Research Laboratories for 14 years and then 11 years with Intermet Corporation. Alan received his Ph.D. in Metallurgical Engineering in 1982 from the Illinois Institute of Technology, Chicago, IL.

Cees van Eldijk
Cees van Eldijk has worked on many different projects including ADI, Improving production processes, Improved production of TDI castings, Thin Ductile Iron for Automotive applications from 1968 – 2006. In 2006 Cees started a new company called TDIvalueWeb.com. This new company was formed to promote market, engineer and manufacture Thin Walled Ductile Iron (2-4 mm) for applications where fatigue strength and safety are critical.

Hans Roedter

Hans Roedter is currently the Foundry Engineer and Technical Representative of Rio Tinto Iron & Titanium in Germany. Hans received his Bachelor of Science degree in Foundry Technology and Metallurgy from Mercator University Duisburg.

Rudolf V. Sillen

Rudolf Sillen founded and today is the CEO of NovaCast Foundry Solutions AB, focusing on foundry technology software especially for pre-production preparation and for metallurgical process control. Rudolf Sillen is a Swedish Foundry Engineer and inventor of thermal analysis systems for gray and ductile iron and a patented process for production of compacted graphite iron “Graphyte Flow”.

Christof Heisser

Christof Heisser is the President of Magma Foundry Technologies, Inc. in Chicago, IL. Christof moved to Chicago in 1995 from Magma GmbH in Aachen, Germany. Christof received his equivalent of a Masters Degree in Foundry Technology at the Technical University of Clausthal in Clausthal/Germany.

Jorge A. Sikora
Jorge Sikora is currently a professor in the Engineering Department at the National University of Mar del Plata. Jorge is also the head of Metallurgy Division of INTEMA (Research Institute in Materials Science and Technology). He also is a researcher of CONICET (National Council for Scientific and Technical Research in Argentina)

Dr. Frans Mampaey

Dr. Frans Mampaey is currently employed at Sirris in Belgium. Frans received his Metallurgical Engineering, Master’s in Computer Sciences and his Ph.D. in Applied Sciences. Frans has written several papers that were published in the AFS Transactions. He also received the Best Paper at the GIFA 2007 Foundry Congress in Dusseldorf, Germany.

David Poerschke

David Poerschke is currently a graduate student at Case Western Reserve University in Cleveland, Ohio. David is pursuing an M.S. in Materials Science and Engineering. He received his Bachelors of Science in the same field from Case in 2008. He has worked in the Case Metal Processing Laboratory since June 2005 on metal casting and materials research.

Al Alagarsamy
Al Alagarsamy is retired but remains very active in the foundry industry in the consulting capacity. Al worked for Grede Foundry, Intermet Foundry and Citation Corporation. Al was educated both in India and in the USA in Mechanical Engineering, Foundry Science and Metallurgy. He has been working in ductile iron and gray iron foundries since 1970 in this country.

**Norberto Rizzo**

Norberto Rizzo is currently the Technical Manager at the Foundry Division of Dana Venezuela in Valencia, Venezuela. Norberto has worked at many different positions with several foundries in Argentina and Venezuela. Norberto received his Metallurgical Technician certificate in 1965 at Escuela Industrial de la Nacion, San Nicolas, Argentina and his metallurgical Engineering from the Universidad Tecnologica Nacional, San Nicolas, Argentina.
Thin-Wall Ductile Iron Castings: Technology Status 2008

Chantal Labrecque
& Martin Gagné
Rio Tinto Iron & Titanium
&
Gangjiun Liao, Wescast
Outline

• Introduction
• Production Methods
• Properties
  – Microstructures
  – Mechanical Properties
• Austempered TWDIC or TWADI
• Application Examples
• Concluding Remarks
Introduction

• Carbide-free Thin-wall ductile iron casting (TWDIC) industrial production is a reality.
• A wide spectrum of properties is achievable.
• Various processing techniques can be used.
• Detailed production methods are not readily available.

➢ Objective: Summarize published data in order to ease launching new TWDIC applications.
Production Method
Ex 1: Patented Ferritic TWDIC

- Treatment Ladle
- Mg treatment Wire Cored Mg or NiMg$_{15}$ or FeSiMg
- 1st step inoculation 0.3%wt*
- Casting Ladle
- Casting stream inoc. Up to 0.8%wt*
- Mould

* Inoculant: FeSi70%; 0.4%Ce, 0.7%Ca, 1%Al, 0.8%Bi

Ref [6]

4%C
2.5%Si
0.02%Mg

2 mm thick
6000 Nod/mm$^2$
Max size
Casting
300 x 300 x 400 mm
Production Method
Ex 2: Low Thermal Conductivity Mould

- Induction Furnace
- Mg treatment FeSiMg6%
- Tundish Ladle 1510°C
- Pouring Ladle 1415°C
- Bassin & Plug
- Mould 50% LDASC

- 35% Pig Iron
- 40% ferritic DI returns
- 25% Steel Scrap
- Graphite FeSi

- FeSi: 62-66% Si; 0.8% Al; 1.8-2.4% Ca; 0.8-1.2% RE; 0.8-1.3% Bi
- Ref [18]

- 1st step inoc: 0.75% wt FeSi
- 2nd step 0.2% inoc*

- 3.6%C
- 2.6% Si
- 0.035%Mg
- 3 mm thick
- 700 Nod/mm²

* Inoculant: Fe; 62-66% Si; 0.8% Al; 1.8-2.4% Ca; 0.8-1.2% RE; 0.8-1.3% Bi

Ref [18]
Production Method
Ex 3: Combined Mg Treatment & Inoc

- Induction Furnace
- Preheated Ladle (~1525°C)
- Mg + Inoc* (~1466°C)
- In-stream inoc**
- Sand Mould Pepset Resin

- 37% Pig Iron
- 49% DI returns
- 12% Steel Scrap
- 0.6% Carbon Raiser
- 1.1% FeSi

- 3,9%C
- 2,7%Si
- 0,04%Mg
- 2 mm thick ~2000 Nod/mm²
- 3 mm thick ~1500 Nod/mm²

* 0,4%FeSiMg3,5+ 0,26%FeSiM6%+ 0,3%FeSi75 Foundry grade (1%Al-0,6%Ca)
**Inoculant: Fe-75%Si 30 x 80 mesh

Ref [11]
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Wall</th>
<th>Mould Process</th>
<th>Casting mm</th>
<th>Pre-inoc / Pre-condition / Mg treatment</th>
<th>Inoculation Post - inoc.</th>
<th>Pour. Temp. °C</th>
<th>Nod/mm²</th>
<th>%Mg</th>
<th>%C</th>
<th>%Si</th>
<th>Yield MPa</th>
<th>UTS MPa</th>
<th>El. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>01</td>
<td>na</td>
<td>Investment casting</td>
<td>Stator 203 x 60</td>
<td>FeSi75 0,3% Zirconoc 0,2% Germalloy 0,15%</td>
<td>1550 na</td>
<td>na</td>
<td>0,055</td>
<td>3,5</td>
<td>2,6</td>
<td>444-480</td>
<td>630-670</td>
<td>6-8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>03</td>
<td>2</td>
<td>na</td>
<td>300x300x400</td>
<td>0,3%wt Sphérix transfer furnace to pouring ladle</td>
<td>Up to 0,8% wt Sphérix transfer ladle to casting</td>
<td>6000 na</td>
<td>0,02</td>
<td>4</td>
<td>2,5</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>03</td>
<td>3</td>
<td>id</td>
<td>id</td>
<td>id</td>
<td>2000 na</td>
<td>0,025</td>
<td>3,8</td>
<td>2,8</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>03</td>
<td>2</td>
<td>LDASC+ Phenolic Urethan</td>
<td>Manifold 380 L x ID 50</td>
<td>FeSi75 during Mg treatment</td>
<td>Before pouring</td>
<td>2550 na</td>
<td>na</td>
<td>3,5</td>
<td>2,4</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>8,9</td>
<td>00</td>
<td>3</td>
<td>CO₂ silica AFS GFN55</td>
<td>Step block 1 to 12</td>
<td>0,1%FeSi+0,1%SiC before tapping</td>
<td>1% in-stream+ 0,1% on filter FeSi75-BIRE</td>
<td>na 1000 na</td>
<td>3,77</td>
<td>2,73</td>
<td>345</td>
<td>517</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>02</td>
<td>1,5</td>
<td>Alkydic resin silica sand 60-62 mesh</td>
<td>Horizontal plates</td>
<td>Sandwich 2%FeSiMg9Ce 0,6%FeSi75</td>
<td>late inoculation</td>
<td>1400 Up to 2400</td>
<td>0,034-0,08</td>
<td>2,98-3,38</td>
<td>2,94-4,84</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>03</td>
<td>1,5 to 6</td>
<td>Pepset resin</td>
<td>Horizontal step and stripes</td>
<td>FeSiMg3,5 FeSiMg6 Minoc + FeSi75%</td>
<td>In stream with FeSi75 20 x80 mesh</td>
<td>1466-1438</td>
<td>2100 Ave in 1,5</td>
<td>0,04</td>
<td>3,9</td>
<td>2,7</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>12</td>
<td>03</td>
<td>2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>~450</td>
<td>~650</td>
<td>~4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>02</td>
<td>2,5 to 6</td>
<td>na</td>
<td>Vertical riser plates</td>
<td>Sandwich³ FeSiMg6%</td>
<td>Post inoc. 72Si-1,19Ca-1,17Al-1,03Ce</td>
<td>na 864 to 200</td>
<td>0,032-0,056</td>
<td>3,29-3,34</td>
<td>2,47-2,57</td>
<td>296-317</td>
<td>413-482</td>
<td>18-25</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>03</td>
<td>50%LDASC 50%Silica</td>
<td>Fig. 1</td>
<td>FeSiMg6 tundish 0,75FeSi transfer</td>
<td>0,2%Bi bearing Inoc. basin</td>
<td>1415</td>
<td>1380</td>
<td>0,035</td>
<td>3,6</td>
<td>2,35</td>
<td>340</td>
<td>550</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>07</td>
<td>3</td>
<td>Ref [18]</td>
<td>Ref [18]</td>
<td>Ref [18]</td>
<td>1450 1410</td>
<td>718</td>
<td>0,032</td>
<td>3,65</td>
<td>2,39</td>
<td>na</td>
<td>&gt;600</td>
<td>&gt;2</td>
<td></td>
</tr>
</tbody>
</table>
Properties: Microstructures

- High nodule count (NC) is required in order to avoid eutectic carbide and achieve good properties.
- The minimum NC varies accordingly to composition, inoculation, sand properties, mould design...
- Empirical models were described.
Properties: Microstructures

Empirical models: Example 1

- Min. NC vs step block thickness in order to avoid carbides [8]
  - 3 mm plate => 1000 Nod/mm²
  - 1 mm plate => 3550 Nod/mm²

Nod/mm² = 310 (section size, mm)²-2675(section size, mm) + 6177

Production method:
Charge: 93% Pig iron, 3% low Mn Steel Scrap, ferroalloys. Mg treatment
tundish with FeSiMg5,5% RE free. RE added as mischmetal. CO₂ bonded silica moulds. %C (3,65-3,95); %Si (2,4-3,4); %Mg (0,03-0,045); %Ce(0,005-0,009); %Mn<0,10. Pre-conditionning immediately before tapping and various in-stream inoculation procedures.
Properties: Microstructures

Empirical models: Example 2

- NC vs solidification time [10]
  - 1,5 mm plate => 2400 Nod/mm²

Nod/mm² = 5600 (solidification time in s)⁻⁰.⁵⁷

Production method:
Charge: Pig iron, steel scrap, returns, ferroalloys. Mg treatment with 2%FeSi9%MgCe (sandwich). Late inoculation 0,6%Fe75%Si (5-15 mesh). Alkidic resin bonded silica sand moulds. Pouring 1400°C. %C (2,98-3,38); %Si (2,9-4,8); %Mg (0,03-0,08);
Properties: Microstructures

Empirical models: Example 3

• NC vs as-cast thickness (t) [11]
  – 1.5 mm plate => 2100 Nod/mm²

  Nod/mm² = 1394 + 3000/t²

Production method:
See slide #6.
Production Method
Ex 3: Combined Mg Treatment & Inoc

Induction Furnace

Mg + Inoc*
Preheated Ladle
~1525°C

Sand Mould
Pepset Resin

~1466°C
In-stream inoc**

37% Pig Iron
49% DI returns
12% Steel Scrap
0.6% Carbon Raiser
1.1% FeSi

3.9%C
2.7%Si
0.04%Mg
2 mm thick
~2000 Nod/mm²
3 mm thick
~1500 Nod/mm²

* 0.4%FeSiMg3.5+ 0.26%FeSiM6%+ 0.3%FeSi75 Foundry grade (1%Al-0.6%Ca)
**Inoculant: Fe-75%Si 30 x 80 mesh

Ref [11]
Properties: Microstructures
Lower NC with Thermal Insulating Sand

3 mm Vertical Plates,
50%LDASC, 2.34%Si, 3.6%C,
491 Nod/mm² [18]
Mechanical Properties

Ex 1: Ferritic DI [13]

- As-cast carbide free vertical plates 2.5 to 6 mm thick
- 200 to 900 Nod/mm²
- Meet ASTM A536
- Composition range
  - C = 3.3 to 3.8%
  - Si = 2.4 to 2.8%
  - Mn = 0.2%
  - Mg = 0.03 to 0.056%

<table>
<thead>
<tr>
<th>UTS [MPa]</th>
<th>YS [MPa]</th>
<th>EI%</th>
</tr>
</thead>
<tbody>
<tr>
<td>413</td>
<td>296</td>
<td>18</td>
</tr>
<tr>
<td>482</td>
<td>317</td>
<td>25</td>
</tr>
</tbody>
</table>

Sand blasted samples
Mechanical Properties

Ex 2: Cu Alloyed Pearlitic DI [14]

- Same procedure as previous example
- Vertical plates 2.5 to 6 mm thick
- NC up to 600 Nod/mm²
- Meet or exceed ASTM A536
- Composition range
  - C = 3.3 to 3.8%
  - Si = 2.4 to 2.8%
  - Mn = 0.2%
  - Mg = 0.03 to 0.056%
  - Cu = 0.5%

<table>
<thead>
<tr>
<th>UTS [MPa]</th>
<th>YS [MPa]</th>
<th>EI%</th>
</tr>
</thead>
<tbody>
<tr>
<td>413</td>
<td>296</td>
<td>18</td>
</tr>
<tr>
<td>482</td>
<td>317</td>
<td>25</td>
</tr>
<tr>
<td>620</td>
<td>413</td>
<td>10</td>
</tr>
<tr>
<td>758</td>
<td>482</td>
<td>5</td>
</tr>
</tbody>
</table>

Fully machined samples
Mechanical Properties

Ex 3: Low %Si Pearlitic DI & 50% lined LDASC Mould [18]

- Vertical plates 3 mm thick at parting line
- 491 Nod/mm²
- Composition
  - C= 3,6%
  - Si= 2,35 %
  - Mn= 0,24%
- Meet ASTM 65-45-12

<table>
<thead>
<tr>
<th>UTS [MPa]</th>
<th>YS [MPa]</th>
<th>El%</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>340</td>
<td>12</td>
</tr>
</tbody>
</table>
Ex 4: Cu Alloyed DI & lined LDASC Mould [19]

Effect of Copper (UTS vs. Elongation)

Ultimate Tensile Strength (MPa) vs. Elongation (%)

- ASTM A-536 Quality Base Line
- %Cu=0
- %Cu=0.27
- %Cu=0.48
Mechanical Properties

Ex 4: Cu Alloyed Pearlitic DI & 50% lined LDASC Mould [19]

3 mm Vertical Plates
3.6%C, 2.4%Si, 0.49%Cu
718 Nod/mm²

3 mm Vertical Plates
3.6%C, 2.20%Si, 0.04%Cu
884 Nod/mm²
Mechanical Properties

Avenues to control mechanical properties
- Nodule Count (by late and strong inoculation)
- %Si
- %Cu
- Thermal insulating sand

Potential detrimental effects on the mechanical properties
- Too high %Si reduces low temperature impact strength and ductility
Mechanical Properties
Fatigue Endurance Limit [20]

• Tests according to ASTM E 466-96
• 4 million cycles R = 0,1
• Machined and rounded edge sample
• Samples:
  – 2 mm – 6000 Nod/mm² ( + 4 & 7 mm)
  – 3,8%C-2,9%Si-0,04%Mn-0,6% Ni
  – UTS = 574MPa; YS = 458 MPa
• Results
=> 183 MPa FEL
=> FEL decreases with increasing thickness !
⇒ size of Nodule = size of defect !!
# Mechanical Properties

## Impact [21]

<table>
<thead>
<tr>
<th>Nod/mm²</th>
<th>Upper Shelf Energy J/cm²</th>
<th>Ductile to Brittle Transition Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>18</td>
<td>-26</td>
</tr>
<tr>
<td>1770</td>
<td>16</td>
<td>-80</td>
</tr>
</tbody>
</table>

Ferritized samples
Austempered TWDIC

• Advantages of TWDIC to produce ADI
  – High NC => low diffusionnal distance for alloying elements
    • No segregation
    • Rapid austenitization
  – Very effective heat transfer during quench => min. alloying addition

=> Total treatment time was reduced to 50 min for 1,9 mm & 2000 Nod/mm² [22]
### Austempered TWDIC

- **Example of TWADI** [23]
  - 3 mm
  - 3,6% C, 2,48% Si, 0,24% Mn
  - 400-600 Nod/mm²

<table>
<thead>
<tr>
<th></th>
<th>UTS MPa</th>
<th>YS MPa</th>
<th>EI %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWDADI*</td>
<td>1160</td>
<td>900</td>
<td>7-10</td>
</tr>
<tr>
<td>TWDIC 0,5% Cu</td>
<td>758</td>
<td>482</td>
<td>5</td>
</tr>
</tbody>
</table>

*Grade ASTM A897-06M 1050-750-07*
Application Examples

Suspension Arm
PSA Peugeot-Citroen (France)

Exhaust Manifold
WESCAST (Canada)
Suspension Arm

Expected Difficulties

- Cold shuts/laps in the thinnest sections; such defects are difficult to detect when producing long series of parts.

- Obtain the desired microstructure (no carbide & <25% pearlite).

- Have good sphericity in thick section (40 mm) & meet the specified chemistry i.e. % Si < 3.1% and CE < 4.60.

- Achieve dimensional tolerances and soundness.
Suspension Arm

Problem Solving – Cold shuts/laps
Increase pouring temperature?
Augment the risk of sand defects and microshrinkage

Optimise the gating/risering system!
Cast a prototype without riser.
Redesign the gating knowing the real location of the shrinkage cavities.

No computer filling simulation but could accelerate the gating design process.
Suspension Arm: Fabrication

• Melting in Arc Furnace
• Transfer in Holding Furnace (16 t)
• Transfer in 3t Converter
• Pre-Inoculation
• Mg Treatment
  – Base Metal: %S ≤ 0,010%
  – Pure Mg and Minimum Mg Content
Suspension Arm: Fabrication

- Transfer in 8t Chanel Furnace with Neutral Atmosphere
- **Inoculation**
  - 1st step: in the automatic pouring vessel with 0,15% FeSi(Bi)
  - 2nd step: in-mould with 0,15% FeSi(Bi)
## Suspension Arm

<table>
<thead>
<tr>
<th>Element</th>
<th>4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.46</td>
</tr>
<tr>
<td>S</td>
<td>0.003</td>
</tr>
<tr>
<td>Si</td>
<td>2.94</td>
</tr>
<tr>
<td>Mg</td>
<td>0.040</td>
</tr>
<tr>
<td>P</td>
<td>0.017</td>
</tr>
<tr>
<td>Mn</td>
<td>0.16</td>
</tr>
<tr>
<td>Cu</td>
<td>0.003</td>
</tr>
<tr>
<td>Al</td>
<td>0.014</td>
</tr>
<tr>
<td>C.E. *</td>
<td>4.45</td>
</tr>
</tbody>
</table>
### Suspension Arm Microstructure

<table>
<thead>
<tr>
<th>Nod. / mm²</th>
<th>% Graphite</th>
<th>% Nodularity</th>
<th>% Pearlite</th>
</tr>
</thead>
<tbody>
<tr>
<td>455 ± 45</td>
<td>12</td>
<td>94</td>
<td>5</td>
</tr>
</tbody>
</table>
## Suspension Arm Mechanical Properties

4 mm thick

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS* [MPa]</td>
<td>448 ± 4</td>
</tr>
<tr>
<td>YS* [MPa]</td>
<td>310 ± 22</td>
</tr>
<tr>
<td>% El * [%]</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>VHN (100 gf)</td>
<td>183</td>
</tr>
</tbody>
</table>
Suspension Arm
Comparative study of three point bending fatigue of 6 and 4 mm suspension arms

Samples Dimensions 31.7 mm x 12.7 mm x 3.5 mm
Stress Ratio R ($\sigma_{\text{min}}/\sigma_{\text{max}}$) = 0.1
Loading Frequency = 30 Hz (sinusoidal Wave)
Fatigue Limit Calculated for $2 \times 10^6$ Cycles for max. stress. Validation Test at $10 \times 10^6$ Cycles

<table>
<thead>
<tr>
<th></th>
<th>50 % Survival Rate (MPa)</th>
<th>90 % Survival Rate (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>466</td>
<td>441</td>
</tr>
<tr>
<td>6 mm</td>
<td>472</td>
<td>459</td>
</tr>
</tbody>
</table>
Suspension Arm

- The manufacture of 4 mm thick DI suspension arms is feasible when high metallurgical quality iron and carefully control processes are utilized.

- The tensile properties of the parts exceeded the minimum values specified for the GS 420-12 grade. UTS was 448 MPa and elongation was 18 %.

- The three points bending fatigue of as-cast 4 mm thick DI is comparable to that of 6 mm when the property is measured on samples machined to a thickness of 3.5 mm.
Exhaust Manifold
Turbo-Manifold

- An **exhaust manifold** is a component mounted to a cylinder head.
- It is used to collect exhaust gases from each cylinder and direct them to a common system whereby gases are treated to remove harmful emissions before being released from the vehicle.
- An **integrated turbo-manifold** is a manifold and a turbine housing designed as one single component/module.
- This integrated approach yields benefits where tight packaging constraints exist, eliminates an assembly operation as well as reduces the potential for leakage between exhaust components.
### Composition wt% of Alloyed TWDIC

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Si</th>
<th>Mo</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Mg</th>
<th>Ni</th>
<th>Cr</th>
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</thead>
<tbody>
<tr>
<td>SiMo</td>
<td>3.4</td>
<td>4.0</td>
<td>0.6</td>
<td>0.45</td>
<td>0.016</td>
<td>0.01</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5-S</td>
<td>2.0</td>
<td>5.1</td>
<td></td>
<td>0.72</td>
<td>0.009</td>
<td>0.013</td>
<td></td>
<td>34.5</td>
<td>1.83</td>
</tr>
</tbody>
</table>
SiMo Microstructures

4 mm thick SiMo Manifold

Fine Moly-rich Precipitates
D5S Microstructures

Chromium Carbides
# Mechanical Properties of Alloyed TWDIC

<table>
<thead>
<tr>
<th>Materials</th>
<th>Room Temperature</th>
<th>at 800°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UTS MPa</td>
<td>YS MPa</td>
</tr>
<tr>
<td>SiMo</td>
<td>592</td>
<td>451</td>
</tr>
<tr>
<td>D5S</td>
<td>489</td>
<td>224</td>
</tr>
</tbody>
</table>
# Microstructural Analysis of Manifolds

<table>
<thead>
<tr>
<th>Materials</th>
<th>Thick.</th>
<th>Nod %</th>
<th>Nod /mm²</th>
<th>Precipitates %</th>
<th>Primary carbides %</th>
<th>G %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiMo</td>
<td>4 mm</td>
<td>98</td>
<td>573</td>
<td>16</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>12 mm</td>
<td>95</td>
<td>486</td>
<td>20</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>D5S</td>
<td>4 mm</td>
<td>90</td>
<td>909</td>
<td></td>
<td>5.3</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>12 mm</td>
<td>93</td>
<td>522</td>
<td></td>
<td>5.5</td>
<td>4.6</td>
</tr>
</tbody>
</table>
SiMo & D5S Durability Test

- Durability tests of a truck manifold were performed on the EES (Engine Exhaust Simulator) for the different materials.

- The test was cyclic heating and cooling with 1030°C EGT (Exhaust gas Temperature) and 860-870°C PMT (Peak Metal Temperature).
SiMo & D5S Durability Test

It is found that D5S (NiResist) has much higher cycles to failure than ferritic Ductile Iron (SiMo). Austenitic stainless steel has the longest life in this test condition.
Concluding Remarks

• The manufacture of TWDIC is technically feasible when state-of-the-art foundry practices are utilized.

• Many production routes and chemical compositions can be employed to achieve as-cast carbide free TWDIC.

• The as-cast mechanical properties meet or exceed the ASTM A536 specifications, either for the high ductility grade (60-40-18) or the high strength one (80-55-06).

• The impact and the fatigue properties of the TWDIC are equivalent to the properties of the DI cast in thicker section size.

• ADI, SiMo and D5-S alloyed Ductile Irons can also be produced successfully.

• NC can be controlled by the inoculation technique and/or the type of inoculant and/or the use of insulating sand.
Concluding Remarks

• The minimum NC necessary to ensure a carbide free structure is difficult to clearly establish since it depends on the solidification rate which is controlled by the geometry of the casting and the type of mould (sand type, mould coating, etc.)

• Hence, carbide free structures were reported for nodule counts in the range of 500 Nod/mm² in 2,5 mm plate. It was also possible to get 6000 Nod/mm² in 2,5 mm.
ACKNOWLEDGMENTS

• The authors wish to thank PSA-Peugeot Citroën (France) for their collaboration regarding the industrial castings fabrication and properties.
The use of oxygen activity measurements to determine compacted graphite structure

Frans Mampaey
Sirris, Belgium

D. Habets, J. Plessers, F. Seutens
Heraeus Electro-Nite, Belgium
Outline

• Background
• Previous work on ductile iron
• Experimental Results
• Two Step method
• Accuracy of sensor
• Conclusions
Background

• Higher peak pressures during combustion in diesel engines
  → Improvement of the fuel economy
  → Diminish the harmful components in the exhaust gases
• Current aluminum alloys and lamellar graphite cast iron have reached their mechanical limits
• Compacted graphite iron with pearlitic matrix has a yield strength of 350 MPa
Compacted graphite iron

- Small production window
- Production control
  - Thermal analysis
  - Acoustic resonance analysis
  - Oxygen activity measurement
Previous work on ductile iron

- Necessity to recalculate all oxygen activities to a reference temperature (1420°C).
- Nodularity
  Particles with length to thickness ratio < 2
Previous work on ductile iron

- Nodularity maximum at the same oxygen activity
- Maximal nodularity and ferrite content (→ ferritic thick wall castings)

What about CGI?
Goal of the present research

Examine if a useful relation can be established between oxygen activity and the production window for compacted graphite cast iron.
Experimental procedure

- Add Mg-wire to a melt (220 kg) – keep the melt at constant temperature (1420°C)
- Measure oxygen activity
- Regularly pour Y-blocks → mechanical properties + graphite morphology + ferrite/pearlite
- Sorel iron – Cu, Mn, Sn (Pearlite increase)

Follow transition from ductile iron (too low Mg) → compacted graphite cast iron → lamellair graphite cast iron
Ferritic matrix

- Sudden drop of elongation and tensile strength (advantage of the ferritic matrix)
- In the vicinity of the transition, nodularity often hardly changes
- ISO Standard
Mg fade (and $a_O$) may be discontinuous as a function of the time (depending on furnace power on/off)

→ plot properties as a function of $a_O$
Ferritic matrix

- Lower values of nodularity occur when initially less magnesium is added.
- Open symbols do not comply with the ISO standard.
• The previous experiments also show that mechanical properties are needed to determine if a Y-block meets the ISO requirements. Examination of the graphite structure alone is not sufficient.
• Extra Y-blocks poured after an extra magnesium addition to the melt, are in line with the ‘normal’ data
Pearlitic matrix

- ISO Standard 16112/JV/500/S
  Tensile Strength 500 N/mm²
  Yield strength 350 N/mm²
Pearlitic matrix

Pearlitic (red)
Ferritic (black)

Left of the vertical line, minimal mechanical properties for compacted graphite are met.
Influence of repeated Mg additions

- Ferritic matrix
- Si $2.0 \rightarrow 3.0\%$
Influence of repeated Mg additions

- Previous results (black)
- All points shown comply with the ISO standard
Influence of inoculant type and sulfur

- General purpose inoculant (Zr)
- Ce-Bi based inoculant
- Extra addition of sulfur
  (30 → 80 ppm)
Influence of inoculant type and sulfur

- Ce-Bi based inoculant (red) previous results (black)
- Extra addition of sulfur (S3)

The addition of fresh sulfur results in lower nodularity at a certain oxygen activity
One step Mg method

- Industrial melt contains S and oxides (variable amount) which consume Mg

- Not suited for the small production window of CGI
Two step Mg method

• First Mg addition → too low a Mg content to produce CGI
• Measure oxygen activity
• (Target – measured) oxygen activity → length of Mg wire
Two step method

Total wire length = length 1$^{st}$ addition plus length 2$^{nd}$ addition

→ Unique curve
Two step method

Add Mg

Measure $a_o$

Length 2\textsuperscript{nd} addition
Accuracy and Reproducibility

Gray iron

<table>
<thead>
<tr>
<th>ppb</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.69</td>
</tr>
<tr>
<td>300</td>
<td>11.1</td>
</tr>
<tr>
<td>1000</td>
<td>36.9</td>
</tr>
</tbody>
</table>

Ductile iron

| 104 | 3.73 |
Conclusions

• A new sensor for oxygen activity
• A well defined oxygen activity for the upper limit of CGI (380 ppb)
• $a_O > 380$ ppb: min values of ISO standard, are not met anymore
• $a_O < 380$ ppb: range of nodularities exists, lower ones for higher S content
• Measurement is easy and quick (12 s)
Solution strengthened ferritic ductile iron ISO 1083/JS/500-10 provides superior consistent properties in hydraulic rotators

Dr. Richard Larker
Indexator AB, SWEDEN
Indexator AB is a leading OEM producer of hydraulic rotators (>15,000/year) for forestry, piece goods & recycling, and of tiltrotator Rototilt® (>3,000/year) for excavator versatility.

Swedish family-owned SME; turnover $70M; 220 employees

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
Currently used major materials in our products:

Rotators: *Ductile iron* >1.300 tonnes/year (≈1% of 1% of the global DI production!); currently *conversion* from ferritic-pearlitic to *Si-solution strengthened ferritic DI*.

Rototilt: *Red* worm gear rotor housings are cast in *Si-strengthened ferritic DI*; *black interfaces* to excavator and tools are *today in welded steel* (sheet + castings), but will at least partially be *replaced by Ausferritic DI (ADI)*.
Our first product in Si-solution strengthened DI:

Swivel housing (138 kg) cast **2005** in ISO 1083/JS/500-10 (3.7-3.8% Si) for a rotator, integrated in a 5-claw recycling grapple for 20 tonne loads.
Why replace ISO 1083/JS/500-7 with JS/500-10?

Five seal grooves in the hydraulic swivel puts very high demands on tight machining tolerances <20 µm.

JS/500-7 gave:
- Tolerances often out of spec., since hardness variations of 30-60 Brinell units consume whole tolerance range!
- High reject rate

JS/500-10 gives:
- Consistent properties (in HBW, etc)
- Tolerances within specification
- Costs <80% (time + tool wear + reject)
"Family" of **structurally strengthened** ductile irons:

Conventional ferritic-pearlithic iron ISO 1083/JS/500-7 shows large variations in properties due to **varying pearlite content**:

- **JS/400-18:**
  - 95% ferrite
  - 5% pearlite
  - $H = 155 \pm 25$ HBW
  - $R_{p0.2} \geq 250$ MPa
  - $R_m \geq 400$ MPa
  - $A_5 \geq 18\%$

- **JS/500-7:**
  - 50% ferrite
  - 50% pearlite
  - $H = 200 \pm 30$ HBW
  - $R_{p0.2} \geq 320$ MPa
  - $R_m \geq 500$ MPa
  - $A_5 \geq 7\%$

- **JS/700-2:**
  - 5% ferrite
  - 95% pearlite
  - $H = 265 \pm 40$ HBW
  - $R_{p0.2} \geq 420$ MPa
  - $R_m \geq 700$ MPa
  - $A_5 \geq 2\%$
Si-solution strengthened 100% ferritic DI:

Properties in 50 mm walls from four (4) first samples:

\[ R_{p0.2} = 402 - 415 \text{ MPa} \quad (\geq 360) \]
\[ R_m = 515 - 534 \text{ MPa} \quad (\geq 500) \]
\[ A_5 = 19.5 - 23.8\% ! \quad (\geq 10) \]

(standard minimas within parentheses).

Standardized as SS 140725 (1998)
& as ISO 1083/JS/500-10 (2004)
Hardness variation reduces by -75%, from ±10 HBW to ±2.6 HBW.

Machinability increase by 20-30%.

Swivel housing for Rotator IR 10; 36 kg casting in

ISO 1083/JS/500-7 "SS 0727"
conventional ferritic-pearlitic ductile iron

Gable: 201, 207, 201, 207, 212, 212, 179, 192, 212 HBW
Flange: 197, 201, 197, 192, 187

ISO 1083/JS/500-10 "SS 0725"
100% ferritic ductile iron

Flange: 192, 192, 192, 192 HBW
Data from one year production of 933 parts, cast at 15 dates:

Hardness level increases linearly with % Si \( (H = 54 + 37 \times \%Si) \), & hardness scatter is drastically reduced (usually ±5 HB-units).
Strength levels vs. % Si during one year production:

- Linear (R_m = 92.9 x Si% + 187) \( R^2 = 0.23 \)
- Linear (R_p0.2 = 138 x Si% - 127) \( R^2 = 0.37 \)

Strength levels increase linearly with % Si; \( R_{p0.2}/R_{m} \approx 0.8 \) (not 0.6).
Ductility level vs. % Si during one year production:

Fracture elongation $A_5$ [%]

$A_5 = -3.23 \times \% Si + 34.7$

$R^2 = 0.01$

Silicon content [wt%]

- SLR1 production Y-block Fracture elongation [%]
- SLR1 production part Fracture elongation [%]
- SLR1: 1st sample Fracture elongation [%]
- SLR2: 1st sample Fracture elongation [%]
- SLR3: 1st sample Fracture elongation [%]
- Vermicular graphite in one 1st sample from SLR1

$A_5=10\%$, in spite of "CGI structure"!

Ductility is *doubled* vs. JS/500-7 & decreases linearly with % Si.
Comparison between JS/500-10 and JS/500-7:

<table>
<thead>
<tr>
<th>Elongation (%)</th>
<th>Tensile strength, 0.2 % Proof strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>116 Lynchburg:</td>
</tr>
<tr>
<td>8</td>
<td>vs.</td>
</tr>
<tr>
<td>10</td>
<td>408 Lynchburg:</td>
</tr>
<tr>
<td>12</td>
<td>Consistent properties!</td>
</tr>
<tr>
<td>14</td>
<td>Scatter in ductility may, without pearlite, be attributed to graphite &amp; porosity.</td>
</tr>
<tr>
<td>16</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

GJS-500-10 Rm
GJS-500-10 Rp
GJS-500-7 Rm
GJS-500-7 Rp

Courtesy: Joop Kikkert, Componenta [16]
Comparison between JS/500-10 and JS/500-7:

Concurrent improvements in yield strength and ductility!

Courtesy: Joop Kikkert, Componenta [16]
**Prevailing misconceptions** about raised Si-levels in DI:

**#1:** "**High Si-levels makes ductile iron more brittle** …”

Already in the first ductile iron US Patent by Millis et al in 1949 [1], it was stated that “… increasing the silicon content over these amounts (>2.5%) apparently lowers the mechanical properties, especially toughness, tensile strength and/or ductility …”.

However, **all** iron alloys containing >2.5 wt% Si in their Tables V-VI (6 out of 54 alloys) **concurrently contained ≥0.8 wt% Mn, stabilizing pearlite!**

This makes the conclusion about Si doubtful, especially since it was also stated that “It is more preferred that the manganese content not exceed 0.3%, particularly when good ductility and/or high impact properties are desired”.

High Mn levels (≥0.8 wt%) were probably also **responsible for low ADI ductilities (0.5-1.5%)** obtained in the pioneering austempering trials described in Table XIV of the same patent.
There is **no doubt that solution strengthening by silicon has negative effects on reducing the impact energy of ferrite** and increasing the notch-impact transition temp. *N.B. Strain rates ≥5000 X slower in applications!*

This fact has commonly been presumed to represent a serious limitation, obviously *without considering that* the alternative & conventional path to reach higher strengths, namely to have a matrix with a substantial amount of harder but **brittler pearlite also reduces notch-impact properties!**

At the *same* tensile strength level (500 MPa), ductile iron matrices with Si-solution strengthened ferrite vs. conventional structurally strengthened ferrite-pearlite show **similar Charpy behavior & energy levels** (while ferritic irons with lower Si & strength do show higher impact energies).

Regarding application-relevant properties **fatigue strength is at least equal**, **fracture toughness** by $J_{IC}$ & instrumented Charpy is **slightly higher**, and as previously shown, **ductility is considerably improved!**

**Pearlite content embrittles far more at equal strength level!!**
Prevailing *misconceptions* about raised Si-levels in DI:

#2: ”High Si-levels increase risk for *chunky* graphite”

The chunky graphite shape (instead of nodular) that may form in the interior of thicker castings may reduce $A_5$ & $K_{IC}$ by -50% and $R_m$ & $R_{fatigue}$ by -25%.

However, thicker castings are *usually loaded in bending* (not uni-axial tension), leading to *lower stress levels in the interior* where chunky graphite may form.

Further, according to the recent Swedish Dr.-Eng. Thesis by R. Källbom, "*Chunky graphite in heavy section ductile iron castings*" (2006) [10], the main reason is a too low oxygen content locally in the melt, that can also be caused by other strong oxide formers like Ce & other RE, by Al & Ca.

To prevent chunky, it is recommended to **aim for a high nodule count**, to **use chills** (increased Si content reduces risk of white solidification!), to **avoid large risers** (partly substituted by less expensive chills!), and to **have balanced Ce + Sb contents**.
Recent "porosity vs. Fe$_3$C" problem in JS/500-7:

Large cooling chills were used to avoid *shrinkage porosity in insufficiently fed* outer tilt axle ears.

This resulted in **white** solidification (cementite Fe$_3$C), making it brittle & very difficult to machine (400 HBW).
This is avoided when cast in JS/500-10, since *silicon promotes grey solidification* (graphite).

⇒ Greater freedom to use cheap chills, reducing costly feeders!

Earlier shake-out (<750ºC) may also be possible, since matrix will always be ferritic, independent of cooling rate at lower T!

Another advantage: While pearlite-containing iron castings get a decarburized surface zone with lower strength (being ferritic with low Si), ferritic DI solution strengthened by silicon *retains its strength out to the casting surface*, being especially valuable when as-cast surfaces are subject to fatigue loading.
Real obstacles for Si-solution strengthened DI:

#1: Large *holding furnaces* cause difficulties for large Si changes (2.4%<=3.7% Si) between batches of different DI grades.

#2: Increased need for low-alloyed scrap (esp. low Mn), and maybe also some hypo-eutectic pig iron to keep CEL down when Si is raised.

#3: Lack of insight that the *total production cost* for manufacturing by machining of castings *is the sum of three (3) categories* [11]:

A. **Purchase price** (model cost + running part cost);

B. **Production cost** (strongly governed by *consistent* HBW & machinability);

C. **Non-conformance cost** (interruptions & rejects related to castings, see B).

#4: **Conservatism & Lack of knowledge** at foundries & customers.
Other "members" in Si-solution strengthened DI "family":

SS 140720 (3.2 % Si), standardized 1998 in Sweden: (typical values)

\[ R_m \geq 450 \text{ MPa (470-500)}; \quad R_{p0.2} \geq 310 \text{ MPa (70\% of } R_m\text{)} (350-380); \]
\[ A_5 \geq 12\% (18-26); \quad H = 165-195 \text{ HBW (170-180)}. \]

Test result with 4.44 wt% Si in thick sections:

\[ R_m = 677 \text{ MPa}; \quad R_{p0.2} = 557 \text{ MPa (83\% of } R_m\text{)}; \quad A_5 = 12.2\%; \quad H = 217 \text{ HBW}. \]

Compare with pearlitic-ferritic ISO 1083/JS/600-3 (with \( R_{p0.2} \geq 370 \text{ MPa} \))
and with fully pearlitic ISO 1083/JS/700-2 (with \( R_{p0.2} \geq 480 \text{ MPa} \))

Typical data for SiMo irons (3.7-5.2% Si + 0.6-0.9% Mo) for high temp. use:

\[ R_m = 610-790 \text{ MPa}; \quad R_{p0.2} = 460-630 \text{ MPa}; \quad A_5 = 16-7\%. \]

Some increase in strength & decrease in ductility are here due to Mo carbides.
Conclusions:

For ductile irons with R_m = 500 MPa, **ductility is doubled** in Si-solution strengthened ferritic vs. conventional ferritic-pearlitic, combined with a **concurrent increase in** R_{p0,2}, raising R_{p0,2}/R_m ratio from 0.6 to 0.8. Impact energy behavior is **comparable** & fracture toughness is **slightly better** vs. ferritic-pearlitic irons.

Ferritic ductile irons, solution strengthened by silicon to various superior combinations of mechanical and machining properties, ought to be entitled **“Second generation of ductile irons”**.

The approaching **“paradigm shift”** towards the 2^{nd} generation of ductile irons will, together with continued development of ausferritic ductile irons (ADI), further **strengthen the cost-effectiveness of ductile irons & facilitate Lean Production**.
Thanks for Your attention!

For additional information, please contact:

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U.S. Ductile Iron Metalcasting: Competing Globally

Al Spada, AFS, MODERN CASTING & ECS
Chandra Rajan, Foseco Metallurgical
Patrico Gil, Blackhawk de Mexico
Anatomy of the Presentation

• U.S. Metalcasting Profile & Forecast
  – Spada
• Global Profile
  – Spada
• Europe & Asia
  – Rajan
• Latin America
  – Gill
Profile of the U.S. Metalcasting Industry

2130 Casting Facilities
- 700+ Ferrous;
  1400+ Nonferrous
- Employs More Than 200,000
- 80% Are Small Businesses
  (less than 100 employees)
- 2007: Adjusted to $31.8 Billion; 13 Million Tons
- 2008: Adjusted to $31.5 Billion; 12.6 Million Tons
- 2nd in Production
U.S. Production

- 1955—6150 Plants
- 1991—3200 Plants
- 2008—2130 Plants
- From ’91-’07, production capacity off only 4%
- From ’91-’07, Alum growth at 80%+
- From ’91-’07, Mg growth at 300%+
- Greater number of castings produced today than in ‘91
# 2008-09 Capacity & Utilization

<table>
<thead>
<tr>
<th>Metal</th>
<th>Capacity (Tons)</th>
<th>Utilization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>11,100,000</td>
<td>78</td>
</tr>
<tr>
<td>Steel</td>
<td>1,650,000</td>
<td>80</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2,550,000</td>
<td>80</td>
</tr>
<tr>
<td>Copper Base</td>
<td>370,000</td>
<td>85</td>
</tr>
<tr>
<td>Magnesium</td>
<td>170,000</td>
<td>76</td>
</tr>
<tr>
<td>Zinc/Lead</td>
<td>350,000</td>
<td>85</td>
</tr>
<tr>
<td>Other Nonferrous</td>
<td>70,000</td>
<td>87</td>
</tr>
<tr>
<td>Investment</td>
<td>190,000</td>
<td>76</td>
</tr>
<tr>
<td>TOTAL</td>
<td>16,470,000</td>
<td>79</td>
</tr>
</tbody>
</table>
2008 Shipment Mix: Tons

- Ductile Iron: 33%
- Gray Iron: 33%
- Alum: 16%
- Copper: 2%
- Zinc: 2%
- Mag: 1%
- Other: 4%
- Steel: 9%
Casting End-Use Markets

- Car/Truck: 31%
- Constr., Mining, Oil Field: 6%
- Int Comb Eng: 5%
- Valves: 5%
- Pipe & Fittings: 15%
- Municipal: 3%
- Spec Ind: 3%
- Railroad: 6%
- Farm Mach: 4%
- Other: 19%
- Pumps & Comp: 3%

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
Projected Shipments
(all metals)

• 2009: 12.8 million tons
  $32 Billion in sales
• 2011: 13.1 million tons;
  $33.7 Billion in sales
• 2018: 14 million tons
  $42 billion in sales

Forecast based on GDP, housing starts, auto, railcar and truck production, construction activity, end-user and supplier interviews.
Shipment Forecast Through 2017

U.S. Shipments
Thousands of Tons

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
Gray & Ductile Iron

- 2008 Shipments: 4.125 million tons gray iron (-3.8%); 4.084 million tons ductile iron (-2%)
- 2009 Forecast: 4.234 million tons gray; 4.236 million tons ductile
- 2018 Forecast: 4.138 million gray (0.3% AGR); 4.761 million ductile (1.6% AGR)
DI Markets (STG ’08-’10/LTG to ‘18)

- Construction (6.3%/1.8%)—replace steel, malleable, gray
- Med to Hvy Truck (39.8%/4.3%);
- Farm Equip (5.5%/0.8%)—replace gray iron
- Light Vehicles (7.9%/1.2%)—loss to alum in suspension/diff parts ad cranks to steel; gain on malleable and ADI growth
- Valves/Fittings (7.1%/1.2%)—replace malleable, gray
- Int. Com. Eng (1.8%/0.5%)—truck growth
- All Major markets show growth (7.3%/1.6%)
- 190 lb of ductile iron per vehicle in 2003 to 150 lb. by 2016
ADI & CGI

ADI: finding new inroads replacing forgings, steel weldments in farm and construction
- 200,000 tons in 2008
- 250,000 tons in 2018

CGI: Markets in motor vehicles and internal combustion engines (engine blocks and heads in diesel engines, bedplates, gear covers)
- 127,000 tons in 2008

Rangeland Planter Boot Casting redesigned from fab
DI Demand Supply in U.S.

- 2009 Vertically-Parted—1.68 million tons supply, 1.34 million demand
- 2009 Horizontally Parted—600,000 tons supply, 492,000 demand
The Switch to Aluminum

<table>
<thead>
<tr>
<th>Part</th>
<th>2005</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Block</td>
<td>50%</td>
<td>65%</td>
<td>75%</td>
</tr>
<tr>
<td>Cylinder Head</td>
<td>93%</td>
<td>97%</td>
<td>98%</td>
</tr>
<tr>
<td>Intake Manifold</td>
<td>33%</td>
<td>24%</td>
<td>17%</td>
</tr>
<tr>
<td>Wheels</td>
<td>75%</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>Suspension</td>
<td>30%</td>
<td>50%</td>
<td>60%</td>
</tr>
</tbody>
</table>

130 lb Al Castings/vehicle in 1992; 260 lb. in 2007; 280 lb by 2016

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost (EUR/Tonne)</th>
<th>Cost (USD/KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>.05 EUR/KWh (.08 $/KWh)</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>22.18 EUR/m3($10/ decatherm)</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>.22 EUR/l ($1.30/gallon)</td>
<td></td>
</tr>
<tr>
<td>Coke 80+</td>
<td>414 EUR/tonne ($600/short ton)</td>
<td></td>
</tr>
<tr>
<td>Steel Scrap</td>
<td>622 EUR/tonne ($900/short ton)</td>
<td></td>
</tr>
<tr>
<td>Pig iron</td>
<td>518 EUR/tonne ($750/short ton)</td>
<td></td>
</tr>
</tbody>
</table>
Imports & Globalization
Imports 2008

3+ million tons of castings
23% of demand (from 7% in 1998)
Imports to U.S. By Market: 2008

- Motor Vehicle: 1,446,000 tons (39.8%)
- Internal Combustion Engines: 379,000 tons (11.1%)
- Farm Equip.: 101,000 tons (2.7%)
- Railroad: 153,000 tons (4.2%)
- Municipal: 310,000 tons (8.5%)
- Valves & Fittings: 308,000 tons (8%)
- Contruc., Mining & Oil: 171,000 tons (4.8%)
- Other: 661,000 tons (20.9%)
- Other: 661,000 tons (20.9%)

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
## Global Production

(in 000s metric tons)

<table>
<thead>
<tr>
<th>Material</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray Iron</td>
<td>40,435</td>
<td>40,788</td>
<td>42,539</td>
</tr>
<tr>
<td>Ductile Iron</td>
<td>18,706</td>
<td>19,591</td>
<td>21,685</td>
</tr>
<tr>
<td>Mall. Iron</td>
<td>1,122</td>
<td>1,233</td>
<td>1,150</td>
</tr>
<tr>
<td>Steel</td>
<td>6,594</td>
<td>9,002</td>
<td>9,938</td>
</tr>
<tr>
<td>Cu-base</td>
<td>1,239</td>
<td>1,511</td>
<td>1,485</td>
</tr>
<tr>
<td>Aluminum</td>
<td>10,357</td>
<td>11,718</td>
<td>12,278</td>
</tr>
<tr>
<td>Mag</td>
<td>134</td>
<td>239</td>
<td>1,256</td>
</tr>
<tr>
<td>Zinc</td>
<td>907</td>
<td>936</td>
<td>941</td>
</tr>
<tr>
<td>TOTAL</td>
<td>79,745</td>
<td>85,741</td>
<td>91,368</td>
</tr>
</tbody>
</table>
Global Production 2006 (metric tons)

1. China: 28.1 million—26,000 plants
2. U.S.: 12.5 million—2190 plants
3. Japan: 7.9 million—1701 plants
4. India: 7.2 million—4750 plants
5. Russia: 6.9 million—1900 plants
6. Germany: 5.5 million—619 plants
7. Brazil: 3.1 million—1372 plants
8. Italy: 2.6 million—1171 plants
9. France: 2.4 million—469 plants
10. Korea: 1.9 million—851 plants
The Global Pie

- China: 31%
- U.S.: 14%
- Brazil: 3%
- EU: 17%
- India: 8%
- Japan: 9%
- Other Asian: 6%
- Others: 14%
- Russia: 7%
- Eastern Europe: 2%

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Comparison of Casting Labor/Benefit Rates 2008

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Co-Sponsored by DIS and AFS
Global Production Per Plant

- Germany: 8,854
- U.S.: 5,739
- France: 5,077
- Japan: 4,662
- Korea: 2,713
- Italy: 2,252
- Brazil: 2,250
- India: 1,511
- Mexico: 1,117
- China: 1,081
Metalcasting Around the Globe

EUROPE
ASIA
ROW
LATIN AMERICA
Germany

- Capacity Utilization: 92% for ductile iron, 83% for gray iron, 90% for aluminum; Maybe Higher, very mature
- **2007:** 1.5 million tons ductile, 2.4 million gray, 730,000 aluminum
- Highest productivity per plant by 30%
- Forecast to 2017: Total same, growth in DI and alum, loss in gray
Ductile Iron Castings
Share of Production Total

Source: CAEF, * = 2004

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Production of Ductile Castings in the European Foundry Industry

- Great Britain: 2.0%
- Germany: 11.5%
- Spain: 35.5%
- Turkey: 73.6%

Source: CAEF
Turkey

- 1262 Plants (7th most in world), 1.2 million tons production (13th in the world)
- Capacity Utilization: 83% for ductile, 77% for gray iron, 78% for aluminum
- Doktas Group: Now Part of Componenta (second largest Europe Group)
- One of the youngest workforces in the world
Russia

- Produced 26 million tons in 1991 as Soviet Union; 7 million tons in 2007 just as Russia
  - 3.8 million gray
  - 850,000 ductile
  - 1.1 million aluminum
- Suppliers love the possibilities
- Forecast to 2017: growth to 8+ million tons (more than 1% per year)
Japan

- Mature market—in 2007, 7 million tons
  - 2.86 million gray
  - 2.1 million ductile
  - 1.56 million aluminum
  - Forecast 0.5% long-term growth, aluminum 1.2%
- Forecast 0.5% long-term growth, aluminum 1.2%
SWOT

• S-HIGH QUALITY AUTOMOTIVE/GREAT WORK ETHICS
• W-HIGH LABOR COSTS/SCARCE AREA
• O-OUTSOURCING FROM CHINA/TAIWAN/S.KOREA
• T-LOW COST ASIAN EMERGING LIKE INDO CHINA/RAW MATERIAL SQUEEZE
China

- 26,000 plants (50% are state-owned)
- 29.7 million tons in 2007
- 14.3 million tons gray, 7.2 million ductile, 3.8 million steel, 2.5 million aluminum
- 20+% growth from 2005-07
- Export 3.5 million tons in 2007
- Forecast to 2017: 33 million tons production (growth of 1%/yr)
SWOT OF DEVELOPED ASIA

- S - LOW LABOR COSTS/HIGH PRODUCTIVITY
- W - CONSISTENCY OF QUALITY
- O - LOW COST NEIGHBORS
- T - RISING LABOR COSTS/TRAINING COSTS/CAPTIVE DEMAND/BOYCOTT
VIETNAM-INDOCHINA-THAILAND
SWOT OF EMERGING ASIA (INDOCHINA)/EUROPE (BALKANS/STAN S)/LATIN AMERICA (COLOMBIA/CHILE)

- **S**-VERY LOW COSTS
- **W**-AVAILABILITY OF INFRASTRUCTURE/RM’S/SKILLED LABOR
- **O**-NICHE ‘COMMODITY’ CASTINGS MARKET/SPECIALTY CASTINGS
- **T**-LABOR UNREST, JIT, CASH FLOW, INTELLECTUAL PROPERTY
CHALLENGES

AND OPPORTUNITIES
Photo/Video of Indian Metalcasting
**Impressive Numbers**

- 350k hrs. to design & test.
- 47’ long, 30’ wide, 23’ tall
- 500 lbs. weld wire = 2.5 miles
- 125 gallons of paint
- 3,550 Hp engine
- 1,800 gallons diesel fuel
- 13’x5’, 11,700 lbs. tires
- 380T payload
- Tot Opr. Weight = 1.4M lbs.
- Over 300 switches/sensors
- 12 onboard computers
- 6.2M lines of s/w code (about = Space Shuttle)
- $3.5M suggested retail
- 12 truck trailers to transport

World's largest concentration
Of 797’s (~100 trucks) in Alberta, Canada Oil Sands

---

**Each 797 Takes:**

Steel Castings
+ Iron Castings
≈ 75T Per Machine

2,000 Ton /yr. to over 9,000 Ton /yr
ARE YOU READY FOR THE INFLUX & EXPLOSION OF DEMAND IN CHINA?

CAN OUR LEAD TIMES BE IN SINGLE DIGITS?
Metalcasting in Latin America
Ductile Iron in Latin America

Patricio Gil
Blackhawk de México
Latin America

33 countries
540 million people

Contribution to America
• 50% of territory
• 63% of population
• 28% of economy

(PPP: Purchasing Power Parity)
## Latin America

<table>
<thead>
<tr>
<th>Country</th>
<th>People</th>
<th>GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>32%</td>
<td>35%</td>
</tr>
<tr>
<td>México</td>
<td>20%</td>
<td>22%</td>
</tr>
<tr>
<td>Argentina</td>
<td>7%</td>
<td>12%</td>
</tr>
<tr>
<td>30 countries</td>
<td>41%</td>
<td>31%</td>
</tr>
</tbody>
</table>
Geographic Territory

USA

Argentina

México

Brazil

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
Currency Stability
Brazilian Real per US Dollar

2008 Keith Millis Symposium on Ductile Cast Iron
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Currency Stability
Argentinean Peso per US Dollar

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
Currency Stability
Mexican Peso per US Dollar

2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
World Casting Production
Thousand Metric Tons

- **DI Casting Demand in Mexico and Brazil is +65% automotive**

<table>
<thead>
<tr>
<th>Country</th>
<th>Thousand Metric Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>28,094</td>
</tr>
<tr>
<td>USA</td>
<td>12,455</td>
</tr>
<tr>
<td>Japan</td>
<td>7,928</td>
</tr>
<tr>
<td>India</td>
<td>7,179</td>
</tr>
<tr>
<td>Russia</td>
<td>6,900</td>
</tr>
<tr>
<td>Germany</td>
<td>5,481</td>
</tr>
<tr>
<td>Brazil</td>
<td>3,087</td>
</tr>
<tr>
<td>Italy</td>
<td>2,637</td>
</tr>
<tr>
<td>France</td>
<td>2,408</td>
</tr>
<tr>
<td>Korea</td>
<td>1,968</td>
</tr>
<tr>
<td>Mexico</td>
<td>1,675</td>
</tr>
<tr>
<td>Taiwan</td>
<td>1,557</td>
</tr>
<tr>
<td>Spain</td>
<td>1,330</td>
</tr>
<tr>
<td>Turkey</td>
<td>1,210</td>
</tr>
<tr>
<td>UK</td>
<td>1,100</td>
</tr>
</tbody>
</table>

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*Co-Sponsored by DIS and AFS*
## Argentina
### Main Ductile Iron Foundries

<table>
<thead>
<tr>
<th>Foundry</th>
<th>Capacity MT / Yr</th>
<th>Iron Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spicer Ejes Pesados</td>
<td>Captive 30,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Metalúrgica Tandil</td>
<td>10,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Fundición San Cayetano</td>
<td>7,500</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Dema</td>
<td>7,500</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Fundición Santiago Martínez</td>
<td>6,500</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Paraná Metal</td>
<td>6,000</td>
<td>GI &amp; DI</td>
</tr>
</tbody>
</table>

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*Co-Sponsored by DIS and AFS*
## Mexico
### Main Ductile Iron Foundries

<table>
<thead>
<tr>
<th>Foundry</th>
<th>Capacity MT / Yr</th>
<th>Iron Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cifunsa</td>
<td>250,000</td>
<td>GI+ &amp; DI</td>
</tr>
<tr>
<td>Novocast</td>
<td>70,000</td>
<td>DI</td>
</tr>
<tr>
<td>Tisamatic*</td>
<td>60,000</td>
<td>GI+ &amp; DI</td>
</tr>
<tr>
<td>Blackhawk</td>
<td>25,000</td>
<td>GI &amp; DI+</td>
</tr>
<tr>
<td>Teknik</td>
<td>9,000</td>
<td>DI</td>
</tr>
<tr>
<td>GM</td>
<td>Captive</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>VW</td>
<td>Captive</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Nissan</td>
<td>Captive</td>
<td>GI &amp; DI</td>
</tr>
</tbody>
</table>

*Note: Tisamatic is an alternate name for an iron foundry.*
## Brazil
### Main Ductile Iron Foundries

<table>
<thead>
<tr>
<th>Company</th>
<th>Capacity MT / Yr</th>
<th>Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tupy S.A</td>
<td>500,000</td>
<td>GI+ &amp; DI</td>
</tr>
<tr>
<td>Br Metals Fundições Ltda</td>
<td>120,000</td>
<td>GI &amp; DI+</td>
</tr>
<tr>
<td>Durametal S.A</td>
<td>60,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Tekfund Ind. E Com. Ltda</td>
<td>45,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Inds. Romi S.A</td>
<td>40,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Fagor Ederlan Brasileira Ltda</td>
<td>35,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Dedini S.A Industriais De Base</td>
<td>30,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Fundimig Ltda</td>
<td>25,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Fund. Sideral Ltda</td>
<td>25,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Farina S.A Componentes Automotivos</td>
<td>25,000</td>
<td>GI &amp; DI</td>
</tr>
<tr>
<td>Intercast S.A</td>
<td>25,000</td>
<td>GI &amp; DI</td>
</tr>
</tbody>
</table>
Vehicle Production in Mexico

Units

<table>
<thead>
<tr>
<th>Year</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>1,507,175</td>
</tr>
<tr>
<td>2005</td>
<td>1,607,376</td>
</tr>
<tr>
<td>2006</td>
<td>1,978,771</td>
</tr>
<tr>
<td>2007</td>
<td>2,022,241</td>
</tr>
</tbody>
</table>

Source: AMIA

+34%
Auto Parts Exported
From Mexico to USA

Million US Dlls

Source: INA
Mexican Economy
Exports

- Oil Related: 67%
- 22%
- 12%

Source: INEGI
Mexican Economy
Competitive Alternatives 2008: KPMG’s Guide
To International Business Location

Operating Cost

<table>
<thead>
<tr>
<th>City</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oklahoma</td>
<td>95.4</td>
</tr>
<tr>
<td>Houston</td>
<td>98.4</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>98.7</td>
</tr>
<tr>
<td>Montreal</td>
<td>99.1</td>
</tr>
<tr>
<td>USA</td>
<td>100.0</td>
</tr>
<tr>
<td>Milwaukee</td>
<td>101.4</td>
</tr>
<tr>
<td>Toronto</td>
<td>101.5</td>
</tr>
<tr>
<td>Chicago</td>
<td>103.5</td>
</tr>
</tbody>
</table>

Source: KPMG
Mexican Economy
Competitive Alternatives 2008: KPMG’s Guide To International Business Location

Operating Cost

-20%

Source: KPMG
Conclusions

Mexico is a good manufacturing option for North America.

Brazil is the best option for South America with good advantages for export to Europe and NA.
Gracias
The development of ADI and IDI in Italy

Enrico Veneri
Zanardi Fonderie S.p.A.
Minerbe (Verona, Italy)
ADI since 1982

Germanite
ADI 750 / 800 / 900 Mpa
Factory layout redesign for ADI started 1995
2008 Keith Millis Symposium on Ductile Cast Iron
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ADI current production

10,000 tons / y

Machined after heat treatment
2008 Keith Millis Symposium on Ductile Cast Iron
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ADI market shares in Italy

- ADI 1050: 46%
- ADI 1200: 13%
- ADI 1400: 3%
- ADI 1600: 1%
- ADI 750-800-900: 37%

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<table>
<thead>
<tr>
<th>ISO 17804: 2005 ADI CLASSIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low hardness grades</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Fatigue resistance grades</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Wear resistance grades</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
2007 RESEARCH TOPICS

• IDI : A NEW INTERMEDIATE GRADE BETWEEN PEARLITIC DUCTILE IRON AND ADI

• ADI : ROTATING BENDING HIGH CYCLES FATIGUE PROPERTIES
IDI
(Perferritic Isothermal Ductile Iron)

Pearlitic Ferritic DI

Heat treatment

Rm [MPa]

A5 [%]

ADIs

DIs

IDI

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IDI

Tentative Specification

Company STD101:2007

500X

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IDI

Tentative Specification

Company STD101:2007

IDI

500X

Perferritic matrix

GS600-3

500X

As Cast matrix

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IDI

Tentative Specification

Company STD101:2007

IDI

Perferritic matrix

500X

ADI 1050

Ausferritic matrix

500X

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IDI
Tentative Specification
Company STD101:2007

ISO 1083 : 2004
ISO 17804: 2005
IDI STD 101: 2007
IDI Process Data

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IDI
Tentative Specification
Company STD101:2007

---

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Co-Sponsored by DIS and AFS
IDI
Tentative Specification
Company STD101:2007

ISO 17804: 2005
ISO 1083 : 2004
IDI STD 101: 2007
IDI Process Data
### IDI

**Tentative Specification**

Company STD101:2007

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Relevant wall thickness</th>
<th>Tensile strength</th>
<th>0.2% Proof strength</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t</td>
<td>$R_m$ (min)</td>
<td>$R_{p0.2}$ (min)</td>
<td>$A_5$ (min)</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>N/mm²</td>
<td>N/mm²</td>
<td>%</td>
</tr>
<tr>
<td>IDI</td>
<td>t ≤ 30</td>
<td>730</td>
<td>440</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>30 &lt; t ≤ 60</td>
<td>700</td>
<td>420</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>60 &lt; t ≤ 100</td>
<td>640</td>
<td>380</td>
<td>5</td>
</tr>
</tbody>
</table>

Properties from test pieces machined from separately cast samples

---

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### Tentative Specification

**Company STD101:2007**

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Relevant wall thickness</th>
<th>Brinell hardness range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IDI</strong></td>
<td></td>
<td><strong>HBW</strong></td>
</tr>
<tr>
<td>( t \leq 30 )</td>
<td></td>
<td>240÷290</td>
</tr>
<tr>
<td>30 &lt; ( t \leq 60 )</td>
<td></td>
<td>240÷290</td>
</tr>
<tr>
<td>60 &lt; ( t \leq 100 )</td>
<td></td>
<td>220÷270</td>
</tr>
</tbody>
</table>

**Relevant wall thickness**

- \( 220 \leq t \leq 270 \) mm
- \( 240 \leq t \leq 290 \) mm
- \( 30 \leq t \leq 60 \) mm

**Brinell hardness range**

- HBW
IDI
Tentative Specification
Company STD101:2007

K on 25 mm (avg of 3)

Test temperature °C

ADI800
IDI
DI700
IDI STD101:2007

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### Tentative Specification

**Company STD101:2007**

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Relevant wall thickness</th>
<th>Typical impact resistance values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t</td>
<td>J</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>23 °C</td>
</tr>
<tr>
<td>IDI</td>
<td>t ≤ 30</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>30 &lt; t ≤ 60</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>60 &lt; t ≤ 100</td>
<td>50</td>
</tr>
</tbody>
</table>

The values in the table are the average of the three highest values of four separate tests.
IDI
Tentative Specification
Company STD101:2007

Kv on 25 mm (avg of 3)

Test temperature °C
IDI
Tentative Specification
Company STD101:2007

K at T = +23°C

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IDI

Machinability Vs ADIs

Turning : cutting speed $V_c$ vs HB

Like pearlitic grade

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IDI
(Perferritic Isothermal Ductile iron)

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IDI
(Perferritic Isothermal Ductile iron)

Machinability

GS700

IDI

ADI

Rm

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IDI
(Perferritic Isothermal Ductile iron)

Fatigue

GS700

ADI

Rm

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ROTATING BENDING HIGH CYCLES
FATIGUE PROPERTIES

INVESTIGATION ON

JS/400-18         JS/900-8
JS/700-2          STEEL 42CrMo4
IDI              JS/1050-6

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ROTATING BENDING HIGH CYCLES

FATIGUE PROPERTIES

CONSTRAINTS

1) Same foundry and heat treatment process
2) Round bar-Shaped samples → ISO17804 Type I
3) Test probe preparation :
   → ISO 1143
   → Residual Stress check
4) Calculation → ASTM E739-91
5) 5 Milion Cycles Rotating Bending Fatigue test
### Static Results

The diagram illustrates the relationship between hardness (HBW) and tensile strength (Rm MPa) for different materials. The equation provided is:

\[
Rm = 4.2 \times HBW - 308.0
\]

**Materials**
- 42CrMo4
- IDI
- JS/400-18
- JS/700-2
- JS/900-8
- JS/1050-6

**Values**
- HBW: 160, 210, 260, 310, 360
- Rm MPa: 434, 746, 734, 926, 1021, 1087, 1172

**Legend**
- Red circle: JS/400-18
- Red diamond: JS/700-2
- Blue triangle: JS/900-8
- Green square: JS/1050-6
- Black circle: 42CrMo4
- Black triangle: IDI

This data is based on the 2008 Keith Millis Symposium on Ductile Cast Iron, co-sponsored by DIS and AFS.
**ADI STATIC RESULTS**

\[ Rp_{0.2} = 3.4 \text{HBW} - 343.2 \]

---

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STATIC RESULTS

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FATIGUE RESULTS

Fatigue limit (Woheler)

\[ \sigma_{AG} = 0.65 \times \text{HBW} + 218.14 \]

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FATIGUE RESULTS

Fatigue limit (Woheler)

Mn 0.23%
160 Nod/mm²

JS/1050-6

Mn 0.17%
245 Nod/mm²

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FATIGUE RESULTS

ΔK_{TH} = 0.016\text{HBW} + 9.309

ΔK_{TH} = 0.076\text{HBW} - 6.102

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FATIGUE RESULTS

\[ \Delta K_{TH} = 0.016 \text{HBW} + 9.309 \]

\[ \Delta K_{TH} = 0.076 \text{HBW} - 6.102 \]

- **42CrMo4**
  - Mn 0.23%
  - 160 Nod/mm²

- **Mn 0.17%**
  - 245 Nod/mm²

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### ADI FATIGUE RESULTS

### ADDITIONAL CHECK

Unstable Austenite Volume (UAV)
Checked by Heat Tinting Method

Result:

<table>
<thead>
<tr>
<th>Mn</th>
<th>Nodules</th>
<th>$\sigma_{AG}$</th>
<th>$\Delta K_{TH}$</th>
<th>UAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.23</td>
<td>160</td>
<td>417</td>
<td>16.11</td>
<td>≈ 15%</td>
</tr>
<tr>
<td>0.17</td>
<td>245</td>
<td>443</td>
<td>21.97</td>
<td>≈ 0%</td>
</tr>
</tbody>
</table>
CONCLUSIONS

ADI1050 is confirmed as a competitor for Steels

High Quality Foundry    Fatigue properties

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CONCLUSIONS

HEAT TREATMENT

FOUNDRY

ADI

DESING (& Co-DESIGN)

MACHINING

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CONCLUSIONS

IDI has shown

- Good static properties
- Fatigue = Pearlitic DI
- Machinability $\geq$ Pearlitic DI
- Impact $>\$ Pearlitic DI
## UPCOMING RESEARCH TOPICS

<table>
<thead>
<tr>
<th></th>
<th>DESIGN PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRACTURE TOUGHNESS</td>
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<tr>
<td>LOW CYCLE FATIGUE</td>
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<tr>
<td>DEFECTS EFFECT ON FATIGUE</td>
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<tr>
<td>RAW SURFACE EFFECT ON FATIGUE</td>
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<tr>
<td>WEAR RESISTANCE</td>
<td>ADI vs Competitors</td>
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</tbody>
</table>

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MEETINGS - BUSINESS - PEOPLE

MEETINGS

The Ductile Iron Society Annual Meeting will be held June 3-5, 2009 at the Best Western Eden Resorts & Suites in Lancaster, PA. There will be a visit to Buck Company in Quarryville, PA.

There will also be a day long spouse tour of Amish country included with this meeting. We must have twenty registrants to do the tour. If we don't receive twenty registrations by May 1, we will have to cancel so please encourage your wife to attend. The registration fee for the wives tour is $200.00

BUSINESS

For immediate release:

**Ductile Iron micro-analysis by thermal analysis**

MeltLab Systems is pleased to announce the release of a new module in their thermal analysis system that measures and tracks many features now analyzed by time consuming micro-analysis.

Fully treated and inoculated ductile iron is poured into an industrial standard non-tellurium thermal analysis cup, and the curve is analyzed in real time as the iron solidifies. Results include nodularity, nodule count, chemical ferrite (*as opposed to loss of ferrite caused by insufficient cooling*), carbides, and shrinkage. The system not only includes the eutectic times G1 and G2 and their ratio, but also determines if the curve is hypo-eutectic, eutectic, or hyper-eutectic. A pass/fail graphic alerts operators on the nodularity status of each sample.

This system is compatible with the same hardware as previous versions of MeltLab, as well as newer systems running Windows XP. Pricing, including MeltLab converter box, starts at $16,000 - but through Tax Day 2009, the price is reduced $2,000! Using an existing MeltLab converter box will reduce costs even further.

For more information regarding system functions and capabilities, visit our web site at [www.meltlab.com](http://www.meltlab.com) or call (765) 521-3181. To request a demonstration or quotation, contact us by e-mail at [info@meltlab.com](mailto:info@meltlab.com).

{Screen shot}
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