ADI solutions in Europe

A Rimmer, ADI Treatments Limited, West Bromwich, England

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Abstract

Establishing the correct process is critical to the successful use of ADI. It requires inspection, testing and verification of the as-cast and austempered materials, and close co-operation between the component manufacturer, casting supplier, and heat treater.

The paper describes the development of an ADI casting for use in rear axle, truck suspension units. Reasons for selecting the casting process versus forging, some aspects of the new design concept, the benefits conferred by the ADI solution, and its mechanical testing, are also covered.

To meet the growing demand for the ADI process in Europe and to accommodate larger castings, special furnace plant and work handling have evolved. These and other steps to ensure the quality and security of the heat treatment service are outlined.

Introduction

Until recently production of ADI in the European Union was confined largely to major foundries with in-house austempering capability; some others outsourced to generalist heat treaters. Ten years ago austempering remained a niche process; applications were few and gross EU output was probably below 2,000 tonnes pa.

In the foundry environment ADI is not the major activity so that resources and focus for development can be difficult to justify. Arguably a specialist contractor can more readily position to optimise both the process and supply, and help grow the market for the benefit of all.

The first heat treatment facility in the EU dedicated to promoting and supplying the austempered material, was launched in 1997. Since that time ADI has made steady inroads into disparate markets. The material stimulates innovation; original design solutions can be found but just as frequently existing parts can be converted to ADI, from product designed initially for fabrication or forging, or by upgrading castings in other materials. The resulting solutions can yield cost and weight savings at the same time as enhanced performance.

In the first of three case studies the paper describes in detail the work of ZF Lemförder GmbH, Georg Fischer Automobilguss GmbH, and ADI Treatments Ltd, to re-engineer a key component for truck suspension units. In this application the designer, foundry and heat treater worked jointly to develop the solution. During the projects the partners were also willing to adjust their practice and plant to achieve final material properties and delivery targets. A large casting from a wind turbine and a rack and pinion from a mini ground excavator, further illustrate the range and flexibility of ADI as a material.

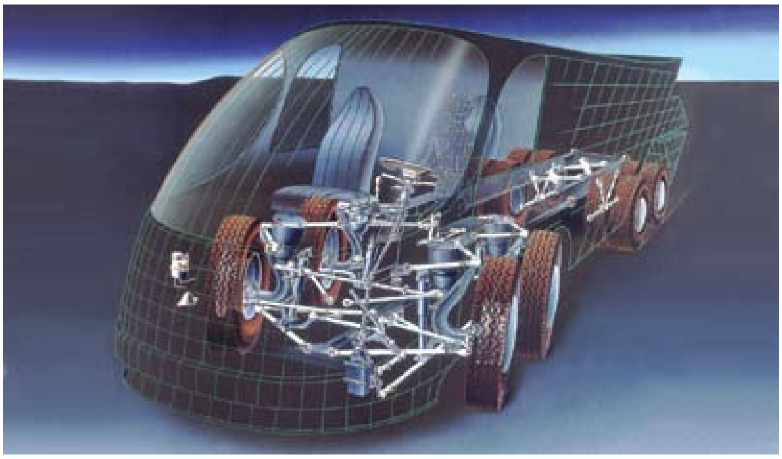


Fig. 1. A 40kg ADI casting is at the heart of this MAN truck, rear axle suspension system

ADI's recent progress in EU manufacturing is summarised with an overview of markets and volumes.

Background

ZF Lemförder was first established as 'Lemförder Metallwaren' in 1947 and was 100% acquired by ZF Group in 2003. Part of ZF's Chassis Technology Division, the company is recognised as a leader in suspension system design and production. The chassis technology operation for commercial vehicles is based in Dielingen Germany and employs 730 personnel. Worldwide ZF-Group employs 57,000.

Georg Fischer (GF) was founded in 1802. The plant in Singen Germany started manufacturing in 1895, employs 1,250 personnel and supplies automotive and truck industries throughout the world. In 2007 GF produced 217,000 tonnes of iron castings. With its record of supplying safety critical items, the foundry was a natural partner for an ADI project.

Located near Birmingham England, ADI Treatments Ltd (ADIT) was founded in 1996 under a technology transfer arrangement. The start up venture installed American austempering plant and know-how to create a centre of excellence with access to European OEMs, foundries and design houses. ADIT found its early market in small series and special components. In 2000 ownership was acquired by Hulvershorn GmbH, providing the platform to supply volume manufacturers in the EU. ZF now had a viable partner for the heat treatment.

Britain is the world leader in offshore wind energy, currently generating 404MW. This is still less than 0.5% of total UK energy consumption in 2007, compared with the 20% target set by government for renewable sources by 2020. While this might seem ambitious, any visitor to the Scottish archipelago would be impressed not only by the seascapes but also by the raw energy of the climate. There, wind and wave are highly reliable. Suitably harnessed, Scotland's resource is considered able to supply potentially 10% of Europe's entire needs.

Meanwhile oil prices continue to escalate; this appears to underwrite ventures to add wind and marine solutions to the infrastructure. At the time of writing The (UK) Crown Estate and Clipper Windpower plc have signed an agreement for The Crown Estate to purchase Clipper's prototype of the world's largest offshore wind turbine, Clipper's 7.5 MW MBE turbine; also known as the Britannia project.

Case study: ZF rear suspension system

ZF Lemförder continuously develops its suspension systems to improve ride in truck and passenger vehicles. Previously, ZF supplied vehicle manufacturers with individual trailing arms and A-arms. The original rear axle suspension configuration was a 'classic' design, tubular steel fabrication, combining the wheel linkage, torque rod and stabiliser system. ZF took the classic design as the benchmark for re-design; new thinking gave rise to the more compact 4-point link (4pl) concept (fig. 1), which was patented in 1995. The patent includes a novel axle-locating bellows-type trailing arm. This component ensures functional integration of axle location in longitudinal direction, and vertical support of the axle load.

In the 4pl suspension, welding and fabrication is eliminated and the number of components reduced; instead the coupling is provided through a singular, high strength, X-profile member or 'X-link'. By removing welding operations labour cost is lower and there is no chance of weld failure. Unlike the classic design complete systems can be delivered, reducing the customer's assembly work.

The first generation 4pl suspensions were engineered with a steel X-link, forged in 42CrMo4 Q & T. Production began in 2003; over 100,000 units had been delivered by 2006. During this period ZF worked with GF and ADIT to make additional improvements to the 4pl design, introducing the ADI cast X-link solution. Now the stabiliser and wheel systems are replaced by one casting with less mass. However compared to the forged version there is a final weight benefit of 33%. Moreover, the savings in tool costs due to casting permit the production of a range of variants. Smaller volumes can be cost-effectively produced and individual solutions for customers can be realised easier and faster. This gives rise to completely new fields of application, in buses for example. Future design changes are intended, to reduce weight elsewhere in the system.

The suspension assembly in fig. 2 is mounted on the chassis behind the cab and is available in '2 bellows', and '4 bellows' versions.

Other than the number of components in the system, and therefore cost, the main difference is ride quality. The 4 bellows version is preferred for long haul freight and intercontinental work, where driver comfort is high priority, and is incorporated typically in 5th wheel articulated designs, buses and coaches. Eventually the goal is to produce a 2 bellows system with the ride quality of a 4 bellows but with fewer parts, lower weight and cost. Weight reduction is particularly important where the chassis is concerned because unsprung mass significantly influences driving characteristics and comfort. Fewer components also mean less weight and greater payload. With higher efficiency the number of vehicles on the road can be reduced, improving the environment and benefiting those outside as well as inside the transport industry.

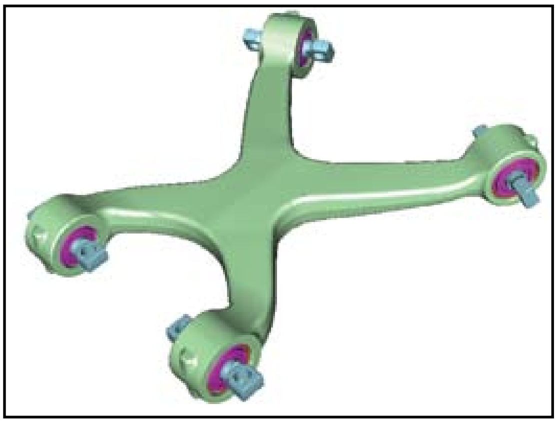


Fig. 3. The forged X-link assembly

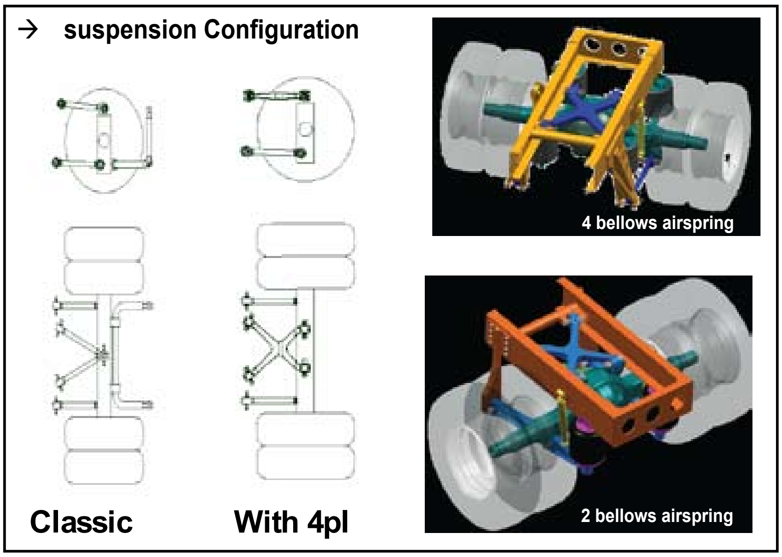


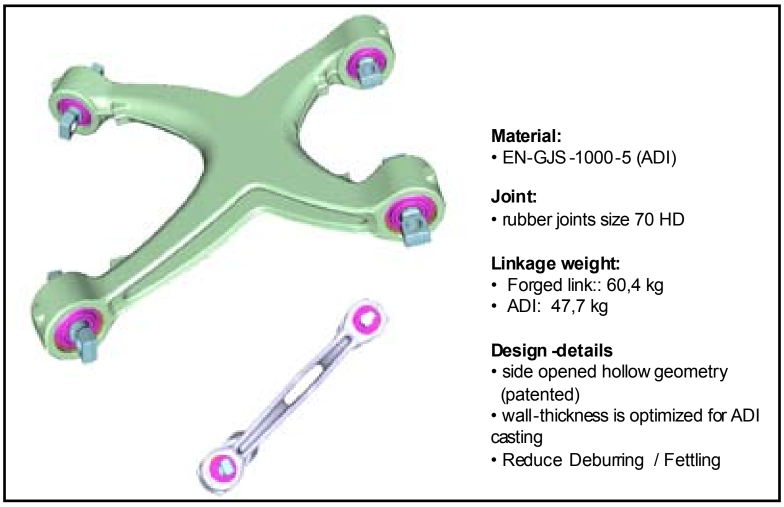
Fig. 2. The 4-pl suspension configuration

At the original design stage, and before the ADI project partners could be established, ZF was aware of casting as an option. The designers recognised the potential benefits: lower weight and energy content compared to steel, ability to cast complex shapes and thin sections, rapid prototyping, more supplier capacity, less work on casting, and less machining. In addition, casting simulation systems can be used to optimise the process for the high quality standards expected of safety critical components. Alterations to design can also be readily checked and approved using casting models, facilitating any changes to feeder systems.

As demand for the 4pl suspension increased, capacity to produce the forged X-link was becoming limited. ZF also recognised that material costs would continue to grow, as would customer expectations of performance. The new design would be required to accommodate greater loads and stresses. While considering alternative materials to replace the steel, ZF investigated whether they could further alter the design to reduce weight across the whole chassis, allowing the customer to use the solution on a wider range of vehicles. At present the 4pl suspension is used on heavy duty MAN TGA (Class 6) trucks; in future it may be possible to extend the application to the TGM (Class 2) and TGL (Class 1).

Given the above factors and the availability of the supply team, casting was seen as the correct route, and ADI the correct choice of material.

Fig. 3 shows the assembly with the original forging. The forged X-link is manufactured from quench and tempered 42CrMo4 and has a solid profile, including four 'eyes' which must be machined out to accommodate the rubber joints. When put into production the original design weighed 65.0 kg (assembled weight 60.4 kg).



Material:
- EN-GJS-1000-5 (ADI)

Joint:
- rubber joints size 70 HD

Linkage weight:
- Forged link:: 60,4 kg
- ADI: 47,7 kg

Design-details
- side opened hollow geometry (patented)
- wall-thickness is optimized for ADI casting
- Reduce Deburring / Fettling

Fig. 4. Assembly with ADI cast X-link

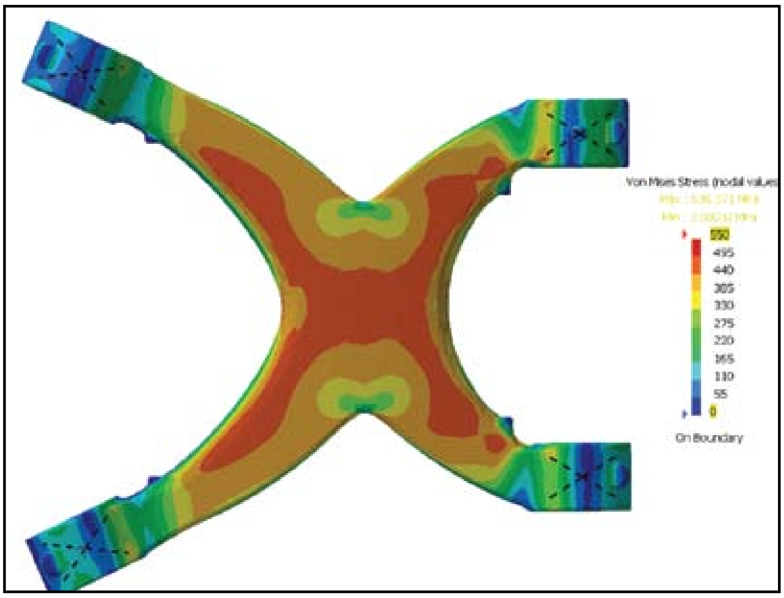


Fig. 5. FEA Von Mises stress pattern (roll torque)

- Casting Line AM 214
- 150 Boxes/Hour
- 300 Casting/Hour Potential

Fig. 6. X-Link production at GF Singen

Fig. 4 illustrates the patented ADI cast assembly. The cast X-link has now superseded the forging. Casting has enabled an optimal geometry to be developed; the use of cores, and the superior mechanical properties of ADI, allows the part to be cast with hollowed central zone and reduced section thicknesses. The 'eyes' are also cored; compared to the forging minimal machining is required before assembly. The final casting design weighs 40.8 kg, a saving over the forging of more than 37%.

The final design for the ADI X-link was obtained using Finite Element Analysis (fig. 5) and rapid prototyping. The FEA pattern shows the maximum stresses that the component experiences in a production environment. The results were verified in both laboratory and real life part testing. Surface stresses are critical to the performance and life of the X-link.

High stresses, coupled with other mechanical considerations (fatigue, ductility) and physical requirements (low weight), lead to the selection of ADI Grade 1000 – 5. The base iron uses a specific alloy developed with GF Singen. Following further rig and vehicle testing, and with the agreement of all parties, the EN Grade of ADI was altered to a MAN standard 1000 – 750 – 6.

Table 1 compares the EN1564 specified mechanical properties for ADI 1000 – 5 with the customer's final specification for the X-link. The MAN specification calls for higher yield and elongation. Specific fatigue data cannot be released at the present time but material is tested to 1x10e6 km using standard and 'real-life' samples from the casting, and the complete assembled casting.

With design and material agreed, the next step was to ensure that the product could be manufactured and supplied in high volumes, with consistent high quality and at a price that was acceptable to the end user. The route chosen was: cast, austemper, machine, and assemble.

Casting

GF Singen employs its AM214 line, producing two links per box at an optimum 150 boxes per hour. The cast tolerance is to CT4 specification. The moulding line, fig. 6, manufactures the upper and lower boxes in bentonite sand. Cores are inserted to create the hollow cavities and wheel eyes, in the iron casting. The box size is 1428mm x 992mm x 320 / 320mm.

After joining upper and lower boxes and loading on weights, pouring can take place. The pouring ladle is filled directly from the furnace; inoculation of the iron is made in stream. The first mould is filled manually; a computer memorises the event. All subsequent pouring is computer controlled. Lasers are not used in the process. Before pouring, a sample is taken from the melt to check analysis. Further checks are performed every 20 minutes, after any break, and on every ladle batch.

The moulds travel down a cooling line, allowing the iron to freeze and relax before removal. Several hours elapse before the shake out point is reached and the mould sand and core sand are cleared. Running system and risers are not yet removed; the whole casting is shotblast to clean out remaining traces of sand.

The clean castings are fettled and dressed on a finishing line; feeders and risers are recycled. (Note the sliding and parting 'wedges' can be formed from ADI). Before packing and dispatch the product undergoes 100% crack detection. Each X-link is labelled and loaded into metal cages (19 per cage) in preparation for the austempering furnaces at ADIT.

Austempering furnaces

At its inception ADIT installed two purpose built, batch austempering furnace systems (fig. 7), each providing 920 x 920 x 1840mm hot space and an integrated 55 tonnes salt bath.

Prüfling	Zugfestigkeit R_m	Dehngrenze $R_{p0,2}$	$R_{p0,2}/R_m$	Bruchdehnung A	Härte	C	Si	Cu	Mn	Mg	P	S	Cr
	MPa	MPa		%	HB 5/750	%	%	%	%	%	%	%	%
Soll EN-GJS-1000-5	1000 min	700 min	0,7 min	5 min	300-360								
Soll MAN M3201 GGG 100 B	1000 min	750 min		6 min	300-360	2,60 bis 3,90	1,6 bis 3,0	wie erforderlich (0,9)	0,01 bis 0,80	0,025 bis 0,090	<=0,08	<=0,01	wie erforderlich (0,15)
Mittelwert	1045,7	781,0	0,75	11,3	339	3,40	2,08	0,89	0,22	0,03	0,04	0,00	0,03
s	18,5	31,0	0,02	2,3	3,1	0,10	0,07	0,03	0,00	0,01	0,01	0,00	0,01
Min	1019,7	742,1	0,72	8,6	336	3,29	1,97	0,85	0,21	0,02	0,03	0,00	0,03
Max	1073,9	814,7	0,79	14,4	344	3,53	2,17	0,92	0,22	0,04	0,04	0,01	0,04

Table 1: Austempered Ductile Iron EN-GJS-1000-5 mechanical properties (Prüfling = Grade, Zugfestigkeit = Tensile Strength, Dehngrenze = 0.2% Yield Strength, Bruchdehnung = Elongation, Härte = Hardness, wie erforderlich = as necessary)

Some key features have proved beneficial in designing and producing ADI:

1. Computer Control: this ensures batch to batch repeatability.
2. A protective atmosphere: prevents scale formation. The entire thermal cycle is contained; the austenitising furnace also has a carbon rich atmosphere to prevent decarburisation and allow processing of as-cast and pre-machined components.
3. High salt to load quench ratio: the high salt mass ensures that quenching takes place at the austempering temperature. As a consequence of very hot work entering the quench at low temperature, the salt temperature will rise but agitation and water injection further reduce this effect. If the salt reaches 5°C above set point an additional automated cooling system is triggered, circulating air around the outer skin of the quench tank to dissipate heat. Attention to the stability of the austemper stage reduces variability in properties and provides consistency of machining. Other systems use a two stage quench process or reduced production loading.
4. Quenchant recycling: the castings are washed in water, which is recycled either by direct injection in the salt or by producing ‘salt cubes’, taking care for the environment.
5. Large batch capacity: enables both low and high volume product to be processed.

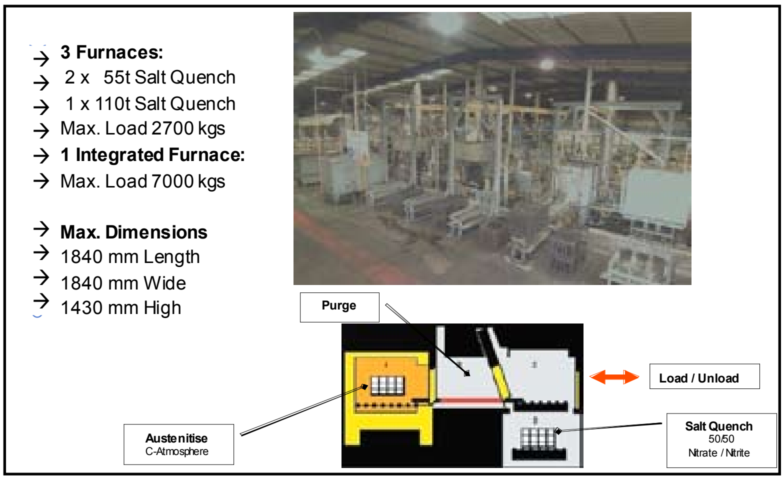
During the development phase of the 4pl project, ADIT recognised that a growing demand for ADI in Europe would quickly outstrip the available capacity. To secure supply, further investment was required. A third furnace was added based on the original design but with the hot zone dimensions (W, H, and L) increased to 1840 x 1430 x 1840mm, and the salt bath to 110 tonnes.

Presentation of the load to the furnace is an important factor in achieving efficiency as well as homogenous heat treatment and final properties. The standard furnaces were originally jigged to accommodate 14 X-links. To reach production targets it was necessary to improve on this figure. With the change in furnace size, a ‘superjig’ (fig. 8) was developed to increase the batch number to 38.

The 37-18Ni/Cr superjig was designed for maximum payload while maintaining the integrity of the salt bath austempering process. Each casting is spaced from the next so as to allow the salt to flow over all surfaces. Other important requirements were ease of assembly and disassembly, and the option to divide the jig for loading 19 castings in the smaller furnaces. Before the new jigs could be used in production, proof was required that increasing the load to 38 X-links did not adversely affect the process result; verification tests and data are described below. Since 2007 the new loading arrangements have improved productivity and brought lower cost while maintaining the high quality requirements. With the correct number of jig systems in place, treatment of up to 532 parts per day is feasible.

Fig. 9 illustrates an example heat treatment cycle and final microstructures. (The actual cycle for the X-link is highly developed and remains client confidential). At ADIT the jig and castings are pre-heated to 600°C in an open atmosphere oven before loading into the austenitising furnace, to reduce costs and cycle time. After austenitising, the load is transported automatically into the quench. The transfer time is monitored for consistency to limit this as a possible source of variation in the product. In this example the quench is sufficient to avoid transformation to pearlite. To obviate pearlite in heavier sections, it would be necessary to alloy with Cu, Ni or Mo, individually or in combination. With correct inoculation and alloying, the furnaces described here are capable of fully austempering up to 200 mm sections.

The ISO standard for ADI does consider section thickness but only up to 100 mm; mechanical properties obtained in heavier sections would be determined in agreement with the customer.



→ **3 Furnaces:**
→ 2 x 55t Salt Quench
→ 1 x 110t Salt Quench
→ Max. Load 2700 kgs
→ **1 Integrated Furnace:**
→ Max. Load 7000 kgs

→ **Max. Dimensions**
→ 1840 mm Length
→ 1840 mm Wide
→ 1430 mm High

Fig. 7. ADI Heat Treatment furnaces

Standard Basket = 14
- Prototypes
- Low Volume Serial Production

Ni / Cr Designed Jig Load = 19 / 38
- High Volume Serial Production

Fig. 8. Furnace loading jigs

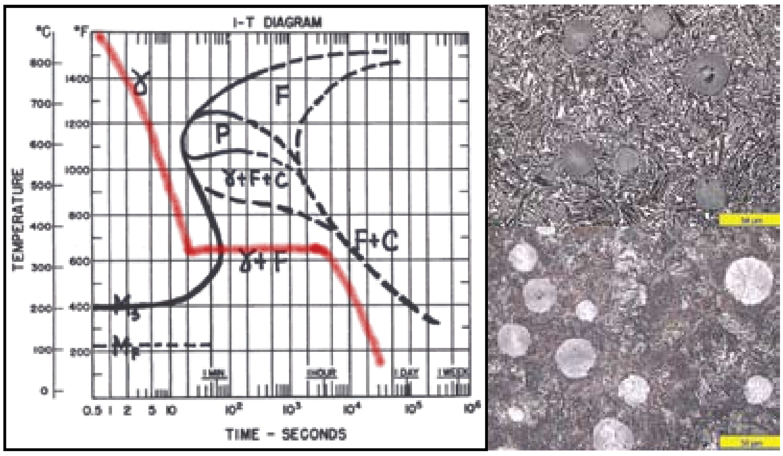


Fig. 9. Typical ADI Heat Treatment cycle and microstructures

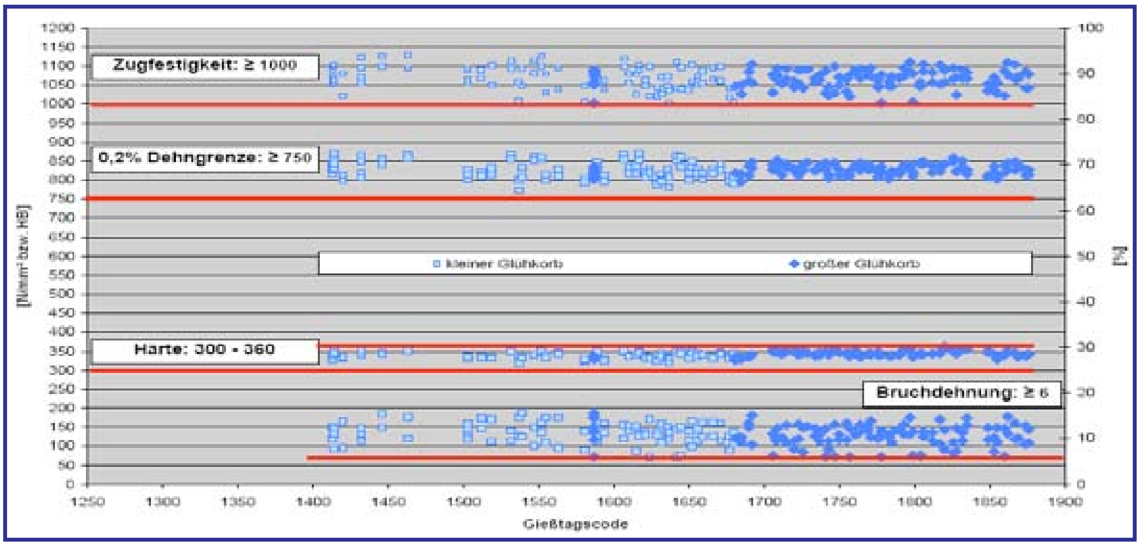


Fig. 10. Mechanical property data (Zugfestigkeit = Tensile Strength, Dehngrenze = 0.2% Yield Strength, Bruchdehnung = Elongation, Härte = Hardness, kleiner Glühkorb = Small Furnace Load, großer Glühkorb = Large Furnace Load, Gießtagecode = Cast Date Code)

Fig. 11. Wind turbine planetary gear carrier

On reaching the austempering temperature, the castings are left to soak for a time to develop the optimal structure and consequently, optimal properties. The parts and jig go through a washing routine (wash, rinse, inhibit); the water use is monitored for salt level and recycled directly via the water injection process or by producing 'salt cubes'.

Process control

Process control begins at the casting stage; every 20 minutes GF checks the composition of the iron to ensure compliance with the alloy developed specifically for the X-link. Any non-conforming material is quarantined. For traceability, each X-link is given two specific codes: the first relates to the pouring date and is cast onto each part at GF; the second is engraved on the casting at ADIT and relates not only to date and time of heat treatment but also the actual batch (the 'heat number'). During the heat treatment, the austenitising and austempering temperatures, and the carbon potential, are read every three minutes. Production, quality and maintenance personnel may then respond to any unexpected deviation in the furnace or load conditions; the full furnace charts are checked every 24 hours.

When cooled, a random Brinell hardness test is carried out on each furnace load (1 hardness per 19/38 castings). A raised pad, cast on the X-link, provides the specific area for the test, to enhance consistency from batch to batch. Any non conformance is reported and the entire batch quarantined while the cause is investigated.

The ADI castings are returned to GF for final shotblast, inspection and testing. An additional random hardness audit is made and a casting from each cast date code is sampled to provide microstructure analysis and tensile mechanical testing. The results, displayed graphically in fig. 10, are consistent both for the low series production (batches of 14) and the high series production (batches of 38). Note that fatigue results are not shown; these were performed only at the development stage to confirm that the superjig batch size has no adverse affect on the required fatigue specification. The full specification set by the end user remains confidential except to clarify that the intermediate results for the superjig exceeded specified lifetime by more than 200%.

Machining

Machinability was another important criterion to be met before the ADI solution could be implemented. The machines, fixtures and cutting tools used on the forging had also to be viable for the casting. ZF found it was able to adapt its existing facilities and practice, altering only the cutting forces for ADI. Furthermore, with significantly less material to remove from the casting (the hardened forging has solid 'eyes') machining time and costs were reduced.

Case study: wind turbine

The adaptability of ADI for niche situations can be seen from a different perspective in this large casting. Fig. 11 shows a planetary gear carrier from a wind turbine gearbox, loaded in an austempering furnace. These components may be cast in SG 400-800 grades, or in alloy steels (42CrMo4, 34CrNiMo6). Generating a nominal 4.2MW from its 126m diameter rotor, the turbine design was selected by the operators for performance and suitability in the UK's North Sea. Where FEA indicates high stresses/torque loads in the operating environment, ADI or hardened and tempered cast alloy steel are stipulated as candidate materials. In this application Grade 800 ADI, with a minimum 2% Ni, 0.3% Mo and a hardness range of 280 – 310 HB was selected.

The ductile iron carrier design presents no special difficulty so standard techniques are used by the foundry. Due to its mass, 4.3 tonnes, the casting is held in the mould for two days before shakeout. Removal of the risers, and machining, reduces the weight to 2.4 tonnes.

Each planet carrier is heat treated individually because of its large dimensions and weight. The quality of the furnace atmosphere prevents scaling

Fig. 12. Mini excavator rack and pinion

so minimal further machining is needed, 1 or 2mm for final dimensional tolerances. A 14-hour thermal cycle was specially developed for the part. At the end of the process the component is washed to remove the recyclable salt, visually inspected and hardness tested. All scrap iron is recycled.

Currently these parts are up to 1200mm in diameter but turbines continue to develop in scale and efficiency (one manufacturer envisages a need for castings up to 3m diameter). To meet present and future supply the heat treater installed an additional austempering unit to accommodate castings up to 7 tonnes, 1,840mm diameter, and 1,430mm height - the largest furnace system of its kind in commercial use.

Austempered Ductile Iron brings a range of advantages. In this case the ADI solution was easier to manufacture and offered a weight saving over steel with concomitant reductions in material and energy costs. Costs associated with the transport and assembly of the system, are also lower. The material properties of ADI allow dimensional savings to be made, giving greater flexibility to the designer. Smaller than the equivalent steel casting, the ADI carrier more readily fits the available space.

Case study: rack and pinion gears

Recent guidelines issued by AGMA are helping to raise the profile of ADI in Europe's gear industry; there is growing interest in ADI, particularly for special situations. Fig.12 illustrates a recent example from the UK Midlands, a rack and pinion set supplied by machinists Quinton Major Ltd for use in JCB mini excavators. The components, cast by Russell Ductile Foundry, are used to control movement and stability of the excavator boom arm.

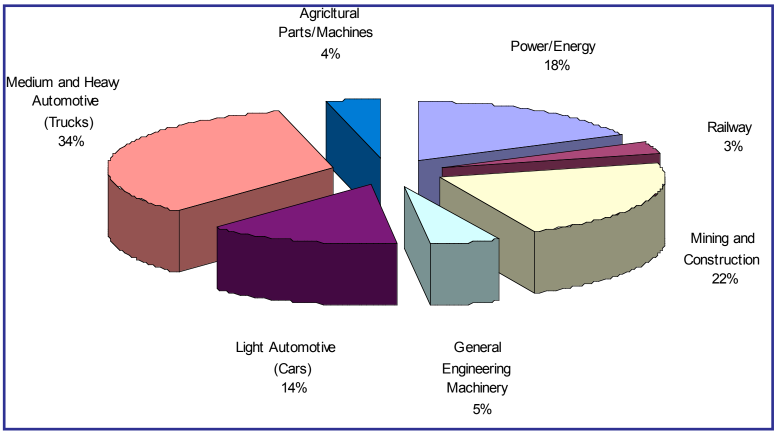


Fig. 13. ADI applications in EU markets, 2007

The 7 kg rack measures 90mm diameter x 275mm long, and the 8 kg pinion 140mm diameter x 210mm long. Both parts are heat treated to ASTM897M Grade 1200 with careful attention to furnace loading. To limit distortion, racks are placed in single layers on mesh with the gear teeth side 'up', while pinions are suspended on bars from their major inside diameter. A typical batch size is 100 sets; due to their different sections, the racks and pinions are processed separately.

Originally the gears were produced as steel forgings that were subsequently hardened and tempered, case hardened to 55 – 60 HRC, then shot peened. The change to ADI enabled the components to be fully machined before heat treatment while maintaining the maximum tolerance of 0.05mm. (Recent development has shown that 0.02mm finish tolerance can be achieved). Near net shape casting, reduction in machining, elimination of case hardening and shot peening, have significantly reduced production cost. An added benefit is the extended life of the ADI parts compared to the forgings, with savings on maintenance.

ADI markets and volumes

In North America the truck industry presents a very large market for austempered parts; almost all manufacturers are designing with ADI or obtaining components designed by suppliers. The market has grown more recently in Europe as engineers have become aware of the material.

Fig.13 indicates the relative demand from industry sectors as experienced by ADIT in 2007; percentage figures are derived from production throughput at the facility. The medium and heavy automotive (truck) sector currently leads the field. Total volume and revenue, from all sources combined, grew by approximately 35% compared to the previous year. From the company's own data, and information from contacts elsewhere in the industry, an estimated 25,000 tonnes of ADI were produced in the EU during 2007. This represents a tiny fraction of the annual ductile iron figure of nearly 5.5 million: ADI has a lot of room to grow.

Summary

ADI solutions can deliver significant cost and weight savings, offering a serious alternative to steel fabrications, forgings and castings. ADI also provides access to the casting and heat treatment processes with design enhancing advantages such as the ability to manufacture complex and near net shapes.

The material is flexible in application. Whether for small or large components, limited or series production, a wide range of ADI grades enables development of innovative solutions.

The best outcomes result from close co-operation between designer, foundry and heat treater. Success through teamwork will continue to develop the market for ADI in Europe.

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