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# Successfully Machining Austempered Ductile Iron (ADI)

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## ABSTRACT

Austempered Ductile Iron (ADI) is a relatively new material to the industrial marketplace. Many have tried to machine ADI as if it were steel, or as-cast Ductile Iron, and have been unsuccessful. Because of this, a myth has developed that ADI is not machinable. When the material properties and metal matrix of ADI are taken into consideration, ADI can be successfully machined.

## WHAT IS AUSTEMPERING?

Austempered Ductile Iron is Ductile Iron that has been Austempered in order to improve properties, such as strength, wear resistance or noise damping. The Austemper heat treatment is an isothermal process that transforms the metal matrix over many minutes or hours, culminating in properties that give the component better performance and strength. **Figure 1** shows a schematic of the heat treat process.

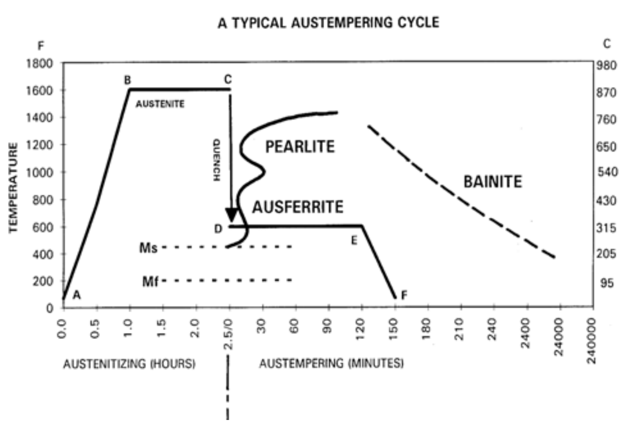


**Figure 1: The Austempering Cycle showing Temperature Versus Time**

In **Figure 1**, A-B shows the heat-up from room temperature to the Austenitizing Temperature. B-C shows the Austenitizing Process, where the component is held at the high temperature until the metal matrix fully transforms into Austenite, and is saturated with carbon. In C-D, the part is rapidly quenched down to the Austempering temperature. This temperature is above the Martensite Start (Ms) temperature, and the quench takes place rapidly enough to avoid the formation of Pearlite. D-E shows the Austempering process, where the metal matrix begins to transform into its final Ausferrite matrix. E-F shows the removal of the component from the quench, and cooling to room temperature.

## WHAT IS ADI?

THE MATRIX – Because of the process described above, ADI has a different metal matrix than as-cast or conventional quench and tempered Ductile Iron. The matrix consists of acicular ferrite and carbon-stabilized Austenite, also known as Ausferrite. Understanding this matrix is key to understanding why it machines differently than other materials.

SPECIFIC PROPERTIES – Ductile Iron components are Austempered to give them superior properties over other materials. **Table 1** shows the ASTM standard properties of ADI.

**Table 1: ASTM 897 Property table for ADI[6]**

| Grade | Tensile Strength (MPa/Ksi) | Yield Strength (MPa/Ksi) | Elong. (%) | Impact Energy (J/lb-ft) | Typical Hardness (BHN) |
|---|---|---|---|---|---|
| 1 | 850 / 125 | 550 / 80 | 10 | 100 / 75 | 269 – 321 |
| 2 | 1050 / 150 | 700 / 100 | 7 | 80 / 60 | 302 – 363 |
| 3 | 1200 / 175 | 850 / 125 | 4 | 60 / 45 | 341 – 444 |
| 4 | 1400 / 200 | 1100 / 155 | 1 | 35 / 25 | 366 – 477 |
| 5 | 1600 / 230 | 1300 / 185 | N/A | N/A | 444 - 555 |

As one can see from the property table, the different grades of ADI have improved strength over conventional Ductile Iron. The improved strength and high hardnesses will make machining ADI difficult, but not impossible. Grades 1 and 2 are considered the structural grades of ADI, often used in suspension components and many other dynamic applications. Grades 4 and 5 are considered wear grades, for their high hardnesses. Grades 4 and 5 can be ground, however, it is not suggested that they be machined. Grades 1 – 3 can be, and are being, machined quite successfully.

## THE MYTH BEHIND THE MATERIAL

ADI has been assumed to be un-machinable by many manufacturers. This is often due to its high hardness values. It has also been brought about by inappropriate machining practices. If one attempts to machine ADI as if it were as-cast ductile iron, the attempt will be unsuccessful. **Figure 2** shows the relative Machinability of ADI compared to other materials. This points out that ADI is not as easily machined as pearlitic or ferritic Ductile Iron, but is comparable to a 30Rc hardened steel in metal removal rates.

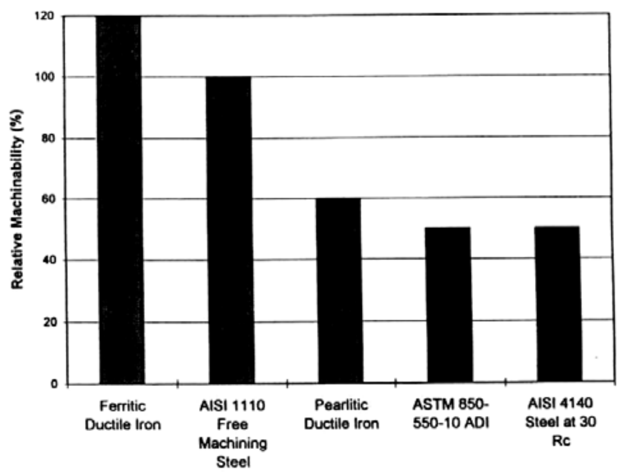


**Figure 2: Relative Machinability of several ferrous materials.**

## WHAT HAPPENS WHEN ADI IS MACHINED

ALLOYING ELEMENTS – ADI often uses various alloying elements to increase the hardenability of the material. Some of these common alloys are Copper, Nickel, Molybdenum and Manganese. Each of these elements behaves differently during the heat treat process. Carbide-forming elements such as Molybdenum and Manganese tend to segregate toward cell boundaries during the casting process. This can cause the formation of carbides in the metal matrix. These carbides can be very detrimental to the machining process, and will significantly reduce tool life. The formation of carbides can be reduced or eliminated by adjusting the use of alloying elements. It is recommended from prior research that the use of Molybdenum be reduced as much as possible, particularly in the presence of higher Mn levels. The use of Copper and Nickel does not seem to have a detrimental effect on machining, as these elements are non-carbide-forming. Good casting quality is a necessity to creating good ADI parts, and significantly assists the machining process.

PHASE TRANSFORMATION – When a high normal force is applied to ADI, a phase transformation occurs on the surface of the part. The force of the tool during cutting, drilling, or turning, can cause a localized transformation in the material in front of the tool. The Austenite on the surface undergoes a strain induced transformation to Martensite. This Martensite structure is harder and more brittle than the Ausferrite structure. Therefore, while you are machining ADI, this transformation right in front of the tool face makes it even more difficult to machine. Because of this effect, it is suggested that ADI be machined with a deeper cut at a slower speed to help the tool avoid this new, hardened surface. When compared to as-cast ductile iron, the speed of the tool should be 50% less, and the depth of cut should be increased by 50%.

DISCONTINUOUS CHIP – One of the benefits of machining ADI is that the chips are discontinuous. Unlike steel, which creates a continuous coil-like chip while it is being machined, ADI produces a discontinuous chip that is easier to handle and recycle. This proves to be beneficial especially for highly automated machining centers, where the small machine chips tend to not clog the equipment.

## HOW TO MACHINE ADI

MACHINE BEFORE HEAT TREAT – In order to circumvent the challenges of machining ADI, one can machine prior to heat-treat. At this point, you will be machining the familiar Ductile Iron structures of ferrite or pearlite. This can be very effective, depending on the design of the component. **Figure 3** shows a constant velocity joint that is fully machined prior to the Austempering process. This application is successful because growth during the Austempering process is predictable. When taken into account during the design phase, these components are machined to tolerances that keep this growth in mind. The final product after heat-treat is dimensionally correct. If the dimensional response to Austempering produces sufficiently small variation, complete machining before Austempering may be the best option.

**Figure 3: ADI Constant Velocity Joint, fully machined prior to Austempering (Courtesy of Delphi Corporation)**

ROUGH MACHINE PRIOR TO HEAT TREAT – FINISH MACHINE AFTER HEAT TREAT – this process is applicable when tight tolerances and surface finishes are required that cannot be held during heat treat. Components such as crankshafts that require high quality surface finishes are often rough machined prior to heat treat, and ground after heat treat. This gives the manufacturer the econimic benefit of rough machining a softer, as-cast iron, and still satisfying stringent surface finish and tolerance requirements. Futhermore, machining or grinding after heat treatment induces significant compressive stresses to the part, thus improving its bending fatigue strength. However, this can create a logistical consideration. The part will need to come from the casting source, to rough maching, then to heat treat and back to final processing. Often, the casting source and the heat treat source are not related to the machining source. This means the component must be pulled from the machining flow, to be heat treated and returned. Therefore, the same increase in compressive stresses and fatigue resistance results. However, these additional process steps may prove cost effective in some cases.

MACHINE COMPLETE AFTER HEAT TREATMENT – In order to alleviate the logistics concerns noted above, as well as maintaining tight tolerances and surface finish requirements, ADI can be fully machined after heat treatment. **Figure 4** shows an on-highway truck-trailer wheel hub that is machined complete after Austempering. ADI can be machined as efficiently and cost-effectively as a typical 4140 grade of steel.

**Figure 4: ADI truck hub, fully machined after heat treatment (Courtesy of Walther EMC)**

CHANGE YOUR FEEDS AND SPEEDS – Due to the hardness of the material, and the strain-induced transformation that occurs in front of the tool face, the way in which ADI is machined must be taken into account. In order to increase tool life, a deeper cut is required. This allows the cutting surface to cut below the strain-induced Martensite region, thus decreasing the wear of the tool. **Figure 5** shows the effect of metal removal on tool life. When looking at the machinability of ADI, you will see a metal removal rate of 75% compared to that of as-cast pearlitic ductile iron. Your metal removal rate will be similar to that of a RC30 steel. A good place to start when setting machining parameters, is to machine ADI at 50% less speed than that of materials with similar hardness, with a 50% deeper cut.

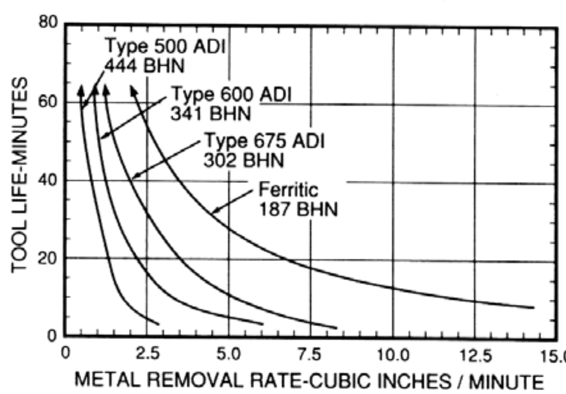


**Figure 5: Tool Life versus Metal Removal Rate on ADI specimens of different hardnesses[6]**

A slower feed rate has been shown to increase tool life and allow for more successful machining. **Figure 6** shows the effect of the hardness of various materials on tool life and cutting speed.

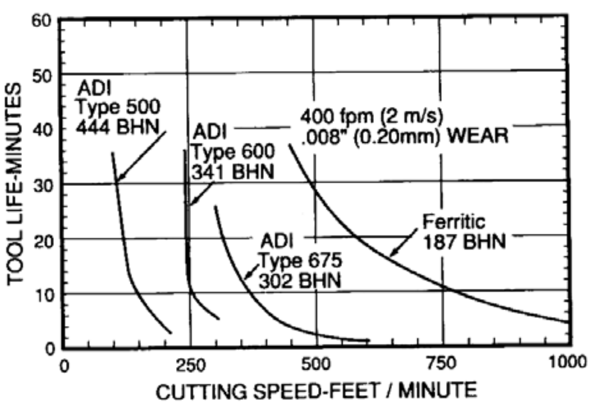


**Figure 6: Tool Life versus Cutting Speed on ADI and Ductile Irons of various hardnesses[6]**

CASTING QUALITY – It is not only important to take into account the properties and unique qualities of ADI. The quality of the initial casting will have a significant impact on machinability. The presence of small, finely dispersed graphite nodules will assist the machining process, therefore nodularity and nodule count are important. It is suggested that nodule count equal or exceed 100 nodules/mm$^2$ and that nodularity is 90% or greater. This creates a casting with small, evenly spaced nodules – which also helps reduce alloy segregation that can cause carbide formation. Other important aspects of casting quality that effect total part quality, as well as machinability are a casting that is relatively free of non-metallic inclusions and porosity.

SUGGESTED TOOL MATERIALS – Considerable research has been done on the use of different tool materials for maching ADI. Due to ADI's high strength and ductility, cutting tools often suffer flank wear and crater wear when machining ADI. Therefore, cutting tools need to have high wear resistance. K-grade carbide tools have sufficient wear resistance, but require the use of cutting fluids. P-grade tools can be used in dry cutting. $Al_2O_3$ ceramics are successful for continuous cut processes. $Si_3N_4$ ceramics and PCBN cutting tools are not suggested for maching ADI. **Figure 7** shows the life of tools of different materials when used to machine ADI. **Table 2** shows an overview of tools, cutting speeds and feeds for different ADI machining operations.

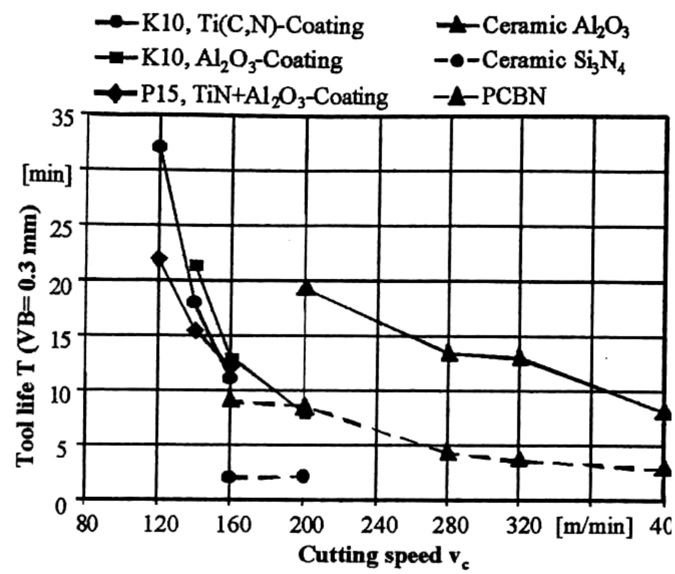


**Figure 7: Tool Life versus Cutting Speed of tools for various materials[1]**

**Table 2: Guidelines for machining lower strength grades of ADI (grades 1 and 2)[6]**

| Machining Operation | Tools | Cutting Speed (m/min) | Feed (mm/rev) |
|---|---|---|---|
| **Turning** | K20 bits with TiC<br>Angle $\gamma$ = -6°<br>No cutting oil<br>Tool force 1.6-1.8 kN/mm$^2$ | 50 – 70 | Roughing:<br>0.5 – 1.0<br>Finishing:<br>0.15 – 0.3 |
| **Drilling** | Carbide-tipped drills | 12 – 15 | 0.05 – 0.12 |
| **Keyway Broaching** | High speed steel<br>$\gamma$ = 10°, $\alpha$= 5° | 3 – 6 | 0.05 – 0.08 |
| **Hobbing** | Hobs flooded with cutting-oil | 8 - 20 | 1.5 – 2.5 depending on module |
| **Grinding** | Grade 37C16-P4B wheels | | |

**SUMMARY**

Due to the high strength and hardness of ADI, it has often been mistaken as an unmachinable material. When the unique characteristics of this material are taken into account and machining practices are modified to suit the material, ADI can be successfully machined. Difficulties can arise from the formation of carbides from the segregation of different alloying elements during the heat treat process. These can be addressed in the casting process. The strain-induced transition to Martensite can also create obstacles in the machining process. However, with the appropriate tool material, feed rate, tool speed and depth of cut, ADI can be successfully machined.

## ACKNOWLEDGMENTS

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## ADDITIONAL RESOURCES

- Applied Process Inc. internal research
- www.appliedprocess.com
- www.ductile.org