# Physical Properties and Application of Austempered Gray Iron

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## ABSTRACT

*Mechanical and acoustical properties were determined in Class 20, 30 and 40 gray irons in the as-cast condition and as austempered at 500, 600 and 700F (260, 316 and 371C).*

*The three classes of gray iron were obtained by varying the carbon and silicon content (carbon equivalent) and/or the inoculation. The variation in the other elements was unintentional. The variation of the graphite volume and morphology caused a significant difference in the microstructure, the mechanical properties and the acoustical properties in the tested irons.*

*Two acoustical parameters were measured: the resonant or natural frequency and the internal damping in the form of the logarithmic decrement. The dynamic (limit) elastic moduli were calculated from the resonant frequency data and were related to the various conditions in the irons.*

*Tensile strength, impact strength, elongation and hardness were determined as a function of the condition (microstructure and heat treat cycle) in the irons. It was determined that austempered gray iron has a unique combination of high strength and high damping. This combination makes austempered gray iron (AGI) applicable to parts in which high strength, high wear resistance and high vibration and/or sound damping is required.*

*Both the technical data and the potential application of AGI are discussed in this paper. A very good relationship was established between the acoustical and mechanical properties. Acoustical measurements offer a good technique for quality and/or process control.*

## INTRODUCTION

Many attempts were made in the past to increase the strength properties in gray iron. These attempts were based mainly on alloying. In some cases, the gain in strength did not warrant the incurred increase in production cost. This paper offers an alternative, a significant increase in the strength and damping for a relatively small cost.

The many successful applications of austempered ductile iron, ADI, suggested a study on austempered gray iron (AGI). There are several major differences between ADI and AGI concerning their austemperability. Most of these differences stem from the chemical composition and the solidification of the two irons. With some modification in the austempering process, however, significant improvements can be made in gray iron as well.

This paper was aimed at two areas. One of these is the technical part in which the attainable mechanical properties and their nondestructive evaluation are discussed. The other aspect of the paper is the economy of AGI and its potential application for industrial use.

It is shown in this paper that a combination of properties, not seen before, can be achieved in gray iron at an affordable production cost. This was made possible by extensive research in the past years, and by a new understanding of cast irons.

Although experience with AGI as an engineering material is limited, the mechanical properties obtained suggest good possibilities for industrial applications. These applications will be discussed later in this paper.

## BACKGROUND

Work was done on austempered gray iron in the late 1930s and early 1940s.[1–5] Flinn of the University of Michigan did some pioneering work on the topic. His work did not receive much attention and was quickly forgotten. Cast irons were not understood as well then as they are today. It was thought that cast iron was a special steel with graphite particles dispersed in it. When the austempered structure was first seen in gray iron, it was thought to be "acicular pearlite." Also, much more attention was paid to the graphite morphology than to the matrix structure. In gray iron, the sharp notches, created by the graphite flakes, were considered to be the limiting factor and not the matrix structure. In the 1930s, no commercial austempering equipment was available; therefore, no industrial application of austempered gray iron was considered.

Shortly after Flinn's study, in 1945, nodular iron was discovered. Much, if not all, attention was turned to the nodulization of graphite particles. It was perceived that a significant improvement in the mechanical properties could be achieved only by changing the graphite morphology. The fascination with the modification of the graphite shape continued and was carried over to compacted graphite iron (CGI). After researchers learned how to produce all shapes of graphite (flake, temper, nodular and compacted), attention was turned to the matrix again.

The most important discovery in recent years has been that the metallurgies of cast iron and steel are fundamentally different. The major difference is in the carbon kinetics. In steel, the carbon content is usually constant, while in the cast iron matrix, it is continuously variable. Silicon in steel is considered detrimental, while it is a necessary ingredient in cast irons. Silicon alters carbon solubility and diffusivity. It plays a major role in the development of the austempered structure, ausferrite, in cast irons.

Now that the austempering of ductile iron is well understood, the question arises: Are the ductile iron austempering principles applicable to CG, malleable and gray irons? This paper addresses the austempering of gray cast iron.

## EXPERIMENTS AND RESULTS

### Sample Preparation

Three types of specimens were prepared for the experiments: tensile bars (per ASTM A48) unnotched Charpy impact bars (per ASTM A370) and sonic resonance bars. The tensile bars were "A" bars with 0.505 in. (1.28 cm) dia and 2 in. (5 cm) gauge length. The sonic resonance bars were 0.5 in. (1.27 cm) dia and 2.5 in. (6.4 cm) long cylinders.

Table 1.
Chemical Compositions

| CLASS | %C | %Si | %Mn | %P | %S | %Cr | %Cu | %Ni |
|---|---|---|---|---|---|---|---|---|
| 20 | 3.75 | 2.68 | 0.57 | 0.038 | 0.179 | 0.14 | 0.14 | 0.06 |
| 30 | 3.45 | 1.95 | 0.58 | 0.031 | 0.12 | 0.19 | 0.18 | 0.07 |
| 40 | 3.46 | 2.02 | 0.52 | 0.037 | 0.125 | 0.17 | 0.16 | 0.07 |

Table 2.
Heat Treat Cycles

| CODE | ASTM CLASS | AUSTENITIZING TEMPERATURE, F(C) | AUSTENITIZING TIME (MINUTES) | AUSTEMPERING TEMPERATURE, F(C) | AUSTEMPERING TIME (MINUTES) |
|---|---|---|---|---|---|
| A | 20 | AS-CAST | AS-CAST | AS-CAST | AS-CAST |
| B | 30 | AS-CAST | AS-CAST | AS-CAST | AS-CAST |
| C | 40 | AS-CAST | AS-CAST | AS-CAST | AS-CAST |
| D | 20 | 1600 (871) | 120 | 700 (371) | 60 |
| E | 30 | 1600 (871) | 120 | 700 (371) | 60 |
| F | 40 | 1600 (871) | 120 | 700 (371) | 60 |
| G | 20 | 1600 (871) | 120 | 600 (316) | 120 |
| H | 30 | 1600 (871) | 120 | 600 (316) | 120 |
| J | 40 | 1600 (871) | 120 | 600 (316) | 120 |
| K | 20 | 1600 (871) | 120 | 500 (260) | 180 |
| L | 30 | 1600 (871) | 120 | 500 (260) | 180 |
| M | 40 | 1600 (871) | 120 | 500 (260) | 180 |

Table 3.
Mechanical Properties

| CODE | ASTM CLASS | TENSILE STRENGTH, ksi (MPa) | ELONGATION % | IMPACT ENERGY ft-lb (JOULES) | HARDNESS BHN |
|---|---|---|---|---|---|
| A | 20 | 24.0 (165) | 0.5 | 2.7 (3.7) | 172 |
| B | 30 | 36.6 (252) | 0.5 | 3.7 (5.0) | 235 |
| C | 40 | 43.1 (297) | 0.5 | 3.3 (4.5) | 245 |
| D | 20 | 34.6 (239) | 0.8 | 3.7 (5.0) | 212 |
| E | 30 | 48.0 (331) | 0.7 | 4.0 (5.4) | 263 |
| F | 40 | 56.4 (389) | 0.8 | 5.0 (6.8) | 282 |
| G | 20 | 39.5 (272) | 0.9 | 3.0 (4.1) | 257 |
| H | 30 | 57.0 (393) | N/A | 4.0 (5.4) | 352 |
| J | 40 | 63.3 (436) | N/A | 4.7 (6.4) | 365 |
| K | 20 | 41.8 (288) | N/A | 3.7 (5.0) | 290 |
| L | 30 | 59.2 (408) | 0.6 | 4.0 (5.4) | 386 |
| M | 40 | 63.9 (441) | 0.6 | 5.0 (6.8) | 410 |

Table 4.
Acoustical Properties

| CODE | ASTM CLASS | RESONANT FREQUENCY, kHz | INTERNAL DAMPING (X 1000) | DYNAMIC MODULUS, Msi (GPa) |
|---|---|---|---|---|
| A | 20 | 30.82 | 8.6 | 16.35 (113) |
| B | 30 | 33.15 | 4.3 | 18.22 (126) |
| C | 40 | 34.34 | 2.8 | 18.79 (130) |
| D | 20 | 27.43 | 11.7 | 12.92 (89) |
| E | 30 | 28.96 | 6.8 | 15.83 (109) |
| F | 40 | 30.14 | 4.2 | 16.50 (114) |
| G | 20 | 25.82 | 13.5 | 11.14 (77) |
| H | 30 | 29.38 | 7.8 | 14.50 (100) |
| J | 40 | 29.56 | 5.2 | 15.21 (105) |
| K | 20 | 25.09 | 14.8 | 10.46 (72) |
| L | 30 | 28.86 | 8.5 | 14.26 (98) |
| M | 40 | 29.83 | 4.8 | 15.16 (105) |

Three heats were cast for the test specimens. The attempt was to obtain Class 20, 30 and 40 gray irons. The various classes were obtained by varying the carbon and the silicon contents or changing the amount of the inoculant. The variation in the chemical composition, other than carbon and silicon, was unintentional. The chemical compositions of the three heats are listed in Table 1.

The graphite size and shape was altered by the variation of the carbon equivalent (CE) and inoculation. The graphite morphology is shown in Figs. 1–3.

Four conditions were developed in the three classes of gray iron. The first group consisted of samples in the as-cast condition. The second group was austempered at 700F (371C) for 60 minutes. The third group was austempered at 600F (316C) for 120 minutes. The fourth group was austempered at 500F (260C) for 180 minutes. All samples were austenitized at 1600F (871C) for 120 minutes. The heat treatments are summarized in Table 2.

## Metallographic Examinations

The microstructures of the samples in the four conditions are shown in Figs. 4–15. The variation in the microstructure, due to the change in the austempering temperature, is apparent. A low (500F/260C) austempering temperature produces a structure that is finer than that of a high (700F/371C) temperature structure. The completion of austempering was verified by means of a heat tinting technique.[6] The samples were held at 500F (260C) for four hours without protective atmosphere.

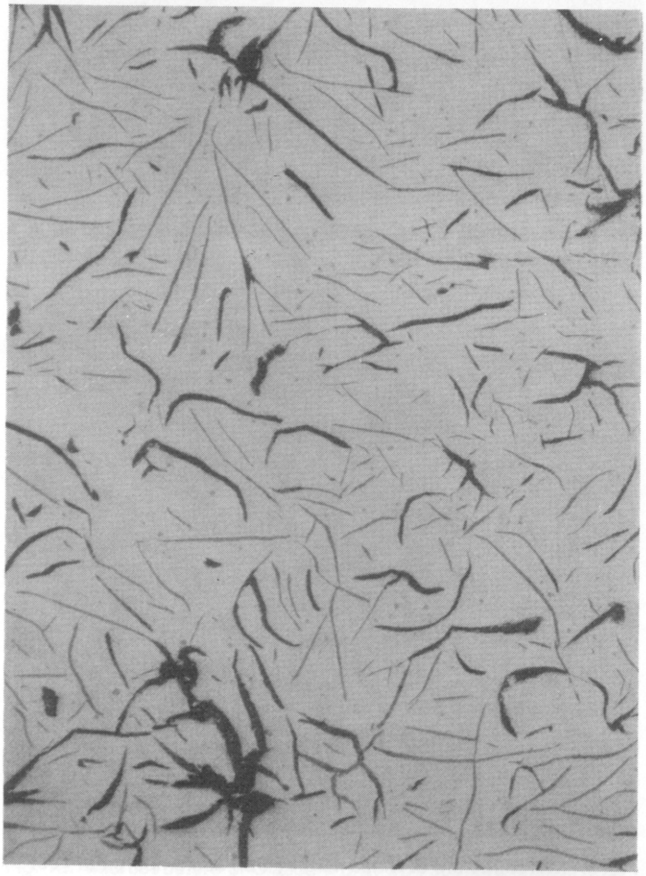

*Fig. 1. Graphite morphology in Class 20 gray iron; 100X.*

## Testing of Mechanical Properties

*Tensile Testing*. Three samples were tested for each condition and the averages were plotted in the graphs. All samples were tested at 0.2 in./in.-min strain rate. The tensile strength and elongation were determined.

*Hardness Testing*. The Brinell hardness values were determined using a 3000-kg load.

The results of the mechanical testing are listed in Table 3.

## Acoustical Testing

Two acoustical properties were measured: 1) the resonant frequency in a longitudinal free harmonic oscillation; and 2) the internal damping in the form of the logarithmic decrement. The dynamic (limit) elastic modulus (DEM) was calculated from the resonant frequency data. The following equation was used for the calculation:

$$\omega_o = 1/2l \sqrt{E_o/\rho}$$

where $\omega_o$ is the resonant frequency, $l$ is the length of the test bar, $E_o$ is the dynamic elastic modulus and $\rho$ is the density of the test bar.

The accuracy of the acoustical measurement is five significant digits. Results of the acoustical measurements are listed in Table 4.

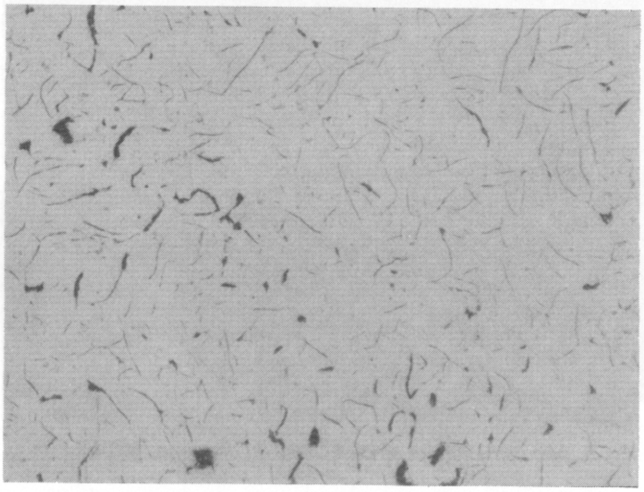

*Fig. 2. Graphite morphology in Class 30 gray iron; 100X.*

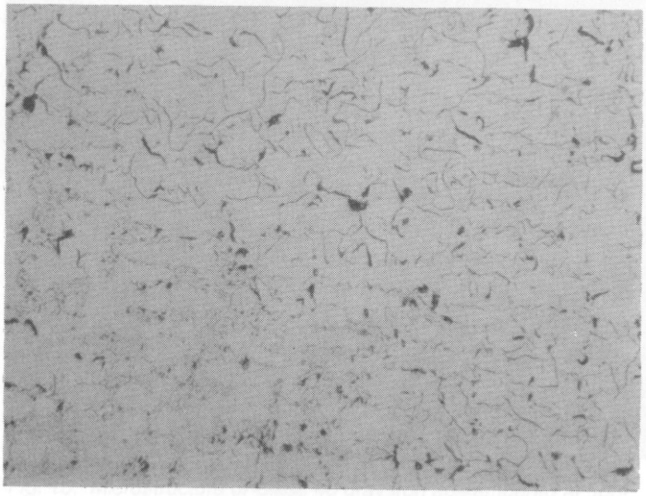

*Fig. 3. Graphite morphology in Class 40 gray iron; 100X.*

*Fig. 4. Microstructure of as-cast Class 20 gray iron; 100X.*

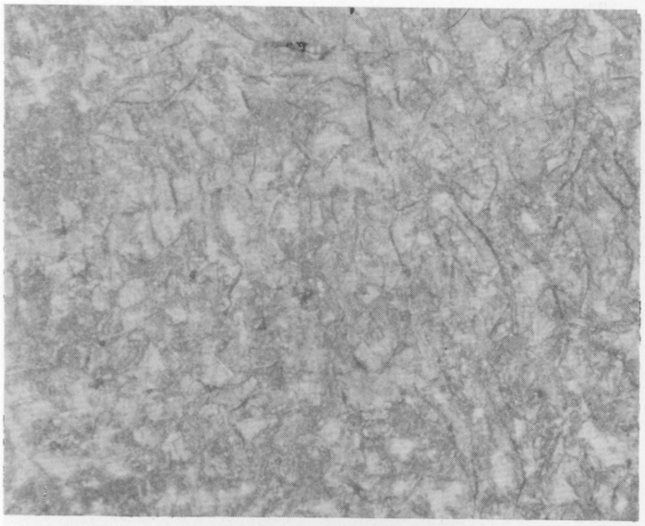

*Fig. 5. Microstructure of as-cast Class 30 gray iron; 100X.*

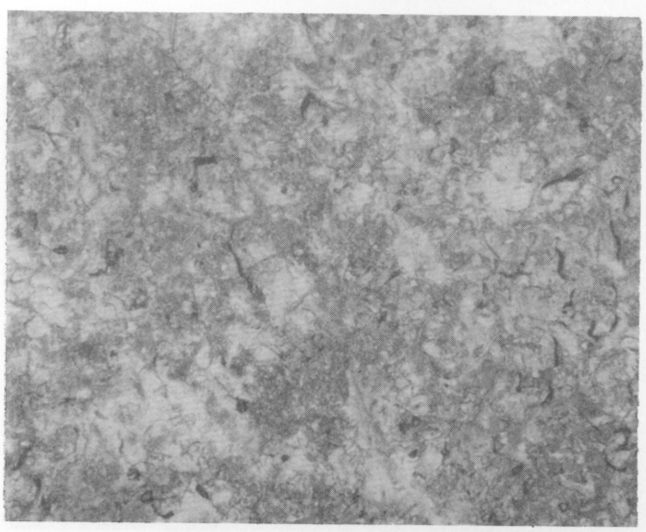

*Fig. 6. Microstructure of as-cast Class 40 gray iron; 100X.*

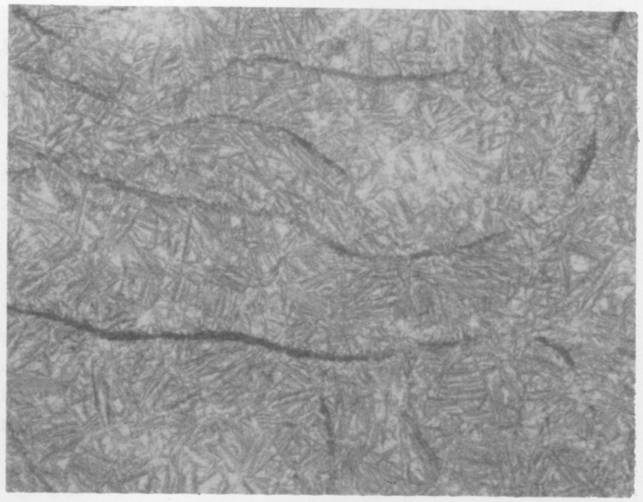

*Fig. 7. Microstructure of Class 20 gray iron austempered at 700F (371C) for 60 minutes; 400X.*

*Fig. 8. Microstructure of Class 30 gray iron austempered at 700F (371C) for 60 minutes; 400X.*

*Fig. 9. Microstructure of Class 40 gray iron austempered at 700F (371C) for 60 minutes; 400X.*

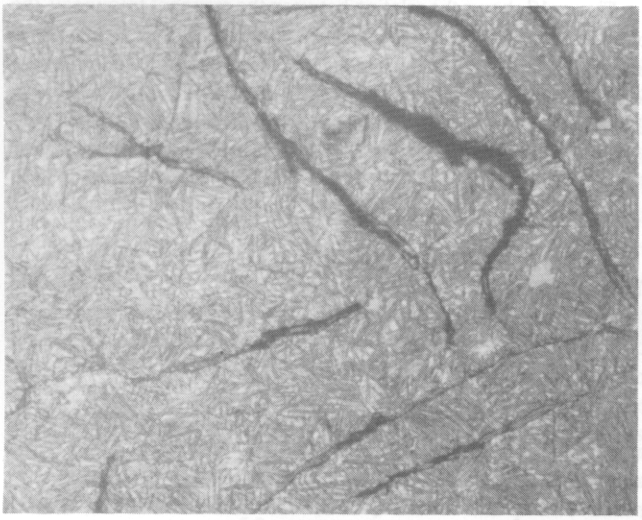

Fig. 10. Microstructure of Class 20 gray iron austempered at 600F (316C) for 120 minutes; 400X.

Fig. 11. Microstructure of Class 30 gray iron austempered at 600F (316C) for 120 minutes; 400X.

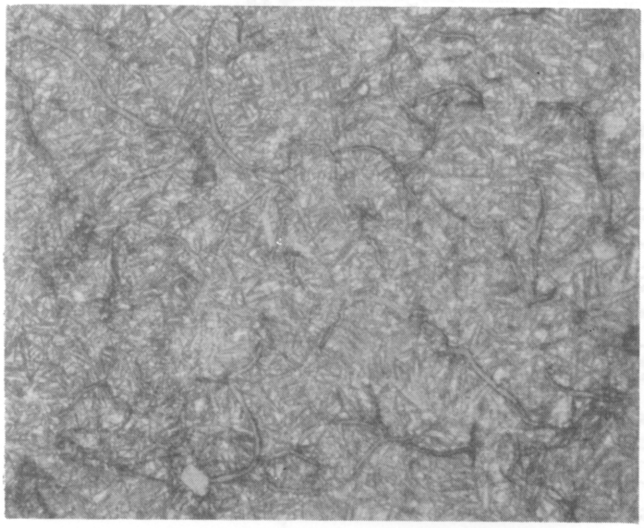

Fig. 12. Microstructure of Class 40 gray iron austempered at 600F (316C) for 120 minutes; 400X.

Fig. 13. Microstructure of Class 20 gray iron austempered at 500F (260C) for 180 minutes; 400X.

Fig. 14. Microstructure of Class 30 gray iron austempered at 500F (260C) for 180 minutes; 400X.

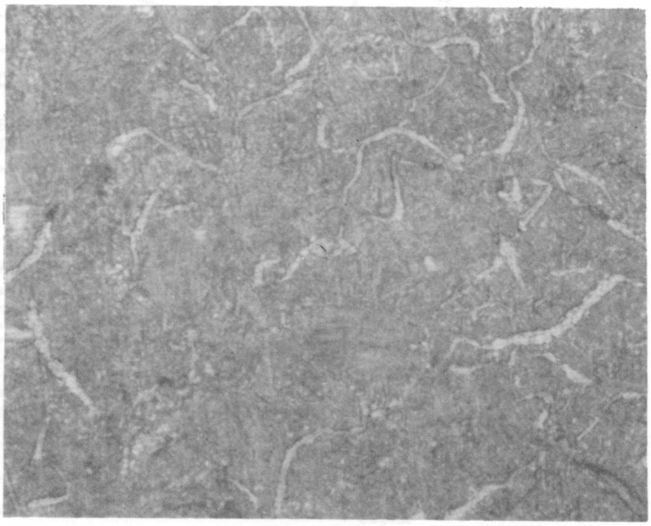

Fig. 15. Microstructure of Class 40 gray iron austempered at 500F (260C) for 180 minutes; 400X.

## DISCUSSION

Silicon has an important role in the development of the ausferritic matrix in cast irons. It suppresses and prolongs bainitic carbide formation, it decreases the carbon solubility in austenite, accelerates carbon diffusion in austenite and raises the upper critical temperature. It influences the time required for the completion of the austempering reaction. In gray iron, the silicon content is usually lower than in ductile iron, and, therefore, it requires a shorter austempering time.

Also, there is higher sulfur content in gray iron. Sulfur segregates at the matrix-graphite interface and creates a very strong carbon diffusion barrier. It slows down carbon diffusion between the graphite flake and the matrix. When a ductile iron casting is cooled after solidification, much of the carbon diffuses from the matrix into the graphite nodules. Because of the segregated sulfur, this does not happen in gray iron. For this reason, gray iron is predominantly pearlitic and it usually has higher matrix carbon content than does nodular iron. Although it has a higher matrix carbon content in the as-cast matrix than nodular iron does, it may take more time in gray iron to saturate the matrix austenite with carbon during austenitization. In gray iron, the austenitization time is usually longer due to the higher sulfur content and the austempering time is shorter due to the lower silicon content. This is reflected in the austempering cycle.

The tensile strength is shown in Fig. 16 as a function of the class and heat treatment. In the as-cast condition, due to the graphite size and shape, the tensile strength is varied. This variation is transmitted into the austempered samples. As the austempering temperature decreases, the tensile strength increases proportionally. The strength starts leveling off at 600F (316C), however.

Figure 17 shows the relation between the resonant frequency, the class of iron and the austempering temperature. The frequency is highest in as-cast samples and it decreases as the austempering temperature is lowered. This is in agreement with the trend found in ductile iron. The reason for the trend is smaller grain size and high internal stresses caused by the low austempering temperature. When Figs. 16 and 17 are compared, it is clear that the tensile strength and the resonant frequency are inversely proportional.

Significant scatter in the impact energy data is shown in Fig. 18. The only safe conclusion that can be made from this graph is that the austempered samples have higher impact energy than those of the as-cast samples and that the austempering temperature has little effect on the impact energy in gray iron.

Figure 19 shows the elongation as a function of the class and the austempering temperature. The elongation does not seem to be affected by the class of iron. It increases with austempering temperature and peaks at 600F (316C). It should be mentioned that the same phenomenon was observed in nodular iron; however, it occurred at about 650–690F (343–366C). It is difficult to say how important it is that the elongation doubles at the 600F (316C) austempering temperature. Obviously, the graphite shape is the primary factor determining and limiting elongation.

The hardness data are shown in Fig. 20 as a function of class and austempering temperature. As was expected, hardness increased with lower austempering temperatures. The relationship is nearly linear; however, there is a break in the line at 600F (316C). It seems as though something changes in the texture at 600F (316C), but the authors are not ready to explain the phenomenon (see elongation in Fig. 19).

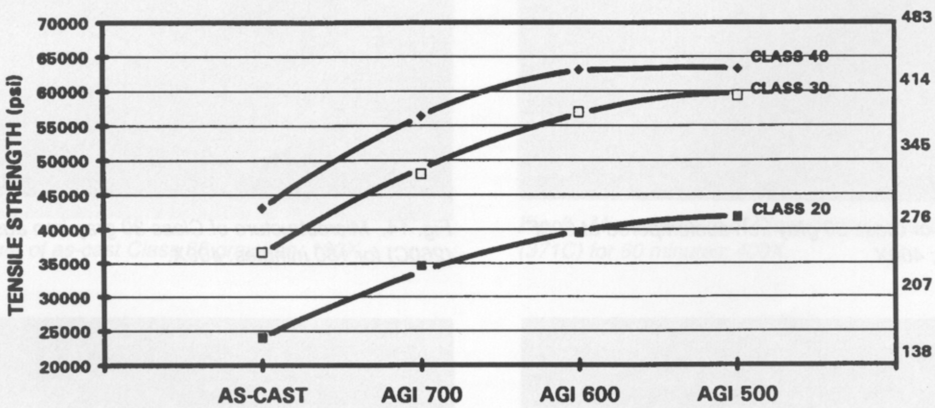


*Fig. 16. Tensile strength as a function of class and austempering temperature.*

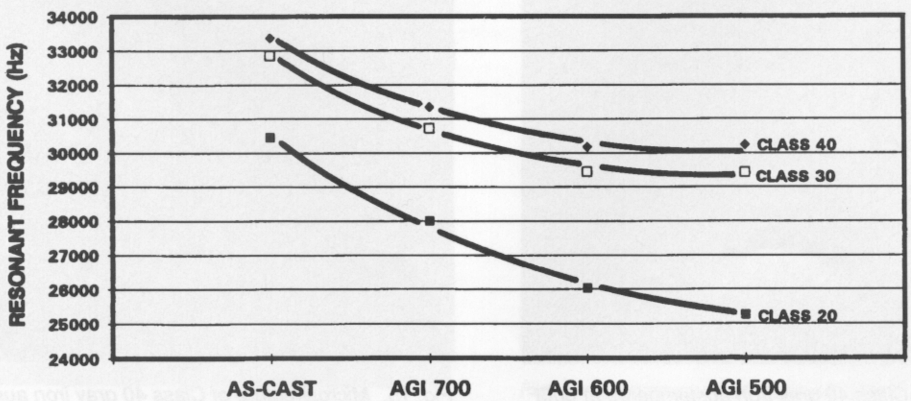


*Fig. 17. Resonant frequency as a function of class and austempering temperature.*

The resonant frequency is an extrinsic property. It depends on the size and shape of the test specimen. To avoid the ambiguity of an extrinsic property, the frequency data was converted to the dynamic elastic modulus (DEM), an intrinsic property. Figure 21 shows a linear relationship between the dynamic elastic modulus, the class and the austempering temperature.

The relationship between the internal damping and the tensile strength is shown in Fig. 22. The relationship is linear as it was between the tensile strength and DEM; however, damping increases with increasing strength. This combination makes AGI unique and very useful for many applications.[7]

It is noted that there is an excellent relationship between the dynamic elastic modulus or the resonant frequency (the modulus is a derivative of the frequency) and the tensile strength. The sonic resonant measurement could be a good nondestructive test method for AGI. It could be used for either quality or process control.

It has been shown that the mechanical properties can be significantly improved in gray iron by austempering. There is a unique combination of properties, which cannot be achieved in any other currently used engineering material. The combination is relatively high in strength and wear resistance[8] and very high damping. Increasing the strength and hardness in AGI means increasing the damping as well. The need for this combination of properties has been shown in the industry. The application of AGI has been limited by the lack of information about its mechanical and physical properties. This paper is intended to provide some of this information.

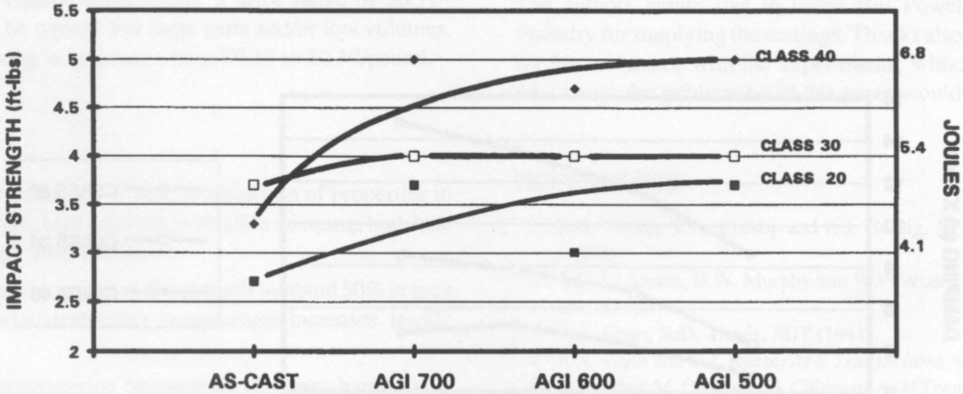


*Fig. 18. Impact strength as a function of class and austempering temperature.*

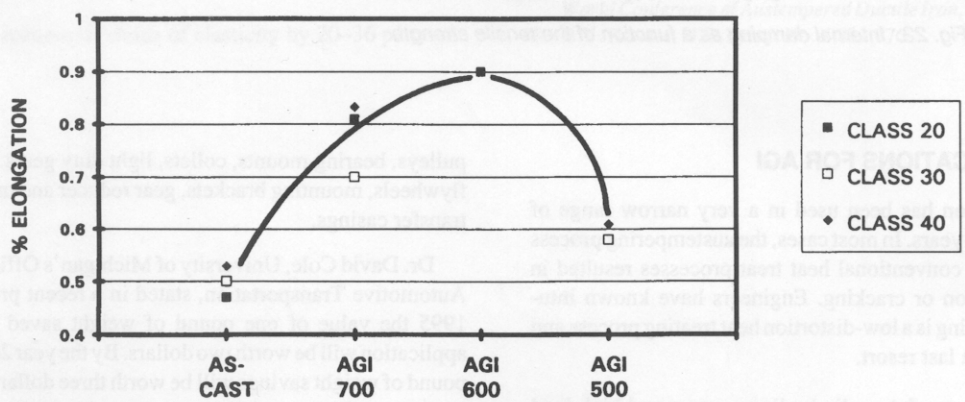


*Fig. 19. Elongation as a function of class and austempering temperature.*

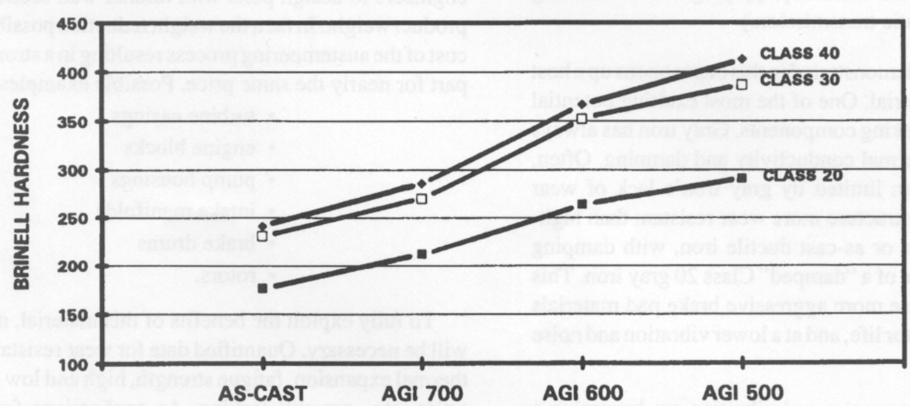


*Fig. 20. Brinell hardness as a function of class and austempering temperature.*

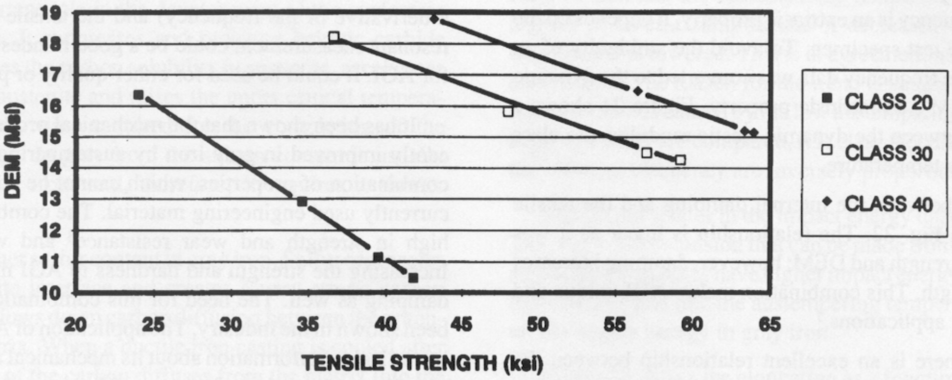


*Fig. 21. Dynamic elastic modulus as a function of the tensile strength.*

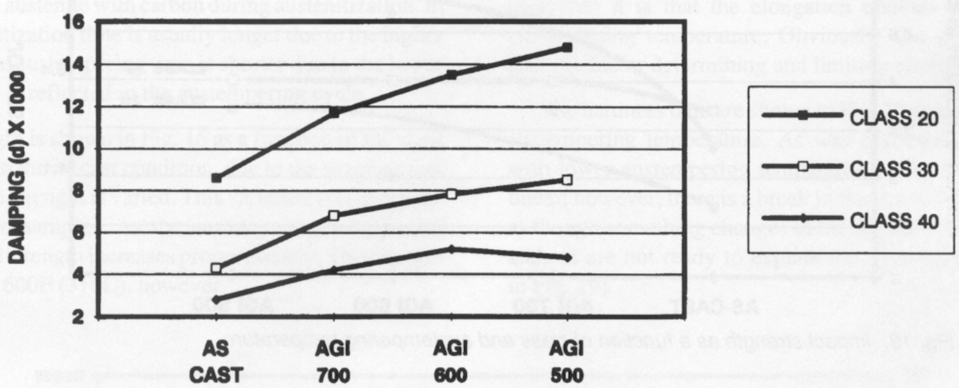


*Fig. 22. Internal damping as a function of the tensile strength.*

## POSSIBLE APPLICATIONS FOR AGI

Austempered gray iron has been used in a very narrow range of applications for some years. In most cases, the austempering process was employed when conventional heat treat processes resulted in unacceptable distortion or cracking. Engineers have known intuitively that austempering is a low-distortion heat treating process and have employed it as a last resort.

AGI parts, like heavy-duty cylinder liners, gears and high load bearing mounts, have been used for some time. (Mizuno, et al. demonstrated a 5-db reduction in noise by applying AGI to a bearing support in a Toyota automatic transmission.)

The range of properties demonstrated in this paper opens up a host of possibilities for this material. One of the most exciting potential applications of AGI is in braking components. Gray iron has always been known for its high thermal conductivity and damping. Often, however, designs have been limited by gray iron's lack of wear resistance. AGI provides a structure more wear resistant than high-strength gray iron, CG iron or as-cast ductile iron, with damping capabilities better than those of a "damped" Class 20 gray iron. This can allow the designer to use more aggressive brake pad materials without sacrificing drum/rotor life, and at a lower vibration and noise level.

In today's product design, noise and vibration are becoming a greater factor. AGI could be used to reduce noise in shaft collars, pulleys, bearing mounts, collets, light duty gears and shafts, geared flywheels, mounting brackets, gear reducer and motor housings and transfer casings.

Dr. David Cole, University of Michigan's Office for the Study of Automotive Transportation, stated in a recent presentation that by 1995 the value of one pound of weight saved in an automobile application will be worth two dollars. By the year 2000, that same one pound of weight savings will be worth three dollars. Because of gray iron's excellent castability, consideration can be given to design changes based on AGI's properties. Higher strength AGI could allow engineers to design parts with thinner wall sections, thus reducing product weight. In fact, the weight reduction possible could offset the cost of the austempering process resulting in a stronger, lower weight part for nearly the same price. Possible examples could include:

- turbine casings
- engine blocks
- pump housings
- intake manifolds
- brake drums
- rotors.

To fully exploit the benefits of this material, more investigation will be necessary. Quantified data for wear resistance, coefficient of thermal expansion, fatigue strength, high and low temperature properties, etc., are still lacking. As applications for the material are developed, investigators will quantify those properties.

## MANUFACTURE AND PROCESSING OF AGI

Facilities for the production of quality gray iron exist worldwide. Those facilities, in general, are underutilized. Aluminum, compacted graphite iron (CGI) and ductile iron have reduced the market demand for gray iron castings. Gray iron has, however, some desirable properties that make it a viable choice. It is easy to recycle, has high thermal conductivity and, because of its excellent fluidity and low shrinkage, is easy to cast. In its as-cast condition, it has excellent machinability and, therefore, a low manufacturing cost.

Austempering can be accomplished by a variety of methods ranging from simple, manually operated salt-to-salt lines to fully automated systems using digitally controlled atmosphere furnaces with specialized quenching and handling equipment. Commercial and captive facilities for austempering are also found worldwide. Cost for the austempering process can vary greatly, depending on the size and volume of parts processed and the type of equipment employed. In high-volume applications, a price range of $0.11–$0.17/pound would be typical. For large parts and/or low volumes, the price for processing would range from $0.18 to $0.30/pound.

## CONCLUSIONS

1. Austempering results in a unique combination of properties in gray iron: high strength, high sound and vibration damping, high heat conductivity and high wear resistance.

2. Austempering can increase tensile strength by about 50% in gray iron. Lowering the austempering temperature increases tensile strength.

3. Lowering the austempering temperature increases hardness.

4. Elongation peaks and doubles at about 600F (316C) austempering temperature.

5. Austempering reduces modulus of elasticity by 20–36 percent.

6. The graphite morphology plays a dominant role in determining the physical and mechanical properties.

7. A linear relationship exists between strength and dynamic elastic modulus (resonant frequency). Increasing tensile strength decreases modulus (resonant frequency).

8. The sonic resonant frequency measurement is a good prediction of mechanical properties and could be useful for quality and process control.

9. AGI has a good potential for application where high damping and high wear resistance are required.

10. The manufacturing facilities for the production of AGI are readily available.

11. More quantified data is needed for the full exploitation of AGI.

## ACKNOWLEDGMENTS

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## REFERENCES

1. E.R. Young, V.A. Crosby and A.J. Herzig, *AFS Transactions*, vol 36 (1939).
2. C.D. D'Amico, D.W. Murphy and W.P. Wood, *ASM Transactions*, vol 26 (1938).
3. R.A. Flinn, ScD. Thesis, MIT (1941).
4. R.A. Flinn and D.J. Reese, *AFS Transactions*, vol 49 (1941).
5. R.A. Flinn, M. Cohen and J. Chipman, *ASM Transactions*, vol 30 (1942).
6. B.V. Kovacs, *Modern Casting*, p 37 (Jun 1987).
7. M. Tada, T. Kurikuma, Y. Makimura and T. Sekiguchi, *Proc. of the 1991 World Conference of Austempered Ductile Iron*, Bloomingdale, Illinois.
8. B.V. Kovacs, U.S. Patent No. 4,891,076.