There are various ways to improve casting machinability. Natural aging’s effect on cast iron machinability differs based on its alloying elements, which are nitride-forming (titanium), carbide-forming (chromium) and nitrogen mobility modifiers (manganese). Relationships between cast iron aging and casting machinability have been verified in multiple laboratory and industrial tests, with respect to parameters such as cutting force, tool wear, surface quality and dimensional accuracy. A recent confirmation test verified the optimal aging time for a specific composition to improve gray iron machinability.

Cast Iron Natural Aging

Understanding how age strengthening affects machinability enables manufacturers to schedule the optimal window for machining. Room-temperature aging phenomena has been documented for different types of ferrous alloys, including cast irons and steels. In gray cast iron, tensile strength increased by 5%-15% after 5-30 days of room-temperature aging.

Aging studies in quenched iron-based alloys indicated a three-stage precipitation process. In some cases, a dip in strength is observed during the start of the aging process. Elevated temperature aging kinetics in the cast iron revealed typical age strengthening curves obtained at different temperatures.
(Fig. 1). An Arrhenius plot was constructed using the rate constants versus the reciprocal of the absolute temperature (Fig. 2).

Effect of Alloying Elements

While elevated temperature aging is less dependent on alloy composition, cast iron chemistry strongly affects room-temperature aging kinetics. From a practical perspective, the effect of variations in manganese and sulfur on cast iron’s aging rate is important. In a study of cast iron with 0.8%-0.83% manganese, aging was completed at 25 days, while this process needed only 15 days for cast iron with 0.51% manganese at similar 0.04%-0.06% sulfur levels.

To study the effect of alloying elements, aging kinetics of cast irons from six heats with variations in manganese, nitrogen and sulphur were evaluated. Strength change curves typically had a prestrengthening peak and a “relaxation valley” before achieving a full age strengthening.

Alloying with manganese affected both the time to prestrengthening and the full strengthening peak. Cast iron from a heat with 0.53% manganese had the highest reaction rate. Iron with lower manganese and especially higher manganese contents each had a longer aging reaction time.

Effect of Carbide/Nitride Forming Elements

Natural age strengthening of cast iron occurs in Fe-BCC (ferrite) by iron nitride precipitation. Carbide forming elements such as chromium promote the decrease of free ferrite in cast iron and reduce the total possible strengthening effect. An as-cast machinability test article produced from cast iron with 0.2% chromium did not show an improvement in machinability after aging.
Nitride forming elements such as titanium, aluminum and boron can fully suppress iron nitride precipitate strengthening. Nitrogen, available at solidification to form metastable solid solution in ferrite, affects the age strengthening of cast iron. Low soluble nitrogen left after titanium nitride formation does not allow for the production of detectible age strengthening of cast iron. The temperature range of super-saturation of ferrite lies from room temperature to 572F (300C), and beyond this range the possibility of aging is limited according to thermodynamics.

Machinability of Aged Cast Irons

Cutting Tool Forces: The machinability test articles recommended by the American Foundry Society were used for facing cuts on a computer numeric control (CNC) lathe. These test articles were produced in a laboratory using nobake molds and in industrial metalcasting facilities using green sand molds. Pearlite/ferrite cast irons with variations in carbon equivalent from 3.9% to 4.3% were tested in as-cast condition and after 25 days of natural aging. In as-cast or in unaged condition, the cutting forces increased with increasing hardness in irons having less carbon equivalent, which is typical and expected. At the same time, a reverse type of dependency appeared in which the cutting force decreased when the increasing hardness was due only to natural aging in each iron.

This unusual behavior could be explained by the energy requirement for chip formation. In unaged cast iron, soft ferrite absorbs energy for significant plastic deformation. This effect results in edge build-up on the tool tip, which also could promote increasing cutting force by enlarging the deformation region (similar to tool wear). In contrast, when iron aging occurs as a result of Fe4N precipitation in ferrite, it increases the iron’s strength and hardness and allows for chip formation with a smaller amount of plastic deformation, which could decrease the cutting force.

Similar results were achieved in other cast irons having ferrite in metal matrix and different graphite shapes. For example, aging decreased cutting forces after aging ductile iron with spherical graphite and significant free ferrite.

However, aging does not always improve cast iron machinability. For example, aging cast iron containing carbide forming elements produced a completely opposite effect on casting machinability. There was a visible and statistically significant increase of the average normal cutting forces for aged samples versus unaged samples. The ratio of passive to normal cutting forces is used as an indicator of tool wear, because as a tool loses sharpness, it has an increasing passive reaction force. This ratio increased more significantly when cutting aged gray iron with carbide-promoting element content. The microstructure in this case was pearlitic with some steadite and free carbide but no free ferrite.

To verify the effect of microstructure on cast iron machinability, castings from the same heat were tested further after ferritizing/resolutionizing heat treatment. This treatment transformed pearlite to ferrite and produced a resolutionizing effect, which allowed repeating the natural aging. The effect observed was opposite to the previously discussed test of cast iron with pearlite matrix and steadite phase, in that aging of ferritized/resolutionized gray iron improved machinability. The cutting forces were decreased at
all cutting speeds studied (Fig. 3). It can be concluded from these tests that all gray iron showing improved machinability in the aged condition contained some amount of free ferrite, while gray iron showing increased cutting forces after aging had no free ferrite but was entirely pearlitic with cementite/steadite phases.

This differing behavior of aged cast irons depending upon metal matrix relates to the energy of chip formation. Although gray cast iron is a brittle material in tension, chips can experience significant plastic deformation because the stress state during machining is dominated by compression and shear. If chip formation is assumed to be a plastic strain to fracture event, then changes in fracture toughness would logically affect machining behavior. Fracture work during tensile testing was estimated from the stress-displacement curve. In the pearlitic iron, the work of fracture and cutting forces increased after aging.

On the contrary, iron ferritized by heat treatment showed decreased work of fracture and cutting forces due to aging.

Tool Wear and Industrial Machining Measurements

Tool wear is lower when machining gray cast iron aged at room temperature because aged iron requires less work input from the machining center to form and break off chips. The decrease in required work has been demonstrated by tool force measurements and by testing amperage drawn while machining unaged and aged iron. The least power was required to machine castings aged for 3-6 days versus iron aged for 1, 9 and 20 days. At that optimal aging time, machined castings had better surface quality (less roughness), but all aged iron had better surface finish than unaged iron.

Other tests were performed with industrial face machining of brake discs for a passenger car. Excessive tool wear produced changing tool geometry and increased cutting forces, which promoted elastic deformation of casting with increasing tilt and destroying required tolerance on perpendicularity (“tilt”). Tilt data from the machining of industrial castings were compared in two ways. The machining of the 50 unaged castings required two tool position changes. Tool position changes were not required during machining of aged castings after 50 or 200 castings, indicating more consistent dimensions and reduced downtime for tool position corrections. Figure 5 gives a comparison of measured tool wear for different operations. Aging decreased tool wear significantly in most of the operations.

Industrial Recommendation for Improving Cast Iron Machinability by Aging

Three possible scenarios exist for changes in machinability of gray iron during natural aging.

First scenario: Aging does not occur and therefore, has no influence on machinability. Lack of aging effects in the iron can be caused by elevated nitride forming elements (particularly tita-nium) relative to nitrogen. Additions of nitrogen to iron are possible and can enhance aging. Thermodynamic data can be applied to determine if there is enough “free nitrogen” to age a cast iron. A simplified criterion might be:
If %N < (0.15-0.20) %Ti, aging will not occur. Second scenario: If cast iron exhibits aging, this phenomenon can be used for improving casting machinability. Aging is accompanied by decreasing cutting forces and tool wear. These irons have enough free nitrogen to promote age strengthening. Decreased cutting forces and increased mechanical properties were proven in laboratory castings having different carbon equivalents. These irons had some free ferrite and no free cementite or steadite. Optimal aging time depends upon particular “free manganese” content and could be evaluated. Decreasing aging time for improving machinability could be done by warm (slightly elevated temperature) aging. Third scenario: Gray iron has elevated concentrations of carbide forming elements such as chromium in addition to a large percentage of phosphorus. These combinations of chemistry with a particular cooling rate could promote steadite/cementite formation in fully pearlitic ma-trix. If this iron has negligible free ferrite, aging will increase cutting forces in this iron. Effective inoculation and chemistry control will affect casting machinability interaction with aging in these cast irons. However, in this scenario, “fresh” castings might prove more machinable. Confirmation Test Five AFS 5J, 10-in. diameter test articles were poured into nobake molds from one 200-lb. induction furnace heat. The cast iron chemistry is shown in Table 2. Microstructure was mostly pearlitic with approximately 5%-10% ferrite. Measured hardness in the middle section of the test article was 200-210HB in the as-cast condition (unaged). The as-cast surface layer (1/8 in.) was removed in preliminary machining to avoid the effects of cast surface structure, mold-metal interaction and geometry variance on test results. Test articles were face CNC machined at day 0, day 5, day 9, day 15 and day 22 with measurement of cutting forces. Eight cuts (30 min. total machining time) were performed from each disc, using a new tool insert each time. The thickness of the test article produced eight duplicate cuts and each test was repeated twice. The test results are shown in Fig. 7. These test results were compared to the predictions according to suggested methodology. Step 1—Evaluation of the possible age strengthening: Nfree = N-0.20Ti = 0.01-0.2*0.008 = 0.0084 wt.% or 84 ppm; total %N and %Ti leads one to expect approximately 0.14 wt. % Fe4N. Age strengthening will occur. Step 2—Control microstructure: In a matrix without free carbide/ steadite having a small amount of free ferrite around flake graphite, age strengthening can improve casting machinability according to the second scenario. Step 3—Aging time: Full aging time is 15-17 days and prestrengthening time is 7-9 days. The tool force dropped significantly during the first five days and was also low at 15 days, roughly corresponding to the expected times for room-temperature age strengthening. The predictions based on the previous studies were confirmed. A significant decrease in cutting force and standard variation were observed after 9-15 days of natural aging, which is between predicted prestrengthening and full aging time. Regarding other machinability parameters, tool wear not only depends on the average value of cutting force but also the stability of cutting process, and tool wear continued to decrease up to the full aging time. These rules can assist in determining the optimal machinability window for aged cast iron: Estimate free nitrogen based on total nitrogen and concentration of titanium as %N >0.2 %Ti, but not high enough to form gas porosity in order to have age strengthening.
Check microstructure concerning ferrite/pearlite content without steadite/carbides. If no free ferrite is present, particularly with all pearlite and some carbide or steadite, the machinability might be better with fresh castings given a composition that will age strengthen. If free ferrite is present, age strengthening will provide a corresponding improvement in machinability.

Estimate room-temperature aging time based on free manganese left after sulfide formation. Aging acceleration is possible with a low temperature bake.

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