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RAPID TEMPERING OF AUTOMOTIVE AXLE SHAFTS

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Rapid tempering of AISI 1050M steel using an in-line tempering furnace with an ultrahigh rate of air convection movement reduced tempering cycle time by 80% with no discernable degradation of mechanical and fatigue properties.

RAPID TEMPERING OF AUTOMOTIVE AXLE SHAFTS

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Automotive axle shaft forging/extrusions are machined and formed to near net shape and then induction hardened and quenched in water. Hardened shafts generally are tempered in a furnace at a temperature of 280 to 325°F (140 to 165°C) for a minimum of 75 minutes to achieve a post tempered hardness of 60 HRC minimum at the bearing journal surface.

Tempering is carried out in a two-zone gas-fired furnace having a sizeable foot print, which was designed to accommodate many different shaft designs. Shafts are manually loaded and unloaded onto conveyers that hold the shaft in a vertical position as it travels through the furnace. Total cycle time, including load, tempering, cool down and unload is between 3 and 4 hours.

The introduction of a new axle shaft design created a need to purchase new manufacturing equipment/processes that could support lean manufacturing concepts. Lean manufacturing is a production philosophy that emphasizes minimization of the amount of all the resources, including time, used to manufacture a component or assembly. The existing tempering equipment/method was not compatible with lean manufacturing of axle shafts.

Rapid Tempering: An Alternative

Alternate furnace technology for tempering interconnecting shafts and constant velocity (CV) joints was being used at a sister division, which afforded an opportunity to perform tempering tests on axle shafts using its furnace technology, called forced air convection tempering (FACT). It uses an efficient furnace design consisting of multiple zones within the furnace to allow for rapid, uniform component heating and soaking, which results in rapid heat transfer to the components. The design provides high rates of thermal radiation, convection, and conduction.

Implementing the rapid tempering method required a new mindset in defining adequate tempering. Historically, time at a particular ambient furnace temperature was considered

Fig. 1 — Thermocouples located at the spline end (a) and bearing region (b) of the axle shaft and overview of instrumented shaft with data recorder attached (c)

***Member ASM International and member, ASM Heat Treating Society* critical regardless of actual furnace loading or heat transfer rate. By comparison, tempering criteria using FACT methodology was redefined as the uniform achievement of the desired tempering temperature in the case hardened component while maintaining the minimum surface hardness requirements in the bearing journal.

Validating FACT

Tempering tests were conducted using the FACT tempering furnace to validate its capability to process axle shafts, and based on the positive test results, a specialized horizontal FACT furnace was designed, purchased, installed and commissioned in 2003. Furnace performance was very good, and resulted in additional testing and the purchase of a higher throughput vertical FACT furnace in 2005 for other established axle shaft production lines.

Thermal Profiles and Furnace Uniformity

Thermocouples were attached to representative axle shafts at critical regions to accurately measure the heat transfer rates of conventional tempering and FACT methods. Because temperature uniformity of the core and surface of the shaft were of primary concern, thermocouples were located both at the surface and core (midpoint) of bearing journal (largest cross sectional area) and the spline (smallest cross sectional area). The thermocouples were connected to a Datapaq (Datapaq Inc., Wilmington, Mass.;www.datapaq.com) recorder to measure temperature versus time. Figure 1 shows an instrumented shaft at different locations.

An instrumented axle shaft was sent through the horizontal FACT furnace six furnace times together with scrap axle shafts to represent a fully loaded production furnace, and temperature was recorded at specific furnace locations and times. Mean temperature readings ±1 standard deviation are shown in Fig. 2. Temperature consistency at the convergence temperature (300°F, or 150°C) region of the furnace is very good.

The rate of temperature rise and convergence in the representative axle shafts was also of interest. The initial goal was to rapidly heat the shaft so both the core and surface of the bearing and spline reached the same convergence temperature. Figure 3 is a thermal profile by location on the axle shaft versus time for the vertical FACT furnace. The blue trace represents the ambient furnace temperature and indicates the two specific heating zones. The black and yellow traces represent the temperature of the spline at the surface and core, respectively, and the red and green traces represent the temperature at the bearing surface and core, respectively.

The instrumented axle shaft was also processed through the conventional temper furnace for comparison

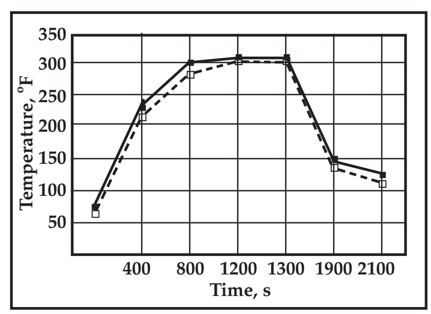

Fig. 2 — Temperature uniformity and repeatability for horizontal FACT furnace. Solid black = mean temperature +1 sigma, hollow square = mean temperature –1 sigma

Automotive Axle Shaft Anatomy

Automotive axle shafts transmit torque from the drive train to the rear wheels, support the vehicle load, and function as the inner race for the wheel bearings. Four key design features of an axle shaft are:

- Flange, wheel, and brake pilot on one end, which are used as attachment points for the wheel and brake rotor or drum.
- The bearing (the largest cross sectional area of the shaft) adjacent to the flange, which is highly machined and polished to tight tolerances because it serves as the inner race for the wheel bearing
- The extruded shaft barrel (beyond the bearing journal)
- A formed or machined spline and retaining button at the end of the shaft barrel opposite the flange.

In an axle assembly, the spline is mated with a differential side gear, and is the portion of the shaft used to transmit torque through the shaft to the wheel end. The button end of the shaft is used as a retention mechanism and keeps the shaft in place within the axle assembly.

Axle shafts used in this study were made of hot-rolled AISI1050M steel bars having a manganese content of 0.8-1.1%. The hot-rolled bar is upset forged to form the flange, wheel and brake pilot details and the barrel is often cold extruded to taper the body of the shaft to the desired diameters. The axle shaft forging/extrusions are machined and formed to a near net shape condition and then induction hardened and quenched in water to 40 HRC with and effective case depth (ECD) of 0.120 to 0.250 in. (3 to 6.3 mm) in the barrel of the shaft. After hardening, the shafts typically are tempered at an ambient furnace temperature of 280 to 325°F (140 to 165°C) for a minimum of 75 minutes. A post tempered hardness of 60 HRC minimum must be maintained at the bearing journal surface. After tempering the shafts go through a series of finish machining, polishing and assembly operations.

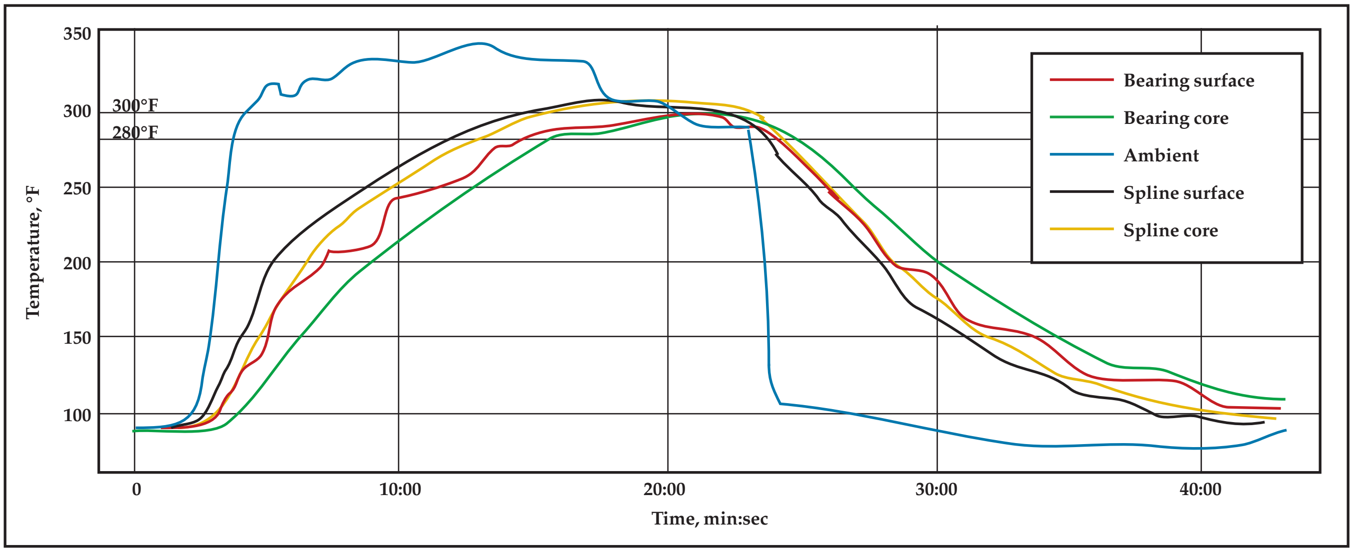

Fig. 3 — Thermal profile by processing time and location on axle shaft for vertical FACT furnace

purposes. Table 1 lists key heat transfer rates. The heating rate in the FACT furnace is six times faster and the time at tempering temperature is reduced six fold compared with the conventional furnace. The spline and bearing did not achieve the same convergence temperature in the vertical FACT furnace. In this application, the spline temperature was 10 to 15°F (6 to 8°C) higher than the bearing temperature. The difference is due to the considerable difference in cross sectional area/mass. However, this was considered a benefit in that the spline portion of the shaft was subject to greater tempering resulting in increased toughness, while the bearing portion still maintained the required post-temper hardness.

The FACT furnaces used in these tests and subsequent production were designed to facilitate both robotic loading and unloading of the axle shafts. The total tempering (cycle) time from load to unload was 31 and 36 minutes for the horizontal and vertical furnaces, respectively. This resulted in an eight fold reduction in tempering (cycle) time compared with that of conventional tempering systems. Both FACT furnace designs used a cool down zone allowing handling parts by hand after tempering. The thermal profiles in Figs. 2 and 3 show the cool down zones in the horizontal and vertical FACT furnaces.

Test Results

For tempering validation testing, axle shafts were forged from a single heat of steel, green machined and induction hardened using the same induction hardening system, and randomly separated into two groups for tempering. One (baseline) group was tempered conventionally and the other group was tempered using a previously optimized FACT process. After tempering, shafts from each group were color coded, then randomly reintroduced into the manufacturing process for the required finishing operations.

Mechanical properties, including surface hardness, microindentation hardness, residual stress profiling, torsional JAEL and rupture strength, rolling bending, and torsional fatigue life, of all tempered shafts were measured to determine if axle shafts of comparable conventionally tempered quality could be made using the FACT tempering process.

Hardness

Surface hardness of several shafts from multiple treatment groups was measured. Figure 4 shows the hardness populations in Box-Whisker plots. Each rectangular box represents the 25% and 75% quartiles of the population, and the horizontal line bisecting the box is the median. The whiskers emanating from a box represent the 0% and 100% quartiles, and the asterisks indicate values that exceed ±3 standard deviations. From Figure 4, the as-quenched hardness of the axle shafts is 64-65 HRC. After tempering, all treatments had comparable hardness in the range of 61-63 HRC.

Microindentation hardness profiles in the spline cross section of axle shafts tempered using the various

Table 1 — Thermal profile of conventional tempering and vertical FACT furnaces

Location on instrumented axle shaft	Ramp rate (°F/min) from 100-280°F		Time (min) at temp. 280-325°F		Peak convergence temp.,°F	
	FACT (new)	Conventional	FACT (new)	Conventional	FACT (new)	Conventional
Bearing core	22.8	3.5	12.7	85.0	302	298
Bearing surface	22.8	3.5	14.0	85.0		
Spline core	30.5	4.3	15.3	95.0	315	298
Spline surface	32.7	5.5	15.3	117.0		
Average	27.2	4.2	14.3	95.5		

methods are shown in Fig. 5. Hardness profiles are identical for the three temper treatments.

X-ray Stress Analysis

The transformation from austenite to martensite in the hardened axle shafts imparts compressive stress on the barrel surfaces, which results in favorable fatigue properties of the shaft [1]. Tempering the shafts in a temperature range of 300 to 400°F (150 to 205°C) relieves some of these compressive stresses resulting in a modest increase in toughness [2], which is adequate for the required wear resistance, high strength, and fatigue resistance in axle shaft applications.

The compressive stresses at various depths in the shaft were measured using an x-ray stress analysis method that uses x-ray diffraction to quantify the amount of crystallographic strain present, and subsequently calculates the corresponding stress value. Figure 6 shows a plot of residual stress versus depth from the surface. The as-quenched (untempered sample) has the greatest compressive stresses at 0.020 to 0.025 in. (0.5 to 0.63) depth from the surface. Both the conventional and FACT processes similarly relieve the compressive stress at that depth. However, some beneficial compressive stress is still present near the surface (<0.005 in., or 0.127 mm) for the FACT sample.

Torsional JAEL and Rupture Strength

The torsional strength of an axle shaft is determined by securing the flange end of the shaft to a bed plate and applying torque to the spline end of the shaft at a known rate of deflection. A plot of applied torque versus deflection is recorded and the load at which the shaft catastrophically fractures is the rupture strength. The Johnson apparent elastic limit (JAEL) method is used to measure the yield strength. JAEL is defined as the torque at which the rate of deformation/deflection is 50% greater than the initial rate of deformation/deflection. The JAEL is advantageous for torsional testing and design purposes, and is similar to yield strength determination in a tensile test.

Figure 7 shows normal probability plots for the JAEL strength for different tempering treatments of the shafts. The x axis is the JAEL torque and the y axis is a cumulative percentage of the population. The straight lines represent the best-fit estimate of JAEL strength. Using the best fit line and reading from the x and y ordinates, predictions of JAEL loads for given percentages of the population can be made for each treatment group. The parabolic lines encompassing each best fit line represent the 90% confidence interval. In making treatment comparisons, any confidence intervals that overlap are not statistically different from one another. From the JAEL plot in Figure 7, the conventional and FACT processes demonstrate similar JAEL strength, which exceeds those of the untempered samples.

Figure 8 is a normal probability plot of rupture strength for the different tempering treatments. This plot indicates that both temper

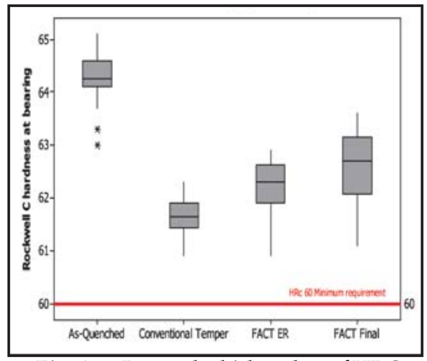

Fig. 4 — Box and whisker plots of HRC at the bearing journal for as quenched, conventional temper, and FACTempering during equipment run off (ER) and final prove out

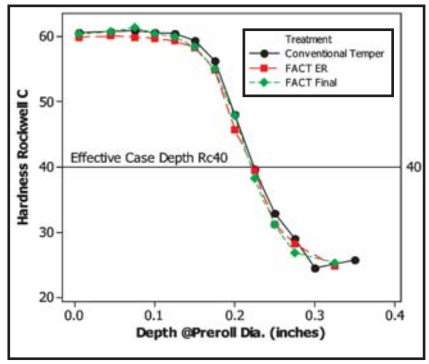

Fig. 5 — Microindentation hardness profiles at the spline cross section for conventional and FACT (equipment run off) samples

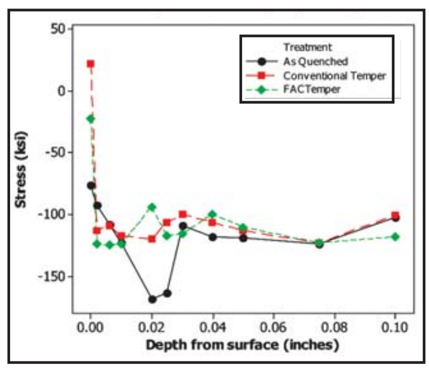

Fig. 6 — Scatter plot of residual stresses as a function of depth from the surface for as-quenched and tempered methods.

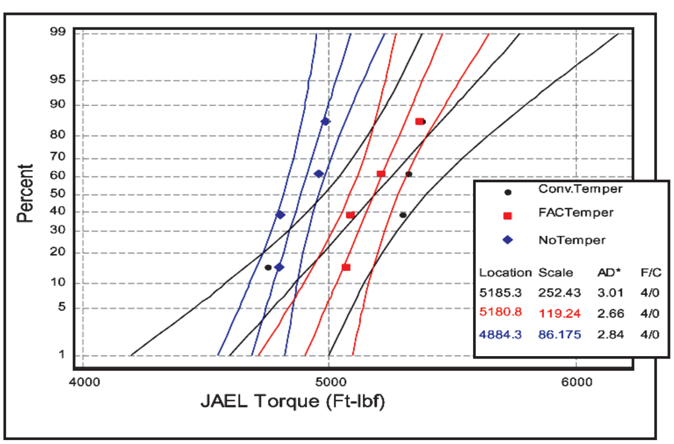

Fig. 7 — Normal probability plot of JAEL strength for various as-quenched and tempering conditions

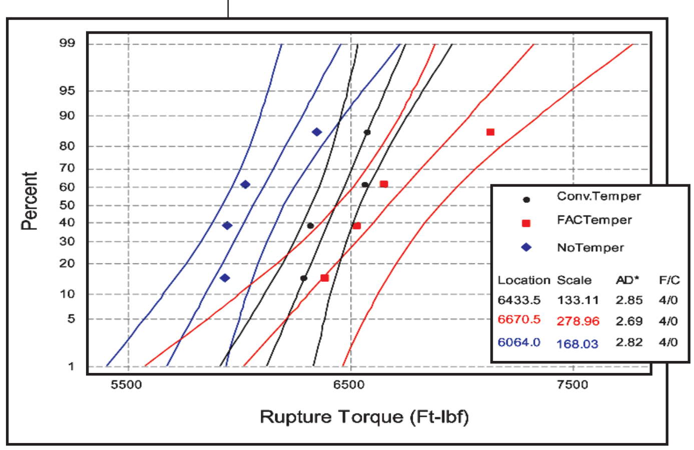

Fig. 8 — Normal probability plot of rupture strength for as-quenched and conventional and FACT treatments

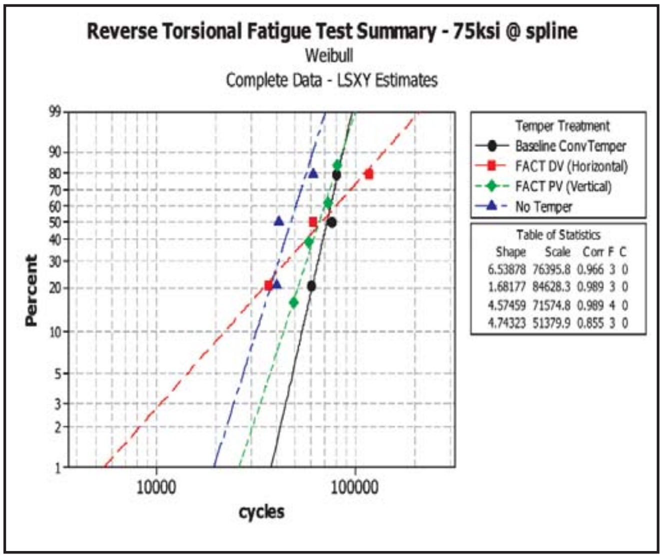

Fig. 9 — Weibull plot of reverse torsional fatigue for various tempering treatments

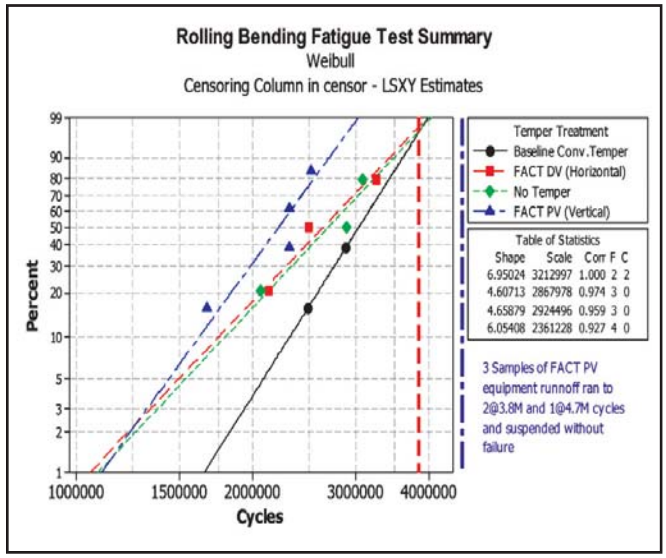

Fig. 10 — Weibull plot of rolling bending fatigue life by tempering treatment

methods result in shafts having similar rupture strength, and the as-tempered strength is superior to shafts that are untempered.

Reverse Torsional Fatigue

The fatigue effects of repeated forward and reverse torque cycles that an axle shaft experiences in a vehicle are reproduced in reverse torisonal fatigue testing. In the test, the flange end of the shaft is fixed and a set torsional stress of 75 ksi (517 MPa) is applied through the spline of the shaft in both the forward and reverse directions at 0.83 Hz. The load required to produce a 75 ksi stress is typically around 50% of the JAEL load. The number of cycles until shaft failure is recorded and then plotted and analyzed using Weibull methods.

The *x*-axis of the Weibull plot records the number of cycles until torsional failure and is logarithmic in scale. The *y*-axis can be used to predict the proportion of a population that will fail at a given number of cycles. To improve the readability of the graph, the 90% confidence intervals were not plotted. However, all treatment groups had similar reverse torsional fatigue life; no significant statistical differences were detected.

Rolling Bending Fatigue

A rolling bending test is used to simulate the fatigue characteristics of simultaneous bending and rotational effects on an axle shaft in a vehicle. In the test, a wheel bearing is installed onto the axle shaft and located on the bearing diameter at the same position that it would be in the vehicle. The flange is then fixed to a fly wheel, which is, in turn, rotated using a belt. A special side gear is attached to the spline end so a vertical load perpendicular to the axis of the shaft can be applied while the shaft is rotating. The value of this applied load is calculated based on the design parameters of the axle assembly. The applied tangential load causes the shaft to bend elastically while it is rotated producing alternating cycles of compressive and tensile stress at the junction of the bearing journal and the back face of the flange and the shaft/bearing interface. The shaft is rotated under a specified load at 1,000 rpm until failure, and the number of cycles until failure is plotted using a Weibull plot.

The Weibull plot shown in Fig. 10 demonstrates considerable variability in rolling bending fatigue life for the different tempering treatments. This may be due to the sensitivity of this test to set-up procedures and to the fact that this testing was performed over the course of several months and by different technicians. Several samples of the vertical FACT furnace had rolling bending fatigue life in excess of 4×10^6 cycles and were suspended without failure. On the low end, several samples had rolling bending fatigue lives of 1.6 to 2×10^6 cycles. The acceptance bogey for this test is 1×10^6 cycles, which was easily met for all tempering treatments.

Conclusions

The results of this work show that effective tempering of induction-hardened axle shafts is dependent on actual heat transfer rates and component temperature rather than on time at a specified ambient furnace temperature. This study verifies that tempering furnace designs that maximize heat transfer rates to axle shafts achieve:

- Equivalent post-temper hardness at the bearing journal surfaces
- Equivalent post-temper microindentation hardness and residual stress profiles within the shaft
- Equivalent torsional JAEL and rupture strengths
- Equivalent reverse torsional and rolling bending fatigue life
- Reduced tempering cycle time (from 4 hours to 36 minutes, or >80% reduction)

References

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