Tempering of Fasteners

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Tempering is actually a complex activity in which all process and equipment variability must be carefully controlled for its successful implementation.

Tempering (a.k.a."drawing") is one of the most common heat treatment processes for fasteners—and one that is all too often taken for granted. As heat treaters, we know it's important, yet we often spend little time focused either on the process or on the equipment in which it is performed. Fastener manufacturers cannot afford the luxury of not knowing how this step in the heat treatment process affects their products.

What is Tempering?

When we temper a fastener, we tend to focus on a single parameter—hardness as the only criterion for success or failure of the tempering operation. We must broaden this perspective and understand that tempering is done to "toughen" a steel that has been previously hardened or normalized. In precipitation hardened alloys as well as many grades of aluminum and superalloys, tempering precipitates intermetallic particles which strengthen the metal. High-speed steels are often tempered multiple times to achieve proper hardness and aid dimensional stability by transforming retained austenite first to untempered martensite and on subsequent tempers to tempered martensite.

Since the as-quenched microstructure of a hardened steel fastener is primarily martensite, we know it to be highly unstable and in a strain-induced state. Tempering is, therefore, the modification of this hardened microstructure towards a more equilibrium condition. The resulting change of martensite also results in a slight increase in grain size and a decrease in volume as a function of increasing tempering temperature.

Tempering temperature, time at temperature, cooling rate from tempering temperature and steel chemistry are the variables associated with tempering that affect the mechanical properties and microstructure of the finished fastener. Changes to the microstructure by tempering typically decrease hardness and strength (tensile and yield) while increasing ductility and toughness. Tempering results in an increase in softness, malleability, impact resistance and improves dimensional stability.

A good rule to remember is that all steel should be tempered as soon as possible after being removed from the quench and before the fastener is completely cold. Failure to temper correctly can lead to a myriad of performance problems such as premature failure or shorter than normal service life. A common call out in various specifications is to "temper immediately" which is subject to broad interpretation throughout the industry. For materials such as 4340, tempering must take place within 15 minutes of removal from the quench to avoid quench cracking. For high-speed steels, you want to cool to 120°F to 150°F (50°C to 65°C) and then temper—but it is all too common to find loads sitting waiting for a temper furnace for up to a day. This practice should be avoided.

Tempering is always performed below the lower critical temperature (A_1) of the steel and this differentiates tempering from such processes as annealing, normalizing, and hardening. When hardened steel is reheated, temper effects start to occur as low as 212°F (100°C) and accelerate as the temperature increases. By selecting a definite tempering temperature, you can predetermine the resulting hardness and strength. One caution is the avoidance of issues such as temper embrittlement (for more detail, see "The Embrittlement Phenomena in Hardened & Tempered Steel", *Industrial Heating*, October 2006).

The minimum time at temperature for tempering should be one hour. A good rule of thumb for furnace or oven tempering is that if the fastener is more than 1" (25 mm) thick, increase the tempering time by one hour for each additional 1" (25 mm) of thickness.

Stages of Tempering

Tempering is said to occur in three distinct stages in overlapping temperature ranges (**Table 1**). The precipitation of finely dispersed alloy carbides responsible for secondary hardening (in highly alloyed steels) is sometimes referred to as the fourth stage of tempering. It is important to know what is happening to the part microstructure at the tempering temperature you select.

Table 1[1]. Tempering Stages.

Stage	Temperature Range	Characteristic
One	210°F - 480°F (100°C - 250°C)	The lowering of the carbon content of the martensite to approximately 0.25%C and the formation of transition carbides.
Two	390°F - 570°F (200°C - 300°C)	The transformation of retained austenite to ferrite and cementite (Fe_3C).
Three	480°F - 660°F (250°C - 350°C)	The replacement of transition carbides and low temperature martensite by cementite and ferrite.

Considerations in Tempering Equipment

When designing a tempering process, consideration must be given to the type and condition of the tempering equipment. In particular, airflow and temperature uniformity play a critical role. Tight temperature uniformity, typically ±10°F (±5.5°C) is required throughout the load, with ±5°F (±2.75°C) preferred especially for high-speed and precipitation hardening steels. The ability to have a rapid heating rate will shorten overall cycle time.

Various forms of self-tempering and accelerated tempering via induction or ultrahigh air convection ovens and furnaces have shown promise in a number of applications[2]. Although soak times and temperatures are typically fixed by steel chemistry, substantial reductions in processing times have been reported by accelerating the heat up time by designing more efficient heat transfer between the heated atmosphere and the load using high speed convective, turbulent flow patterns.

Temper Colors

The use of temper color is one method of not only visually determining if a fastener has been exposed to the proper tempering temperature, but to check if all parts in a given load reached a uniform temperature.

When steel is heated and exposed to air (or an oxidizing atmosphere) for a short period of time it will change color due to the presence of a thin, tightly adhering oxide. The temper color and thickness of the oxide layer varies with both time and temperature (**Table 2**). Different steel chemistries also result in slight color variations. The colors produced are typically not uniform, because of surface condition and fluctuation of temperature.

In order to see the colors clearly, you must turn the part from side to side and have good lighting. Natural lighting is always best.

Table 2. Steel Color Changes as a Function of Tempering Temperature.

Temperature ºF (ºC)	Temper Color
400 (205)	Faint straw yellow
425 (220)	Light straw yellow
440 (225)	Straw yellow
475 (245)	Deep straw yellow / light brown
500 (260)	Orange / brown
520 (270)	Bronze / dark brown
525 (275)	Light purple
545 (285)	Purple / peacock
560 (295)	Dark blue
590 (310)	Full blue
620 (325)	Grey
660 (350)	Grey-purple
705 (375)	Grey-blue
750 (400)	Dull grey
>750 (400)	Black*

* Oxide adherence issues occur above 750ºF (400ºC), with surfaces appearing first as a velvet-textured oxide, progressing to loose, flaky scale.

Case Study

As an example, a fastener manufacturer was interested in establishing the relationship between tempering temperature and (final) hardness for a number of common fastener materials (see **Table 3**) while holding the hardening parameters constant.

A number of controlled tests was conducted (**Table 4** on next page of this article) in order to develop the desired relationship (**Figure 1** on next page of this article) targeting values in the middle of the targeted range.

Charts or graphs developed from testing such as done in this case study simplify the tempering process and make the job of the heat treater easier.

Final Thoughts

Tempering, because it is often the last heat treating operation, is considered by most to be relatively simple and straightforward yet the heat treater must remember that it is a complex process in which all of the process and equipment variability must be carefully controlled.

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References:

[1] *Krause, G., Steels: Heat Treatment and Processing Principles, ASM International, 1990.*

[2] *Grenier, Mario and George E. Totten, Rapid Stress Relieving and Tempering, Gear Solutions, May 2005.*

[3] *Herring, D. H., What Do We Really Know About Tempering?, Industrial Heating, July 2007.*

[4] *Herring, D. H., The Embrittlement Phnomena in Hardened & Tempered Steel, Industrial Heating, October 2006.*

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Table 3. Materials Selected for Tempering Study.

	C		Mn		Si		Cr		Ni		Mo		As		V		W		B		P	S	Ac_1	Ac_3
Grade	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Max	Max	°F	°F
1022	0.18	0.23	0.70	1.00																	0.040	0.050	1317	1505
1035	0.32	0.38	0.60	0.90																	0.040	0.050	1319	1454
1038	0.35	0.42	0.60	0.90																	0.040	0.050	1319	1443
1038H	0.34	0.43	0.50	1.00	0.15	0.35															0.035	0.040	1332	1463
1042	0.40	0.47	0.60	0.90																	0.040	0.050	1319	1429
1045	0.43	0.50	0.60	0.90																	0.040	0.050	1319	1421
1050	0.48	0.55	0.60	0.90																	0.040	0.050	1319	1408
1541	0.36	0.44	1.35	1.65																	0.040	0.050	1305	1439
4037	0.35	0.40	0.70	0.90	0.20	0.35					0.20	0.30									0.035	0.040	1332	1483
4140	0.38	0.43	0.75	1.00	0.20	0.35	0.80	1.10			0.15	0.25									0.035	0.040	1360	1471
5115	0.13	0.18	0.70	0.90	0.20	0.35	0.70	0.90													0.035	0.040	1357	1548
8637	0.35	0.40	0.75	1.00	0.20	0.35	0.40	0.60	0.40	0.70	0.15	0.25									0.035	0.040	1329	1465
8637H	0.34	0.41	0.70	1.05	0.20	0.35	0.35	0.65	0.35	0.75	0.15	0.25									0.035	0.040	1329	1465
10B21	0.18	0.23	0.60	0.90															0.0005	0.0030	0.035	0.040	1319	1505
10B30	0.28	0.34	0.60	0.90															0.0005	0.0030	0.035	0.040	1319	1467
10B31	0.28	0.34	0.60	0.90															0.0005	0.0030	0.035	0.040	1319	1467
15B30	0.28	0.34	0.60	1.00															0.0005	0.0030	0.035	0.040	1318	1467
15B30H	0.27	0.35	0.70	1.20	0.15	0.35													0.0005	0.0030	0.035	0.040	1328	1487
15B35	0.33	0.38	0.70	1.20	0.15	0.35													0.0005	0.0030	0.035	0.040	1328	1472
15B35H	0.31	0.39	0.70	1.20	0.15	0.35													0.0005	0.0030	0.035	0.040	1328	1474
50B35	0.33	0.38	0.75	1.00	0.20	0.35	0.40	0.60											0.0005	0.0030	0.035	0.040	1346	1474

Table 4. Results of Experimental Trials.

Material Grade	Austenitizing Temperature °F (°C)	Oil Temperature °F (°C)	As-Quenched Hardness (HRC) Min	As-Quenched Hardness (HRC) Max	Targeted As-Tempered Hardness (HRC) Min	Targeted As-Tempered Hardness (HRC) Max	Actual As-Tempered Hardness (HRC)	Tempering Temperature °F (°C)
1022	1600 (870)	160 (70)	42	47	25	29	27.0	775 (415)
1035	1600 (870)	160 (70)	44	49	25	34	29.5	940 (505)
1038	1600 (870)	160 (70)	45	50	24	30	27.0	980 (525)
					25	29	27.0	980 (525)
					25	34	29.5	940 (505)
					29	34	31.5	900 (480)
					28	35	31.5	900 (480)
					33	39	36.0	820 (440)
					35	39	37.0	810 (435)
1042	1600 (870)	160 (70)	46	51	20	28	24.0	1100 (595)
1045	1600 (870)	160 (70)	47	52	20	28	24.0	1100 (595)
					22	26	24.0	1100 (595)
1050	1600 (870)	160 (70)	48	52	28	35	31.5	975 (525)
1541	1600 (870)	160 (70)	49	55	28	35	31.5	940 (505)
					32	36	34.0	
4037	1600 (870)	160 (70)	50	56	25	34	29.5	1020 (550)
					28	37	32.5	970 (520)
					33	39	36.0	900 (480)
					39	42	40.5	820 (440)
4140	1600 (870)	160 (70)	48	53	25	34	29.5	1130 (610)
					33	36	34.5	1020 (550)
					33	39	36.0	980 – 990 (525 – 530)
					38	42	40.0	900 (480)
					43	47	45.0	800 (425)
5115	1600 (870)	160 (70)	35	40	80	95	87.5	
8637	1600 (870)	160 (70)	51	56	25	34	29.5	1100 (595)
					30	38	34.0	980 (525)
					33	38	35.5	940 (505)
					33	39	36.0	930 (500)
					37	42	39.5	840 (450)
					38	42	40.0	830 (445)
10B21	1600 (870)	160 (70)	44	46	25	34	29.5	880 (470)
10B30	1600 (870)	160 (70)	46	50	21	25	23.0	1090 (590)
					25	34	29.5	900 (480)
					26	32	29.0	900 (480)
					33	39	36.0	770 – 780 (410 – 415)
					35	39	37.0	760 (405)
					38	42	40.0	710 (375)
10B31	1600 (870)	160 (70)	46	51	33	39	36.0	770 – 780 (410 – 415)
15B30	1600 (870)	160 (70)	49	52	33	39	36.0	800 (425)
					36	42	39.0	730 – 740
								(388 – 393)
15B35	1600 (870)	160 (70)	51	55	33	39	36.0	820 (440)
					36	42	39.0	760 (405)
50B35	1600 (870)	160 (70)	50	54	25	29	27.0	1060 (570)
					25	34	29.5	1000 (540)
					33	39	36.0	880 (470)
					35	39	37.0	860 (460)
					37	42	39.5	815 – 820 (435 – 438)

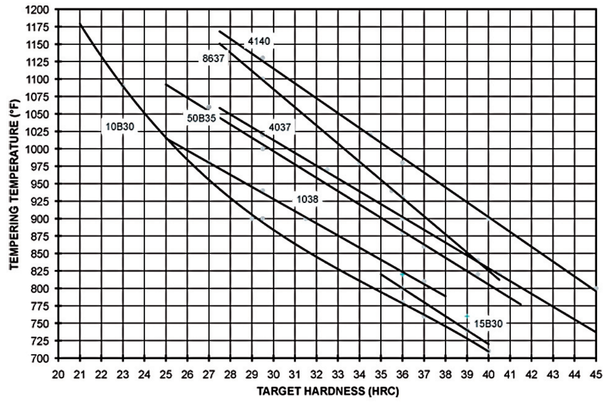

Fig. 1 — Example of the relationship of tempering temperature to final hardness for selected steels.

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Company Profile:

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