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# The tempering parameter for evaluating softening of hot and warm forging die steels

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ABSTRACT

The tempering characteristics of three different hot and warm forging die steels (FX, 2714, and WF) were systematically studied over a range of temperatures (316–677 °C) and a range of times (1–300 h). The softening rate for each steel was determined by the change in room temperature hardness. In this study, the hardness data are quantitatively related to the tempering parameter via regression analysis. The tempering parameter (also known as the Hollomon–Jaffe parameter or the Larson–Miller parameter) accounts for the effects of both tempering time and tempering temperature. Room temperature hardness is a measure of the microstructural change that occurs during the tempering process. Results from this study show a bilinear softening as a function of the tempering parameter. For hot and warm forging application the second portion of the curve is more applicable, since these die steels are tempered to some extent before initial use. The slope of the curve can be used as a measure of softening, which is one of the contributing factors on how well the die steel will perform in actual forging operations. These results indicate that WF has the highest resistance to softening during use, FX is somewhat less resistance to softening, and 2714 is the least resistant of the three die steels studied.



## 1. Introduction

Tempering is a low temperature heat treatment given to martensitic steels usually after the steel has been quenched. Tempering improves the toughness of the steel but causes a decrease in the hardness. Tempering is performed on forging die steels before they are initially put into service so that they will have the prerequisite toughness to meet the demands of the process. During production of hot or warm forgings the dies are subjected to heating usually of short duration by contact with the workpiece. This subsequent heating of the die steels can cause further tempering to occur especially in the surface layer of the die.

The tempering parameter, also known as the Hollomon–Jaffe (1945) parameter or the Larson–Miller (1952) parameter, combines the effect of time and temperature to describe the change in hardness during tempering of steels. The kinetics of the solid state reactions, which control the decrease in hardness depends primarily on the diffusion of carbon or nitrogen in the steel. The tempering parameter has been used for a number of industrial operations that depend upon both time and temperature. Such operations include the strain aging or paint bake aging of steels and the tempering of martensite. Gomes et al. (2010) have used the tempering parameter to predict the mechanical properties of quenched and tempered carbon steel. Janjusevic et al. (2009) have examined a high strength low alloy steel using the tempering parameter.

The present study evaluates the tempering parameter for steels with higher alloy content than in previous studies and at longer times and higher temperatures than are typically used for tempering martensite. The resulting data are applicable for evaluating the performance and softening resistance of hot or warm forging die steels during use. With greater resistance to softening the die steel can be used for longer production runs.

Shivpuri et al. (2005) indicate that adhesive wear, which is the primary cause for loss of dimensional control in hot forged parts, is a major factor that limits die life. Adhesive wear depends on the softening of the extreme outer surface layers of the hot forging die. The surfaces of the impressions in hot or warm forging dies are softened by repeated contact with hot workpieces. The tempering parameter can be used to quantify the surface softening, which is one of the contributing factors in wear of dies during production.

Various studies have been conducted in examining hot forging die life based on a die tempering analysis. Kang et al. (1998) have used the tempering parameter in a wear model to predict the useful die life of hot and warm forging tools. The die steel that they investigated was H13. Kang et al. (1999a) developed a wear model for

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**Table 1**
Nominal compositions of the forging die steels.

| Steel | C | Mn | Si | Ni | Cr | Mo | V |
|---|---|---|---|---|---|---|---|
| FX | 0.50 | 0.85 | 0.25 | 0.90 | 1.15 | 0.50 | |
| 2714 | 0.55 | 0.85 | 0.25 | 1.65 | 1.15 | 0.50 | 0.10 |
| WF | 0.42 | 0.75 | 0.50 | 0.80 | 2.50 | 1.00 | 0.08 |

hot forging dies which incorporates the tempering parameter. They developed a four parameter empirical fit of the tempered hardness for various dies as a function of the tempering parameter. The fitted equation exhibited a curvilinear behavior consistent with their experimental data. Kang et al. (1999b) used their wear model, based on the tempering parameter to compare with actual wear profiles in forging dies. They found very good agreement between their model and the experimental results. Kim et al. (2005) also used the tempering parameter in developing a model for the useful service life of H13. The limitations for the use of H13 were a combination of wear and local plastic deformation and the resistance of dies to both mechanisms decreased with increased values of the tempering parameter. Choi et al. (2012) examined the die wear and plastic deformation limits of warm forging dies with the use of the tempering parameter. They integrated their model into a finite element analysis of the process. They found that plastic deformation in addition to wear on the surface of the die caused limitations of die life. Zhao et al. (2011) used the tempering time and tempering temperature as two separate variables to study and improve the die life for hot forging of a steel gear ring. They observed that more wear was seen after forging for longer times or at higher temperatures.

Tempering of steel can be studied by metallographic observation or by hardness measurements. Since metallographic observation is time consuming compared to measuring hardness, hardness is normally used as a measure of the amount of tempering. In evaluating the hardness results, it must be recognized that the reported hardness values do not represent strength of the die steel at forging temperatures. The hardness measurements are used as a generalized metric to quantify the microstructural changes that occur due to tempering as the hot or warm forging production progresses. The change in microstructure at the extreme surface of the die controls both local die wear and local yield strength which leads to loss of dimensional control in forged parts.

The billets for hot steel forging are normally heated to 1100–1200 °C, and the forging dies are usually preheated to 200–300 °C. When the hot workpiece comes in contact with the forging dies, the surface of the die is heated to high temperatures for relatively short periods of time. In this study, die heating in the range from 316 to 677 °C is investigated by use of the tempering parameter. Three commonly used hot forging die steels, FX, 2714, and WF, were held for times ranging from 1 to 300 h over the temperature range of the study. Since the tempering parameter is a proven method for determining the combined effect of time and temperature on tempering of steel, the room temperature hardness of these die steels is assessed as a function of the tempering parameter. The objective of the study is to determine the behavior of the three die steels as a function of times and temperatures consistent with a steel forging process and to make a comparison between the expected performance of the three die steels.

## 2. Experimental procedures

### 2.1. Materials

This investigation examined three die steels – FX, 2714, and WF. Table 1 shows the nominal compositions for these three steels. The initial materials were received in the form of as-quenched rectangular blocks with dimensions of 50.8 mm by 44.5 mm by 12.7 mm.

**Table 2**
Hardness of as-received forging die steels.

| Steel | Hardness (HV) | Uncertainty[a] (HV) | Hardness (HRC) | Uncertainty[a] (HRC) |
|---|---|---|---|---|
| FX | 753 | ±18.2 | 61.5 | ±0.9 |
| 2714 | 716 | ±29.1 | 59.8 | ±1.3 |
| WF | 773 | ±17.3 | 62.6 | ±0.9 |

[a] One standard deviation.

Table 2 gives the initial hardness of the as-received steels. Each block was sectioned into four specimens before heat treatment. The specimen dimensions were 25.4 mm by 22.2 mm by 12.7 mm.

Table 3 lists the tempering temperatures and times for the three steels. All combinations of temperatures and times were used in the experimental work, resulting in forty-eight tempering conditions for each steel. The specimens were tempered in air using a resistance heated furnace followed by air-cooling. The holding time at temperature started when the furnace returned to the set point temperature after placing the specimen into the furnace. Normally there was about a 20 °C drop in temperature when specimens were placed in the furnace, and it took about 5 min to return to the set point temperature.

### 2.2. Specimen preparation prior to hardness testing

Prior to heat treatment one side of each sample was ground. After heat treatment, the surface was ground to a fine roughness and followed by polishing with a 6-μm diamond paste suspension. Sample hardness was measured within one hour of polishing.

With longer heating times and higher temperatures, a thin hard layer of reaction products was created on steel surface that was assumed to have formed by oxidation of the steel surface during heating. The thin oxide layer was more difficult to remove by grinding as compared to the surface of the non-heat-treated steel. The thin oxide layer had a negligible effect on sample preperation. For the two highest temperatures, some samples had a thicker scale layer that peeled off when they were being prepared for grinding. The thickest scale, which occurred at the 677 °C temperature for 300 h, was less than 0.2 mm. The effect of the thin oxide layer or the peeled oxide layer as well as any small amount of decarburization was believed to have no significant effect on the results.

### 2.3. Micro hardness testing

After samples had been heat-treated and polished to a fine surface finish, micro hardness was determined using a Vickers indenter with a 500 g load for 10 s. Micro hardness measurements were used because they can be accurately converted to nano hardness as demonstrated by Mencin et al. (2009). In determining the hardness of the surface layer of a die, the use of nano hardness testing is preferred because it more accurately represents the extreme surface of the die, which is where wear occurs.

**Table 3**
Tempering temperatures and times.

| Temperatures | | Times |
|---|---|---|
| (°C) | (°F) | (h) |
| 316 | 600 | 1 |
| 371 | 700 | 3 |
| 427 | 800 | 10 |
| 482 | 900 | 30 |
| 538 | 1000 | 100 |
| 593 | 1100 | 300 |
| 649 | 1200 | |
| 677 | 1250 | |