Induction Tempering of Steel

Time-temperature relationships for short-time tempering cycles were determined. The accuracy of conventional tempering parameters, such as the one proposed by Grange and Baughman, for short-time treatments at a fixed temperature ("isothermal" treatments) was established in salt-pot experiments for a variety of carbon and alloy steels fully hardened to martensite. In addition, the concept of an effective tempering parameter for tempering processes consisting of continuous heating and cooling (typical of induction- heating techniques) was developed. Determination of this effective tempering parameter is based on finding an effective time and temperature which allows the continuous cycle to be described in terms of an equivalent isothermal cycle. The applicability of this new technique was verified through laboratory induction tempering trials.

INTRODUCTION

The tempering of hardened steels is surely one of the most important of industrial heat-treating operations. For this reason, the mechanisms underlying the process as well as the effect of tempering on final mechanical properties have received wide attention over the past half century. Much of this information is well summarized in a variety of reference books on steel heat treatment.[1-4]

It was recognized by early researchers[5,6] that similar properties could be obtained in fully hardened steels that were tempered using a variety of time-temperature cycles. In other words, a high-temperature, short time cycle could readily be used to obtain tensile (but not necessarily fracture) properties identical to those developed during a lower- temperature, longer time treatment. Probably the first quantitative method for describing this effect, and a qualitative theoretical explanation for the relationship proposed, were put forth by Hollomon and Jaffe.[5] In their work, the tempered hardnesses obtained from various time-temperature cycles were found to be correlated through a parameter of the form $T(C + \log_{10} t)$, where T is the absolute tempering temperature in degrees Kelvin (assumed to be fixed during the entire treatment), C is a material constant, and t is the time in seconds. The values of C depended on alloy content. For plain carbon steels, it was found to assume values between approximately 10 and 20; its value decreased with increasing carbon content. Values of C for a number of alloy steels were also determined.

Hollomon and Jaffe also proposed a means by which a tempering parameter could be calculated for treatments involving continuous heating and cooling. However, there is no report of their method ever having been applied.

Following the pioneering work of Hollomon and Jaffe, equivalent time-temperature relationships for tempering martensite were further investigated by Grange and Baughman.[7] In this work a *unique* tempering parameter,

S. L. SEMIATIN, D. E. STUTZ, and T. G. BYRER are Principal Research Scientist, Metalworking Section; Research Scientist, Electronic Systems and Technology Section; and Director, Center for Metals Fabrication, respectively, of Battelle's Columbus Laboratories, Columbus, OH 43201.

7X18 + logio *t*), in which T is in degrees Rankine (=1.8 times degrees Kelvin) and t is in hours, or equiv- alently, 7(14.44 + $\log_{10} t$), in which t is in seconds, was established for the correlation of hardness data. The Grange and Baughman parameter was also found to be useful for a wide range of carbon and alloy steels. In addition, a method was developed whereby the relation between the tempered hardness of alloy steels and the tempering parameter could be deduced from that for the corresponding plain carbon steel. This method made use of a number of hardness point increments (or "alloying factors") whose magnitude depended on the alloying elements present and the amount of each. These increments are added to the tempering curve for the carbon steel to obtain that for the alloy steel.

The development of time-temperature relationships for very short tempering cycles such as may occur with heating *via* induction appears to have been neglected in the heat- treating literature. This is surprising in view of the extensive work on austenitizing and hardening *via* such methods, which dates from the 1940s.[8,9] This dearth of information is perhaps one reason why induction tempering is not used nearly as much as its hardening counterpart in commercial heat-treating operations.

In view of the potential benefits that could be realized *via* induction tempering, the present work was undertaken. Its objective was to develop an understanding of time- temperature relationships for very short tempering cycles at fixed temperatures as well as those involving no soak time *(i.e.,* those comprised solely of continuous heating and continuous cooling). This work included isothermal, salt-pot treatments as well as induction tempering trials and was conducted for a number of carbon and alloy steels. It was demonstrated that time-temperature parameters similar to that developed by Grange and Baughman could indeed be used to correlate hardness data for steels tempered using these kinds of cycles.

EXPERIMENTAL PROCEDURE

Materials

The tempering investigation made use of a range of steels in the form of solid, round bars and tubes. The work described herein utilized only 2.54-cm (1.0-in.) round bars to deduce tempering parameters for correlating hardness data. Round bars of different sizes as well as tubular materials were employed in related work to determine the effect of temperature gradients, nonuniform as-quenched hardness patterns, etc., on induction tempering response. This latter work is described in the accompanying Part II paper.[10]

Bar stock of each steel was received in the as-hot-rolled condition. Chemical compositions of the alloys used are given in Table I. These chemistries are typical of the designated AISI grades except for 1020, which contains a high manganese content and residual amounts of nickel, chromium, and molybdenum.

Salt-Pot Tempering Treatments

Salt-pot treatments were conducted to establish the applicability of the Grange and Baughman parameter in correlating hardness data for martensite tempered at various temperatures for relatively short times. Specimens for this part of the investigation consisted of 0.25-cm (0.10-in.) thick disks cut from the 2.54-cm (1.0-in.) diameter bar stock. These specimens were thin enough to allow rapid heating when placed in a molten salt pot, yet thick enough to ensure a reliable Rockwell C (R_c) measurement following tempering.

Prior to tempering, the disks were austenitized in lead pots for 20 minutes and water quenched. Austenitizing was conducted at temperatures of 925 °C (1700 °F) for the 1020, 4620, and 8620 steels or 845 °C (1550 °F) for the 1042, 1095, 4130, and 4340 steels. Following hardening, selected samples were examined metallographically to verify that they had been fully hardened to martensite. Furthermore, the as-quenched hardnesses of R_c 44, 60.5, 65.5, 54.5, 60.5, 44, and 46.5 for the 1020, 1042, 1095, 4130, 4340, 4620, and 8620 steels showed reasonable agreement with the well-known relationship between the hardness of fully hardened steels and carbon content.[11,13]

Tempering of the hardened disks was conducted in molten salt pots at nominal temperatures of 370°, 540°, or 675 °C (700°, 1000°, or 1250 °F). These so-called "isothermal" tempering treatments consisted of placing the samples in the salt pots for 10, 64, or 604 seconds followed by water

Table I. Chemical Analyses of Steels Used In Investigation

	Chemical Composition (Wt Pct)											
Steel	C	Mn	P	S	Si	Cu	Sn	Ni	Cr	Mo	A1	V	Co
1020	0.22	0.81	0.014	0.036	0.18	0.17	0.010	0.13	0.18	0.046	0.003	0.001	0.005
1042	0.44	0.92	0.025	0.050	0.26	0.029	0.003	0.053	0.078	0.019	0.039	–	0.002
1095	0.96	0.45	0.023	0.029	0.24	0.013	0.002	0.021	0.094	0.015	0.025	0.002	–
4130	0.32	0.52	0.012	0.021	0.25	0.11	0.007	0.13	1.04	0.16	0.024	0.005	0.005
4340	0.40	0.76	0.008	0.020	0.28	0.13	0.009	1.62	0.85	0.22	0.039	0.001	0.010
4620	0.17	0.54	0.007	0.016	0.29	0.17	0.009	1.80	0.14	0.26	0.012	0.001	0.033
8620	0.19	0.83	0.016	0.025	0.25	0.054	0.004	0.48	0.56	0.19	0.041	0.001	0.006

quenching. Using a sheathed thermocouple of 0.25-cm (0.10-in.) diameter, it was determined that heating'from room temperature to the nominal tempering temperature required between 3 and 5 seconds. Thus, the actual tempering times used in calculations were set at 6, 60, and 600 seconds. Each time-temperature treatment for a given alloy was done in duplicate.

Following tempering, the samples were ground and hardness tested. These hardnesses were plotted as a function of the Grange and Baughman parameter, $T(R) \cdot [14.44 + \log_{10} r(s)]$, where $T(R)$ was the actual (measured) tempering temperature in degrees Rankine (= 1.8 times degrees Kelvin).

Induction Tempering Treatments

Related tempering trials using induction heating were performed to deduce time-temperature relationships for the case of continuous heating and cooling. In these experiments, a number of 15.24-cm (6.0-in.) long pieces of the 2.54-cm (1.0-in.) diameter bars were cut for each steel. These samples were austenitized for one hour at the same temperatures as the previous specimens in a circulating-air, electric furnace and water quenched. Because subsequent tempered hardness measurements were to be taken 0.25 cm (0.10 in.) below the surface, the as-quenched hardnesses were measured here. These hardnesses were R_c 43.5, 56, 65, 52, 59, 43, and 43.5 for the 1020, 1042, 1095, 4130, 4340, 4620, and 8620 steels. These readings averaged about two R_c points lower than those for the corresponding samples hardened in lead pots, suggesting perhaps that the bars were not quite fully hardened or may have suffered a small amount of decarburization. However, metallo- graphic differences between the thin disk and bar micro- structures (at the 0.25-cm (0.10-in.) subsurface location) were not detected.

The hardened bars were induction heated for the purpose of through tempering using a solenoidal coil and an Ajax Magnethermic motor generator. This power supply had a frequency of 10 kHz and power capacity of 100 kW. Although tempering treatments utilizing various power settings (and thus heating rates) were conducted, only those at the 5 kW level are discussed below. The effect of heating rate on tempering response is described in detail in another paper.[10] For the present induction tempering trials, the bars were heated continuously to nominal peak surface temperatures of 400°, 540°, or 675 °C (750°, 1000°, or 1250 °F) and then allowed to air cool *via* free convection *(i.e.,* without a soaking period at the peak temperature). Under the above conditions, average heating rates were of the order of 7 °C per second (12 °F per second). Cooling rates of about 1 °C per second (2 °F per second) were obtained immediately after the cessation of heating.* All treatments were done in duplicate.

^Typical temperature vj time profiles are shown in the accompanying Part II paper.[10] Note, however, that the power density and heating rate used in the trials discussed here are typical for parts *through-heated* by induction methods. The heating rates for surface heat-treated parts *{e.g.,* parts surface hardened by induction) are typically much greater [50° to 100 °C per second (90° to 180 °F per second)].

Temperatures during induction tempering were measured using several types of thermocouples. During initial (set-up) trials, sheathed thermocouples were welded at the center, mid-radius, and surface locations in several bars. Using these bars, it was found that a 5-kW heating rate gave rise to a steady-state surface-to-center temperature difference of approximately 30 °C (50 °F). During cooling, the surface temperature dropped by about 5 °C (10 °F) below the center temperature, an effect which is characteristic of induction heating of metals.[14] In subsequent trials, fine-wire thermocouples were spot-welded at the surface. Also, sheathed thermocouples were inserted mechanically to a depth of about 0.25 cm (0.10 in.) into tight-fitting holes in the bars which had been drilled prior to the hardening operation. The steady-state temperature difference between the welded and sheathed thermocouples during heating was of the order of 10 °C (20 °F) in these instances.

The temperature records were analyzed to determine an effective tempering parameter, as will be described below, which allowed *surface* hardness data from the induction tempering trials to be compared to those from the isothermal (salt-pot) experiments. Hardness profiles through the cross sections of the induction-tempered steels were also interpreted using the effective tempering parameter; these results are discussed in the Part II paper.[10]

RESULTS AND DISCUSSION Salt-Pot Tempering Data

Hardness measurements on samples which were tempered in salt pots showed excellent correlation with the Grange and Baughman parameter. For example, tempering data for the carbon steels (1020, 1042, and 1095) are shown in Figure 1. The short time treatments (6 seconds) are seen to give rise to hardnesses which follow the same dependence on the tempering parameter as those for longer times (60 and 600 seconds).

It is also apparent that the present results for carbon steels show reasonable agreement with those obtained by Grange and Baughman, whose 1020, 1050, and 1080 tempering curves (involving times of 600 seconds or longer) are also plotted in Figure 1. The largest deviations between the present and former work are found for 1020. However, this

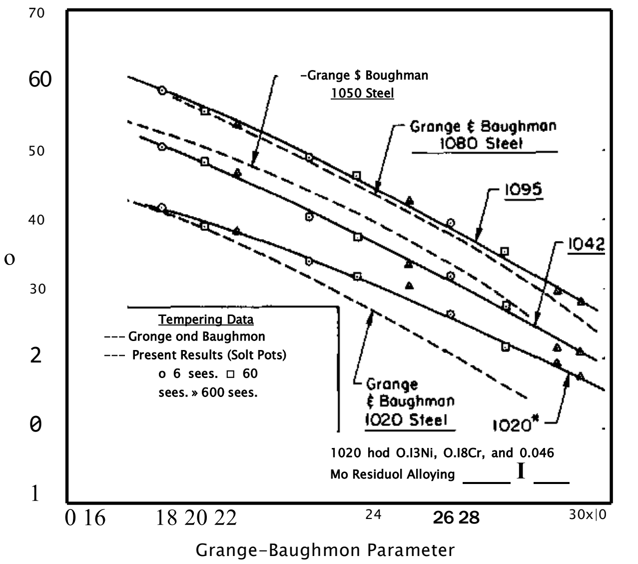

Fig. 1—Comparison of tempering data for carbon steels from present investigation ("salt pots") and those obtained by Grange and Baughman.[7] The present results are for isothermal treatments lasting 6, 60, or *>00 seconds.

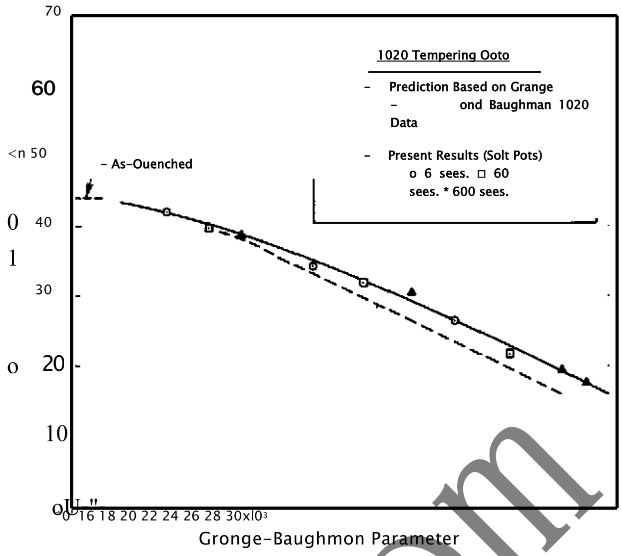

Fig. 2—Comparison of present 1020 tempering data from salt-pot treatments, with a prediction based on Grange and Baughman's 1020 results and hardness-increment factors ("alloying factors").

difference can be explained by the fact that the present 1020 steel contained residual amounts of nickel, chromium, and molybdenum not ordinarily found in this steel. Because of this, a modified tempering curve was constructed from Grange and Baughman's 1020 curve and the hardness increments tabulated in their paper for various alloying elements.[7] The required hardness increments (in Vickers hardness points) for each of the residual elements in the present 1020 steel were added to the Grange and Baughman 1020 curve (plotted in terms of Vickers hardnesses), and the resulting final hardnesses were converted back to the Rockwell C scale. The agreement between the "predicted" tempering curve thus obtained and the present measurements for 1020 is much better, as shown in Figure 2.

The short-time tempering data for alloy steels obtained with salt pots in the present investigations also revealed excellent agreement with predictions based on Grange and Baughman's results from longer tempering times. These results for 4130, 4340, 4620, and 8620 steels are shown in Figure 3. For each alloy, the measurements compare favorably to a prediction based on the tempering curve for the corresponding Grange and Baughman carbon steel plus hardness-increment factors whose magnitudes have been estimated from the measured composition (Table I) and the Grange and Baughman factors. Moreover, the short-time (6-second) treatments gave rise to hardnesses which follow the same dependence on the tempering parameter as the longer-duration ones.

The sensitivity of tempering response to chemical composition is illustrated in Figure 3(b). Here, the present hardness data for 4340 steel are compared to (1) a tempering curve predicted as described above and (2) Grange and Baughman's own results for a 4340 steel. It is seen that the present measurements agree well with the prediction but are slightly different from the former measurements. This is presumably because of small differences in composition which are allowable in the specification for this grade of steel.

Induction Tempering Data

Effective Tempering Parameter. The interpretation of tempering data from the induction trials is not as simple as that from the salt-pot trials. In the latter trials, tempering took place for a given time at a fixed temperature. In contrast, the induction treatments involved continuous heating and cooling. Therefore, the time and temperature to be employed in evaluating a tempering parameter (such as the Grange and Baughman one) are not obvious.

Hollomon and Jaffe[5] recommended a numerical integration procedure for determining the tempering parameter for cycles involving continuous heating or cooling. Attempts at applying this technique in the present investigation led to computational instabilities. For this reason, an alternate procedure was developed and is illustrated in Figure 4. Here, the schematic induction-tempering cycle [Figure 4(a)] consists of a heating portion and a subsequent cooling portion, the latter occurring at a somewhat lower rate. A means by which this arbitrary cycle can be converted into an equivalent fixed temperature or isothermal treatment [Figure 4(b)] is sought. To this end, the total continuous cycle is broken into a number of very small time increments, each of duration A?, and characterized by some average temperature 7V It is assumed that the temperature for the equivalent isothermal treatment is the peak temperature of the continuous one, or $T*$. This specification of the temperature for the isothermal cycle is arbitrary, however.

Having specified the temperature of the equivalent isothermal cycle as $T*$, an effective tempering time $t*$ for this cycle can be estimated. This is accomplished by solving

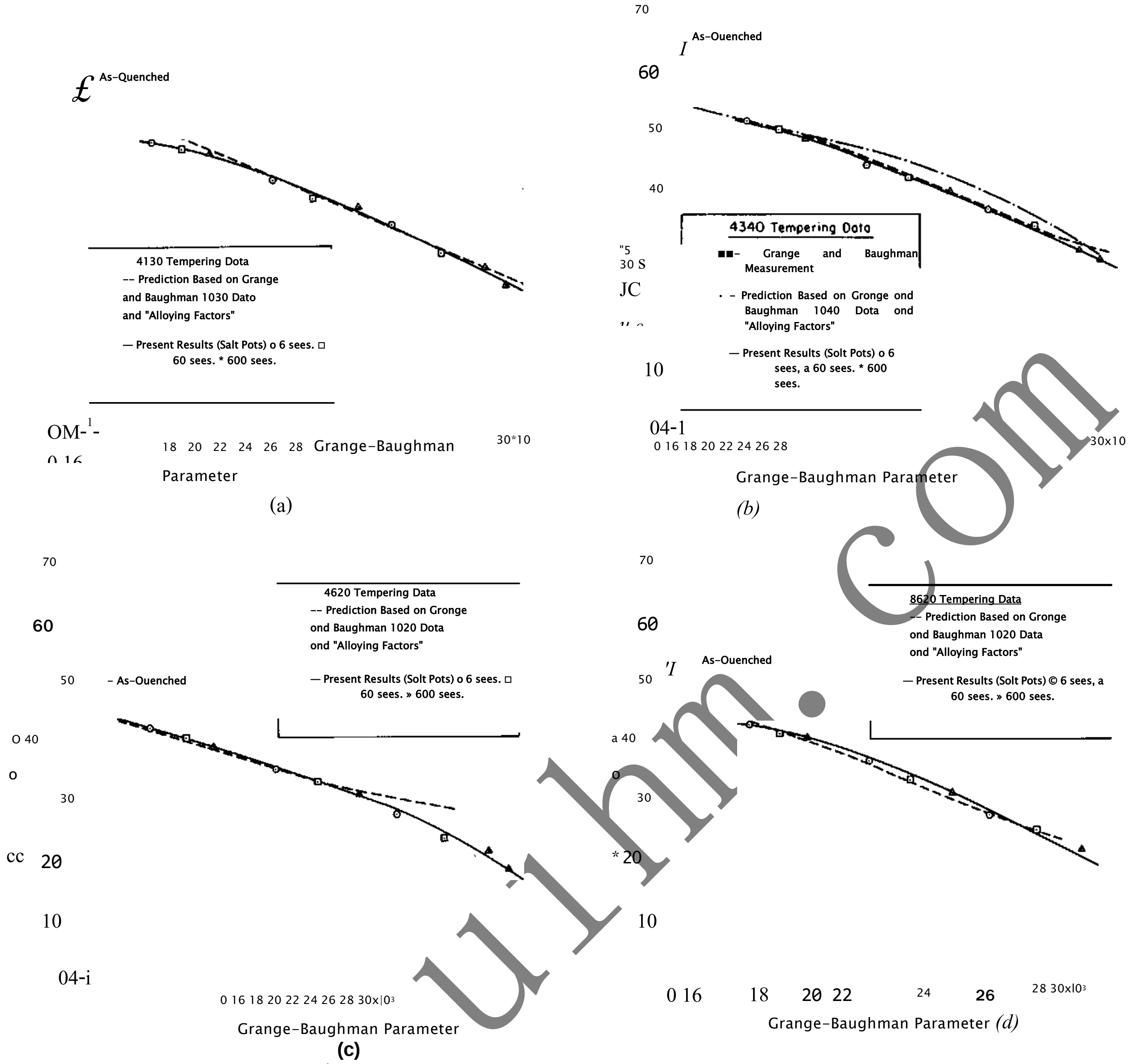

Fig. 3—Comparison of present alloy steel-tempering data from salt-pot treatments, with predictions based on Grange and Baughman's carbon steel results and hardness-increment factors ("alloying factors"): (a) 4130, (*b*) 4340, (c) 4620, and (*d*) 8620. In *(b),* Grange and Baughman's measured 4340 tempering curve is also included.

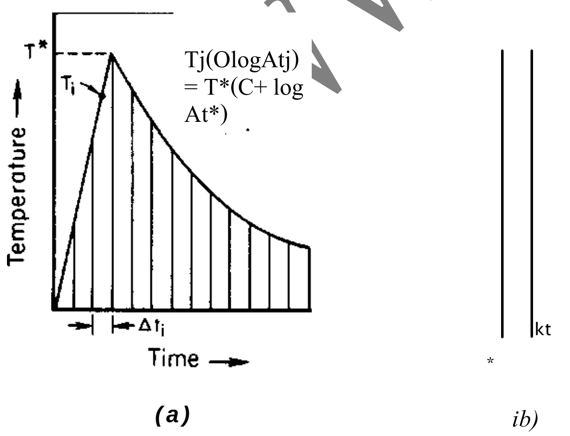

Fig. 4—Equivalence of (a) a continuous heating/cooling tempering cycle and *(b)* an "isothermal" treatment through the use of an effective tempering time ((*) and temperature *(T*)*.

for the increment in *t**, or *At"* for each of the *At,* in the continuous treatment by using the equation T_i *(C +* log Af,-) = *T*(C* + log A*tj),* where *C* = 14.44 for a Grange and Baughman type of tempering parameter. Summing the *At* * for each portion of the continuous cycle yields the total effective tempering time *t** at temperature *T** and hence the effective tempering parameter *T*(C* + log *t*).*

Application of the Effective Tempering Parameter to Induction Data. Using the method described above, effective tempering parameters were estimated for each of the laboratory induction-tempering trials. The calculations relied on measured temperature-time data taken at the same near-surface locations in the bars as those at which hardnesses were read. Because the objective was to compare these results with salt-pot data (which were correlated *via*

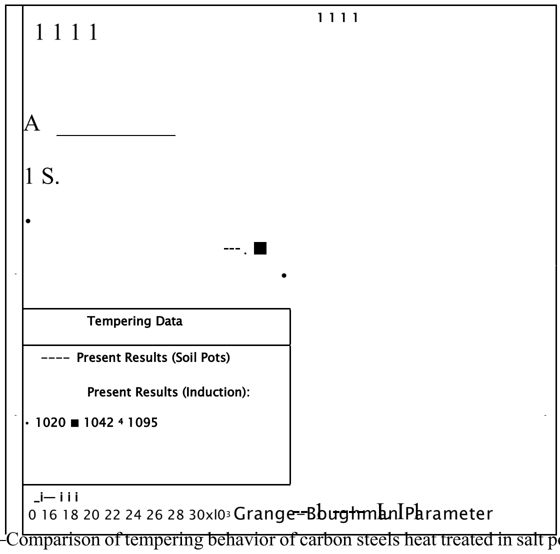

Fig. 5—Comparison of tempering behavior of carbon steels heat treated in salt pots (solid lines) or *via* induction (data points). The induction results are plotted in terms of hardness *vs* the *effective* Grange and Baughman parameter.

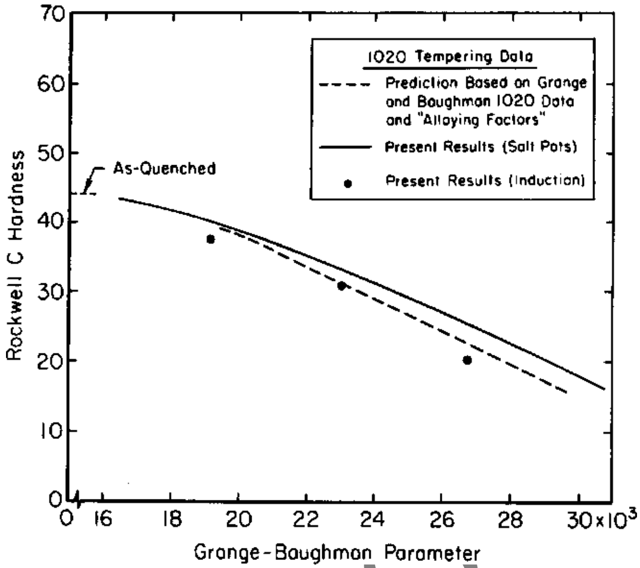

Fig. 6—Comparison of present 1020 tempering data from salt-pot and induction treatments, with a prediction based on Grange and Baughman's 1020 results and hardness-increment factors ("alloying factors").

the Grange and Baughman parameter), the value of C = 14.44 was employed in deriving the effective tempering parameter.

Induction-tempering data for the carbon steels in terms of Rockwell C hardness *vs* the Grange and Baughman parameter are shown in Figure 5. The overall decrease of hardness with increasing tempering parameter is replicated in the induction results. However, the induction samples exhibited somewhat lower hardnesses (1 to 3 Rockwell C points) than the salt-pot samples, the measurements of which are indicated by the solid trend lines reproduced here from Figure 1. The difference between the induction and salt-pot results is greatest for the 1020 steel. Nevertheless, when the 1020 induction data are compared to the tempering-curve prediction, based on the Grange and Baughman 1020 steel and the hardness increment factors (whose derivation was discussed with regard to Figure 2), the derivation is narrowed (Figure 6). In fact, the prediction lies *between* the induction and the salt-pot results.

The induction-tempering data for the alloy steels reveal a trend similar to that for the carbon steels (Figure 7). The hardnesses are lower than the corresponding salt-pot-treated samples. For these steels, the difference is only about 1 to 2 hardness points, though, which is almost within experimental scatter. The source of the slightly lower tempered hardnesses in the carbon and alloy steels is not known at present. They could be a result of the fact that the induction- tempered bars were not fully hardened, as discussed in Section II. However, because first-order agreement of the data was realized, the exact determination of the source of the differences was taken to be beyond the scope of the present work.

The usefulness of the present formulation was also validated by analysis of data from a commercial induction- tempering line at Tubulars Unlimited.[15] Making use of the effective tempering parameter concept, hardnesses within a few R_c points of measured values were predicted for an oil-well pipe steel similar to 1030 which is processed on a continuous basis. The predicted quenched-and-tempered hardness was one point below or four points above the measurement when based on either the effective forms of the Hollomon and Jaffe or Grange and Baughman parameters, respectively.[16]

CONCLUSIONS

Time-temperature relationships for tempering of martensite were deduced from short-time, salt-pot ("isothermal") treatments and induction-heating experiments. These experiments and the accompanying analysis lead to the following conclusions:

(1) The conventional tempering parameters developed by Hollomon and Jaffe or Grange and Baughman can be applied for isothermal tempering treatments that are very rapid *(i.e.,* lasting for only several seconds). For these very short processes, the tempering curves for alloy steels (in terms of hardness vs tempering parameter) can be estimated from the corresponding carbon steel curves and the hardness- increment factors established by Grange and Baughman for longer time cycles.

(2) An effective tempering parameter can be used to correlate tempered hardnesses to the time-temperature history experienced during a continuous heating/cooling cycle such as the kind imposed in an induction-based heat treatment. The derivation of the effective tempering parameter

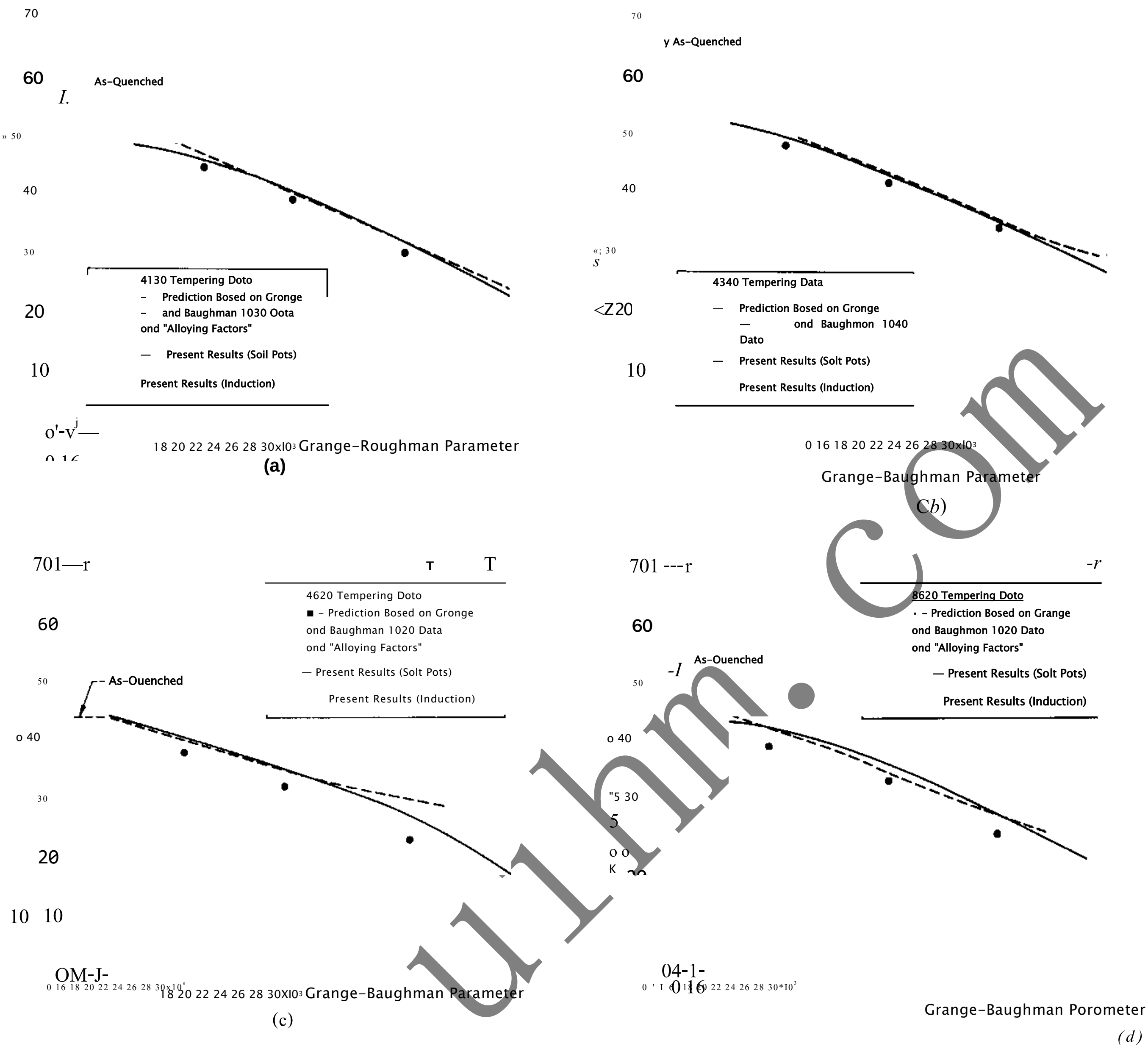

Fig. 7—Comparison of present alloy steel-tempering data from the salt-pot and induction treatments, with predictions based on Grange and Baughman's carbon steel results and hardness-increment factors ("alloying factors"): (a) 4130, *(b)* 4340, (c) 4620, and *(d)* 8620. The induction results are plotted in terms of hardness *vs* the *effective* Grange and Baughman parameter.

consists of estimating an effective tempering time and temperature with which one of the standard (Hollomon and Jaffe or Grange and Baughman) tempering parameters can be calculated.

(3) Total cycle times for the tempering process (relative to conventional, gas-fired furnace operations) can be reduced substantially by using induction heating methods. The data here suggest that a reduction in time of one order of magnitude does not seem unreasonable.

ACKNOWLEDGMENTS

The research reported here was part of a larger project on induction heating and heat-treating technology being conducted by Battelle's Center for Metals Fabrication. Center support through a contract with the Electric Power Research Institute is gratefully acknowledged. The authors thank the EPRI program manager, Mr. I. L. Harry, for helpful advice and encouragment. In addition, the assistance of Messrs. W. W. Sunderland and C. R. Thompson in conducting the experiments is appreciated.

REFERENCES

1. M.A. Grossman and E. C. Bain: *Principles of Heat Treatment,* American Society for Metals, Metals Park, OH, 1964.
2. G. Krauss: *Principles of Heat Treatment of Steel,* ASM, Metals Park, OH, 1980.
3. K. -E. Thelning: *Steel and Its Heat Treatment,* Butterworths, London, 1975.

4. C. R. Brooks: *Heat Treatment of Ferrous Alloys,* Hemisphere Publishing Corporation, Washington, 1979.
5. J. H. Hollomon and L. D. Jaffe: *Trans. AIME,* 1945, vol. 162, p. 223.
6. D.K.Bullens*: Steel and Its Heat Treatments,* Wiley, New York, 1948.
7. R. A. Grange and R. W. Baughman: *Trans. ASM,* 1956, vol. 48, p. 165.
8. J.W. Poynter: *Trans. ASM,* 1946, vol. 36, p. 165.
9. D. L. Martin and W. G. VanNote: *Trans. ASM,* 1946, vol. 36, p. 210.
10. S. L. Semiatin, D. E. Stutz, and T. G. Byrer: *J. Heat Treat.,* vol. 4, 1985, p. 47-55.
11. J.L. Burns, T.L. Moore, and R. S. Archer: *Trans. ASM,* 1938, vol. 26, p. 1.
12. Z. Jeffries: *Trans. ASST.* 1927, vol. 12, p. 871.
13. J.M. Hodge and M. A. Orehoski: *Trans. AIME,* 1946, vol. 167, p. 627.
14. C. A. Tudbury: *Basics of Induction Heating: Volume 1,* John F. Rider, Inc., New Rochelle, New York, 1960.
15. B. Urband: *Ind. Heat.,* April 1983, vol. 50, no. 4, p. 20.
16. S.L. Semiatin and D.E. Stutz: *Induction Heat Treatment of Steel,* ASM, Metals Park, OH, 1985 (in press).