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Temperature Distribution within the Friction Stir Welding Tool

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Abstract—This work is motivated by several recent publications, which reported an unexpected temperature distribution within the welding tool during friction stir welding (FSW). It was found that the temperature in the tool shoulder was lower than that in the probe. This result appears to contradict the common assumption that the shoulder plays the dominant role in heat generation during friction stir welding. In an attempt to clarify this issue, we perform direct temperature measurements within the tool and numerical simulations of heat transfer. Extensive measurement data confirm that temperature within the shoulder is relatively low, which is in agreement with the literature data. Finite element modeling (FEM) shows that the lower temperature results from rapid cooling of the shoulder area due to enhanced heat transfer to the tool shank.

Keywords: friction stir welding (FSW), temperature, finite element modeling (FEM), thermal analysis

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1. INTRODUCTION

Friction stir welding is an innovative solid-state joining technique [1–3]. Due to the solid-state nature, friction stir welding avoids (or minimizes) solidification issues of conventional fusion welding and therefore enables sound joining of materials that are commonly believed to be unweldable (particularly aluminum alloys). Hence, friction stir welding is often considered to be one of the most significant recent achievements in the field of joining, which attracts considerable research interest.

Extensive research over the last two decades has conclusively demonstrated that welding temperature is one of the key issues in friction stir welding [1–3]. In particular, it is well accepted that welding temperature essentially influences both material flow and microstructure evolution during friction stir welding, thereby virtually governing material weldability and service properties of joints [1–3]. Thus, temperature control is of great importance in friction stir welding.

Due to severe deformation imposed during friction stir welding, direct temperature measurements in the stir zone are challenging, and thereby the actual temperature distribution is virtually unknown. However, it is widely believed that the upper part of the welding tool (i.e. its shoulder) is the main contributor to the heat generation during friction stir welding. This concept originated from the classical work by Tang et al. [4]. In this study, friction stir welding was conducted using two different welding tools: conventional tool with the shoulder and the probe and the probeless tool. In both cases, the welding temperature was found to be nearly the same. From this observation, it was concluded that the tool probe exerts a minor influence on the FSW heat. Considering the relatively large friction area of the tool shoulder, this idea seems to be entirely natural.

However, some recent measurements of the temperature distribution within the welding tool have shown that the temperature within the shoulder area is lower than that near the probe tip [5–7]. This observation seems to fall outside the current fundamental understanding of the FSW process.

The aim of the present work is to explain this surprising result. For this purpose, experimental measurements of the temperature distribution within the welding tool were used for finite element modeling (FEM).

2. TEMPERATURE MEASUREMENTS

To measure temperatures within the welding tool, bead-on-plate friction stir welding was performed for

4-mm-thick aluminum alloy 1100. A simple welding tool fabricated from tool steel and consisting of the concave shoulder and the threaded probe was used for this purpose (Fig. 1). For temperature measurements, K-type thermocouples were embedded into the tool: at the shoulder edge and at the probe tip, as indicated in Fig. 1. Hereafter, these two locations of the temperature measurements are referred to as "shoulder" and "probe", respectively. During welding, the temperature data were monitored and transferred to the receiver using a 2.4 GHz ZigBee wireless network with the frequency 30 Hz. To examine the possible influence of FSW variables on the tool temperatures, several welding trials were conducted, in which the tool rotation rate was systematically varied from 500 to 1000 rpm and the tool travel speed from 300 to 600 mm/min. On the other hand, the tilt angle and the plunge depth of the tool were kept unchanged (3° and 3.5 mm, respectively) during the experiments. In all cases, friction stir welding was conducted on the stainless steel backing plate, and the length of the welding path was ≈150 mm.

The typical temperature profiles measured at the shoulder and the probe are shown in Fig. 2a. It is important to point out that the data represent both FSW stages: tool plunging corresponding to the abrupt temperature increase and tool traveling corresponding to relatively small changes in temperature. In the entire studied range, the probe temperature was evidently higher than the shoulder temperature. It is worth noting, however, that the temperature difference tends to reduce with welding time.

The effects of the welding variables on the tool temperature are summarized in Fig. 2b. It is clear that the probe temperature is higher than the shoulder temperature in the entire range of the welding pa-

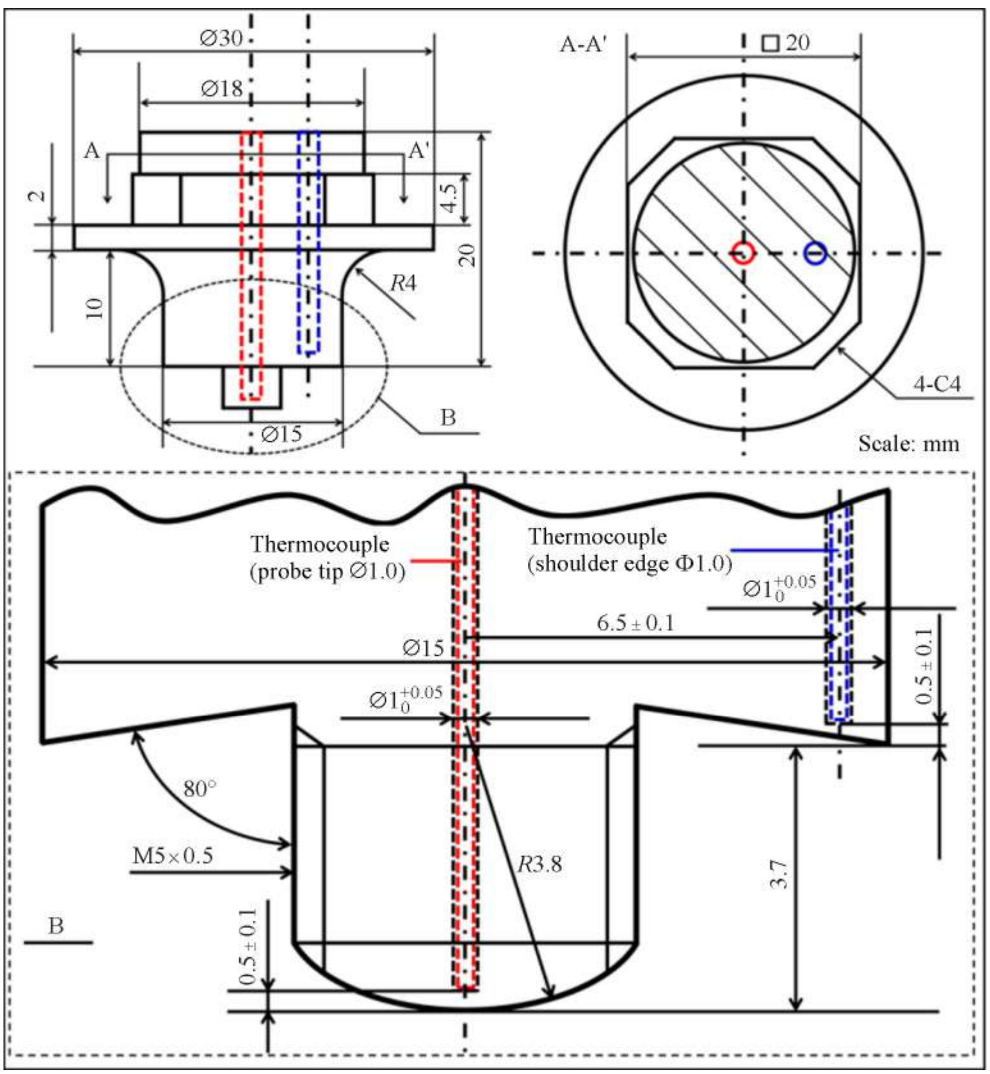

Fig. 1. Schematic of the welding tool with embedded thermocouples (color online).

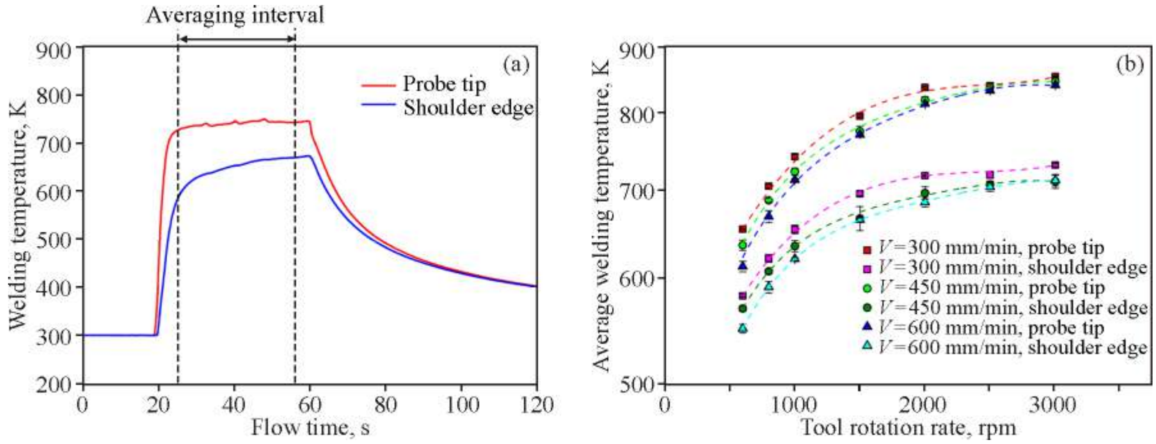

Fig. 2. Typical evolution of the measured tool temperature (travel speed $V = 300$ mm/min, rotation rate $N = 1000$ rpm) (a), and average measured tool temperature as a function of FSW variables (b) (color online).

rameters. The temperature difference was found to increase with the tool rotation rate from ~65 K at 600 rpm to ~135 K at 3000 rpm.

Friction stir welding is normally associated with a relatively high temperature gradient, and therefore the above result can be associated with the measurement error. In this context, it is important to emphasize that the temperature distribution within the stir zone is typically believed to be much smaller than that outside it (at least, in the case of aluminum alloys). Moreover, the temperature difference between the tool shoulder and the tool probe was reproduced in 21 welding trials (Fig. 2b) and showed good agreement with the literature data [5–7]. Hence, it was assumed that the relatively low welding temperature within the shoulder area measured in the present work (Fig. 2) reflected a real situation. If so, this phenomenon should have a physical reason.

3. FINITE ELEMENT MODELING

The temperature distribution within the FSW tool is a result of the balance between the heat generation and the heat dissipation. As was emphasized in the

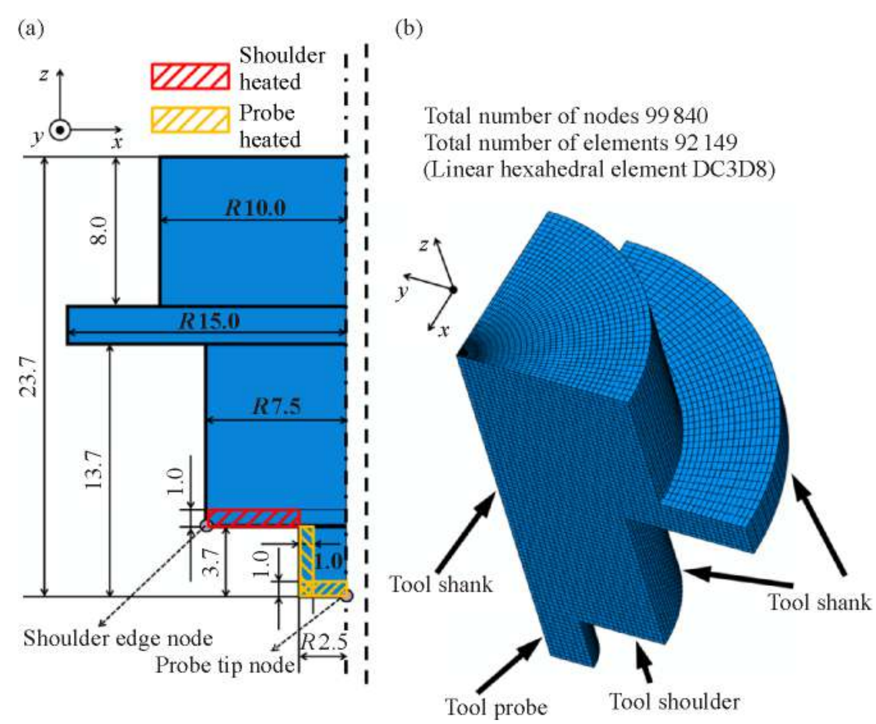

Fig. 3. Geometry and meshing of the computational model (color online).

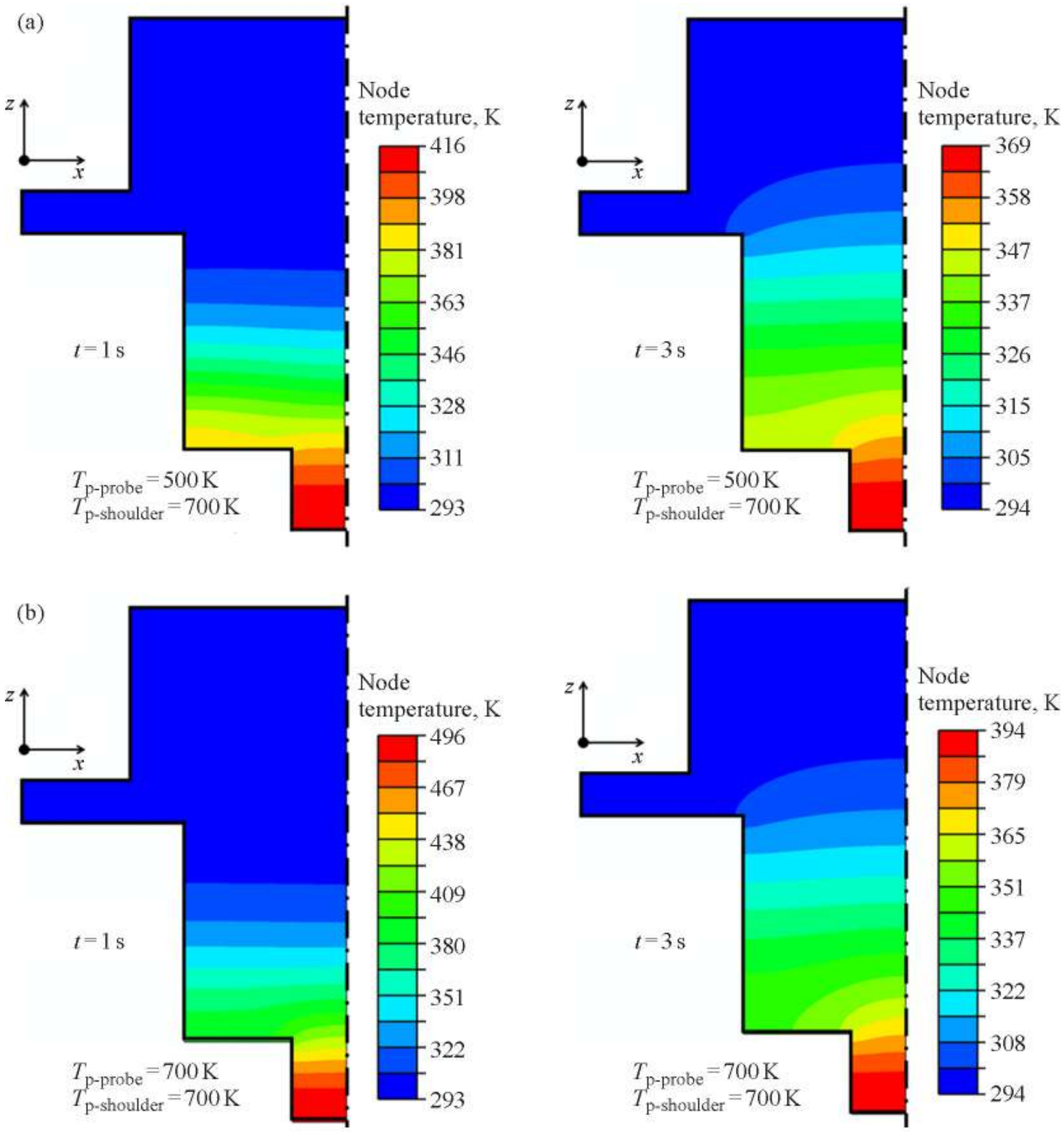

Fig. 4. Finite element calculation of temperature distributions within the welding tool at different moments of time t and at different initial temperatures of the shoulder $T_{\text{p-shoulder}} = 700$ K and the probe $T_{\text{p-probe}} = 500$ (a) and 700 K (b) (color online).

classical work by Schmidt et al. [8], since the shoulder has a larger friction area and a higher linear velocity than the probe, it should generate a greater heat than the probe. If so, the relatively low temperature measured in the shoulder (Fig. 2) can be attributed to the relatively fast heat dissipation.

To examine the feasibility of this simple concept, cooling kinetics of heated regions of the shoulder and probe was simulated by the FEM approach. For this purpose, a three-dimensional thermomechanical coupled model of the welding tool was developed using the commercial ABAQUS 6.10 software package [9]. To simplify the simulation process, the tool surfaces were assumed to be flat, as well as the shoulder concavity and thermocouple holes were ignored. The modeled tool was then quarter cut due to its symmetric geometry and meshed with 92149 linear hexahedral elements and 99840 nodes (element DC3D8) [9], as shown in Fig. 3. Heat dissipation was assumed to be governed by heat transfer to the massive tool shank and by air convection on the exposed surfaces of the shoulder at the convection coefficient 30 W m^{-2} K^{-1} and room temperature 293 K. The material parameters of the steel were assumed to be constant and included the material density 8080 kg m^{-3}, heat capacity 400 J kg^{-1} K^{-1}, and thermal conductivity 26 W m^{-1} K^{-1} [10, 11]. Heat transfer to the backing plate, base material, and clamping system were not taken into account because the welding tool was not in direct contact with these objects. The model considers only the stationary stage of the welding process (tool traveling) but ignores the tool plunging stage. Although the above model is very simple, it can be used for a qualitative insight into the examined phenomenon and even for the evaluation of possible reasons for the observed effect.

As indicated in Fig. 3a, the initially heated regions of the shoulder and the probe were assumed to be tool-workpiece contact interfaces. Figure 4 shows two typical examples of the simulated evolution of the temperature distribution within the tool. Considering the shoulder as the main contributor to heat generation, in the first case (Fig. 4a), its initial temperature was set to be higher than that of the probe (700 K and 500 K, respectively). In the second case (Fig. 4b), the initial temperatures of the shoulder and the probe were set to be the same (700 K). The temperature history of the shoulder and the probe in these cases is detailed in Fig. 5. In the latter diagram, the temperature in two particular locations within the shoulder and the probe (indicated as “Shoulder edge node” and “Probe tip node” in Fig. 3a) was calculated as a function of time. As discussed above, the initial temperatures (at zero time) were set to be either 700 or 500 K.

From Figs. 4 and 5 it is clear that the cooling rate in the shoulder region is much larger than that in the probe. During the first cooling second, the cooling rate of the shoulder achieved ~350 K/s in all modeling conditions, and the shoulder temperature rapidly became lower than the probe temperature (Fig. 5). Rapid cooling of the tool shoulder was contributed primarily by the heat sink to the massive tool shank indicated in Fig. 3b.

Thus, despite the large heat which is presumably generated by the tool shoulder during friction stir welding, the cooling effect predicted by the above simulation can explain the relatively low temperature measured in the shoulder area (Fig. 2).

It is expected that the cooling rate should increase with the welding temperature. Therefore, the cooling effect can also explain the observed increase in the temperature difference between the shoulder and the probe with the tool rotation rate, as shown in Fig. 2b. On the other hand, gradual temperature equilibration within the tool during long-term friction stir welding should reduce the temperature difference between the probe and shoulder, as seen from Fig. 2a.

It is hypothesized that the temperature variations within the welding tool can influence the stability of

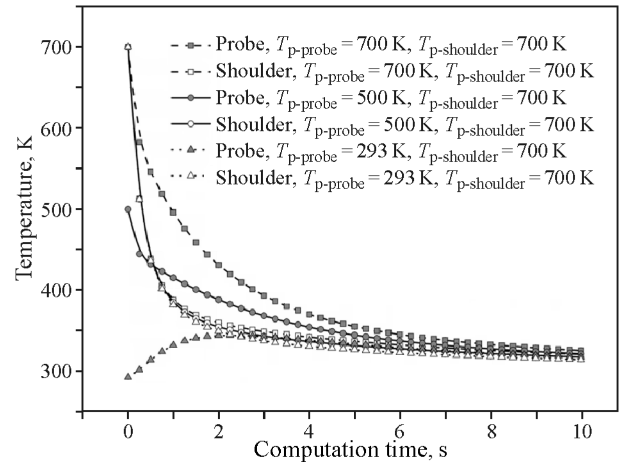

Fig. 5. Typical temperature history of the tool nodes from the computational model. $T_{p\text{-probe}}$ and $T_{p\text{-shoulder}}$ are the initial temperatures of the probe-heated part and of the shoulder-heated part, respectively. ”Probe” and “shoulder” are the nodes of the probe tip and shoulder edge shown in Fig. 3.

material flow during friction stir welding, thus affecting the weldability and service properties of long-scale joints.

Considering the repeatability of the relatively low temperatures measured within the tool shoulder as reported in the literature [5–7], it is thought that the revealed cooling effect is a more or less intrinsic characteristic of the FSW process. However, the extension of this effect can be influenced by a number of factors, including chemical composition and design of a particular welding tool, alloy grade and thickness of the welded material, welding conditions, and material of the backing plate.

4. CONCLUSIONS

In this work, the temperature distribution within the FSW tool was examined using direct measurements and FEM simulations. In a wide range of welding parameters, the temperature in the shoulder area was found to be significantly lower than that in the probe tip. FEM simulations showed that this surprising result can be explained by rapid cooling of the shoulder region due to extensive heat transfer to the massive shank of the tool.

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CONFLICT OF INTEREST

The author declares no conflicts of interest.

REFERENCES

1. Mishra, R.S. and Ma, Z.Y., Friction Stir Welding and Processing, *Mater. Sci. Eng. R.*, 2005, vol. 50, pp. 1–78. https://doi.org/10.1016/j.mser.2005.07.001
2. Nandan, R., DebRoy, T., and Bhadeshia, H.K.D.H., Recent Advances in Friction-Stir Welding—Process, Weldment Structure and Properties, *Progr. Mater. Sci.*, 2008, vol. 53, pp. 980–1023. https://doi.org/10.1016/j.pmatsci.2008.05.001
3. Heidarzadeh, A., Mironov, S., Kaibyshev, R., Cam, G., Simar, A., Gerlich, A., Khodabakhshi, F., Mostafaei, A., Field, D.P., Robson, J.D., Deschamps, A., and Withers, P.J., Friction Stir Welding/Processing of Metals and Alloys: A Comprehensive Review on Microstructural Evolution, *Progr. Mater. Sci.*, 2021, vol. 117, p. 100752. https://doi.org/10.1016/j.pmatsci.2020.100752
4. Tang, W., Guo, X., and McClure, J.C., Heat Input and Temperature Distribution in Friction Stir Welding, *J. Mater. Proc. Technol.*, 1998, vol. 7, pp. 163–172. https://doi.org/10.1106/55TF-PF2G-JBH2-1Q2B
5. Record, J.H., Covington, J.L., Nelson, T.W., Sorensen, C.D., and Webb, B.W., A Look at the Statistical Identification of Critical Process Parameters in Friction Stir Welding, *Weld. J.*, 2007, April, pp. 97–104.
6. Assidi, M., Fourment, L., Guerdoux, S., and Nelson, T., Friction Model for Friction Stir Welding Process Simulation: Calibration from Weld Experiments, *Int. J. Mach. Tool. Manuf.*, 2010, vol. 50, pp. 143–155. https://doi.org/10.1016/j.ijmachtools.2009.11.008
7. Yi, D., Onuma, T., Mironov, S., Sato, Y.S., and Kokawa, H., Evaluation of Heat Input during Friction Stir Welding of Aluminum Alloys, *Sci. Technol. Weld. Join.*, 2016, vol. 22, pp. 41–46. https://doi.org/10.1080/13621718.2016.1183079
8. Schmidt, H., Hattel, J., and Wert, J., An Analytical Model for the Heat Generation in Friction Stir Welding, *Model. Simul. Mater. Sci. Eng.*, 2004, vol. 12, pp. 143–157. https://doi.org/10.1088/0965-0393/12/1/013
9. ABAQUS, Version 6.10, SIMULIA Inc. (HTML documentation).
10. *Metals Handbook*, ASM Int., 1990.
11. *ASM Speciality Handbook: Carbon and Alloy Steels*, ASM Int., 1996.