SteCalÒ 3.0

User Manual

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Chapter 1: Getting Started

1.1 What is SteCal

SteCal is a Microsoft Windows-based application that calculates the parameters and behavioral properties representative of low-alloy steels, and predicts the effects of heat treating such steels. SteCal is also useful in comparing the properties of two steels of different composition, which can help to suggest the most appropriate composition for a given application.

SteCal is a compilation of the most effective and precise calculation methods currently available; it is not a database in which the properties and behaviors of different types of steels are memorized. On occasion, it also establishes relationships between them with a view to obtaining the most applicable results possible. The methods have been selected based on a rational approach. The program is protected against the entry of values for which no calculation method is appropriate or that can introduce appreciable errors into the calculation.

Nevertheless, the accuracy of methods, suitability for a particular purpose, or confidence offered with regard to a specific problem cannot be guaranteed, even thought most of them are widely used and accepted.

The program is provided "as is," with its defects and faults, and the responsibility for the acceptance of its results and the possible consequences is with the user. It is not intended as a substitute for the user's own good judgment or for making decisions in the user's stead. Therefore, any decision made by the user or any action carried out based on information obtained from this program are at the user's own risk.

This program has also been created to serve didactic purposes. By allowing students to observe the effects varying alloy content and grain size, SteCal can help them to appreciate the quantitative and qualitative influence of different alloy elements on diverse aspects of the behavior and properties obtainable with low-alloy steels. SteCal has been in use as an instructional method since 1985 in the Materials Department of the School of Aeronautical Engineering at the Polytechnic University of Madrid [Ref. 45].

Comments, advice, suggestions, and criticism from users are valuable and are actively sought by the author. Likewise, suggestions regarding calculation methods that might prove more exact than the ones included in this program would be very much appreciated.

1.1 System Requirements

In order to install and run SteCal, the computer should have the following:

- Microsoft Windows 95 or higher operating system
- 100 MHz or higher processor
- 32 MB RAM (128 recommended)
- 15 MB free disk space for installation
- Monitor resolution of 640 x 480 or higher (800x600 highly recommended)
- A CD-ROM drive if you are installing the program from CD
- The SteCal.msi file (on your hard drive or network) if you are installing the program without a CD

The following are optional:

- A program for viewing the results in text format, (which SteCal saves as .rtf or .txt files) e.g., Microsoft Notepad, WordPad, Word
- A program for viewing the results in graphic format, (which SteCal saves as .bmp files) e.g., Microsoft Paint, Microsoft Photo Editor, Adobe Photoshop
- Sufficient disk space to save the data tables and curves (The .bmp files may be as large as 1 MB.)
- A printer for printing data tables and curves

1.2 Installing SteCal

To install the SteCal program:

1. Locate the **SteCal.msi** file on the SteCal CD, the network, or your hard drive. The icon may appear as in Figure 1-1.

Figure 1-1: SteCal Installation File

2. Double-click the SteCal.msi file to begin the installation.
3. The dialog shown in Figure 1-2 will appear. Click **Next** to continue the installation.

Figure 1-2: SteCal Setup Welcome Dialog

4. By default, the SteCal installation will create a new folder called C:\Program Files\SteCal 3.0. The program files will be installed there. (The folder also contains several sample steel data files). To accept this location, click **Next** on the dialog shown in Figure 1-3. If you want to select a different folder, click **Browse**, select the folder, and click **OK**. Then click **Next**.

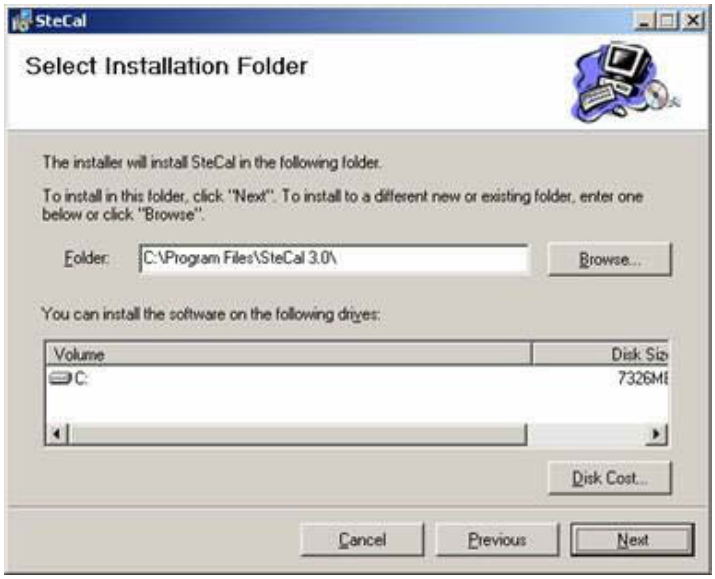


Figure 1-3: Installation Folder Dialog

5. Click **Next** again on the subsequent dialog, shown in Figure 1-4.

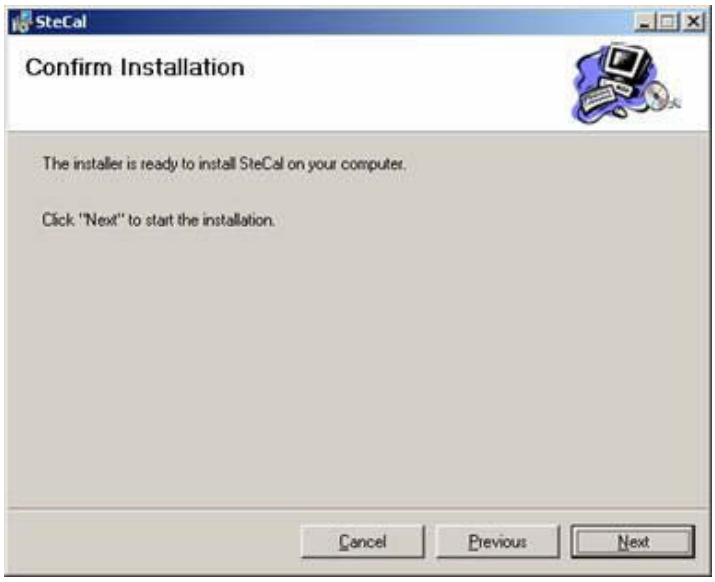


Figure 1-4: Installation Confirmation Dialog

The dialog shown in Figure 1-5 will appear during the installation. There is no need to click or press anything until this is complete.

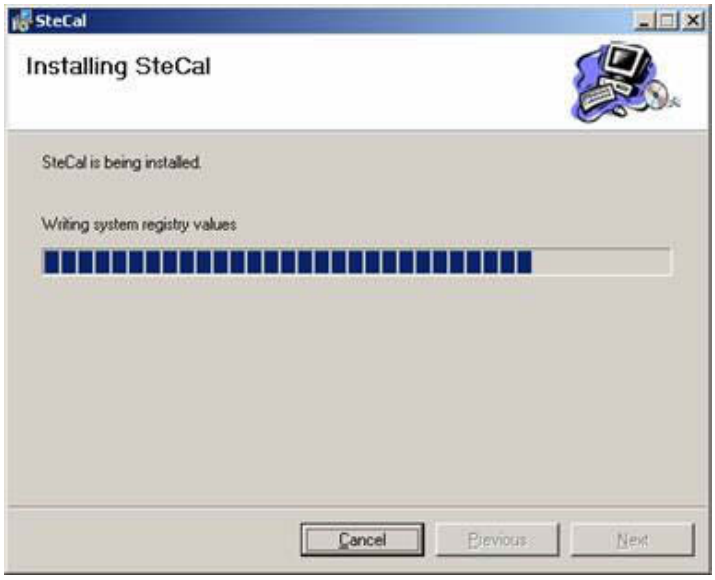


Figure 1-5: Installation Dialog

6. When the installation is complete, click **Close** (see Figure 1-6).

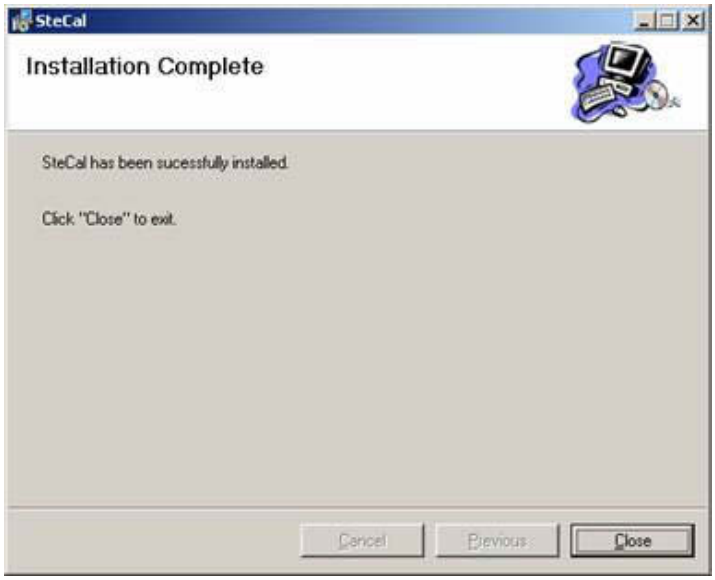


Figure 1-6: Successful Installation Dialog

The SteCal icon, shown in Figure 1-7, should appear on the desktop.

Figure 1-7: SteCal 3.0 Icon

1.3 Removing SteCal

To uninstall SteCal:

1. Double-click the **SteCal.msi** icon.
2. Select **Remove SteCal** on the dialog shown in Figure 1-8. Click **Finish**.

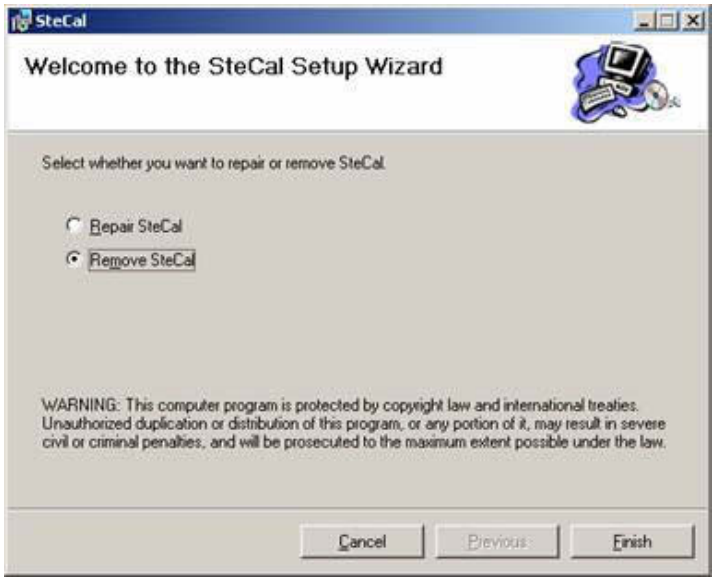


Figure 1-8: SteCal Setup Wizard Dialog (for Removal)

The dialog shown in Figure 1-9 will appear during the removal. There is no need to click or press anything until this is complete.

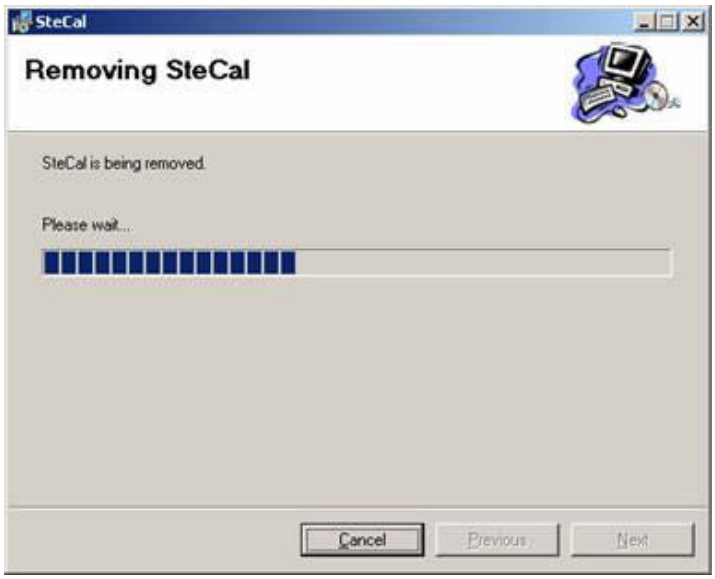


Figure 1-9: Removal Dialog

3. Click **Close** when the removal is complete (see Figure 1-10).

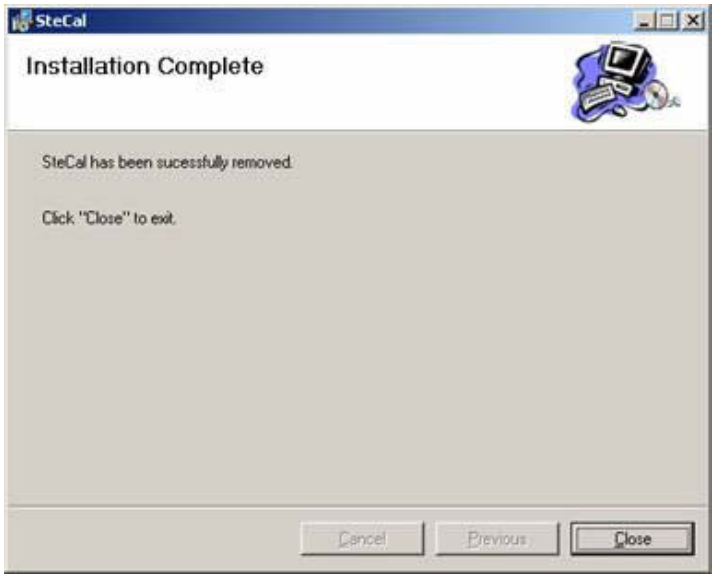


Figure 1-10: Successful Removal Dialog

1.4 Starting SteCal

To start the SteCal program:

1. Double-click the SteCal icon (see Figure 1-7) on the desktop. You may also be able to open the program by selecting **Start** ð **SteCal 3.0**. The first time SteCal is opened, the "splash screen" shown in Figure 1-11 will appear.

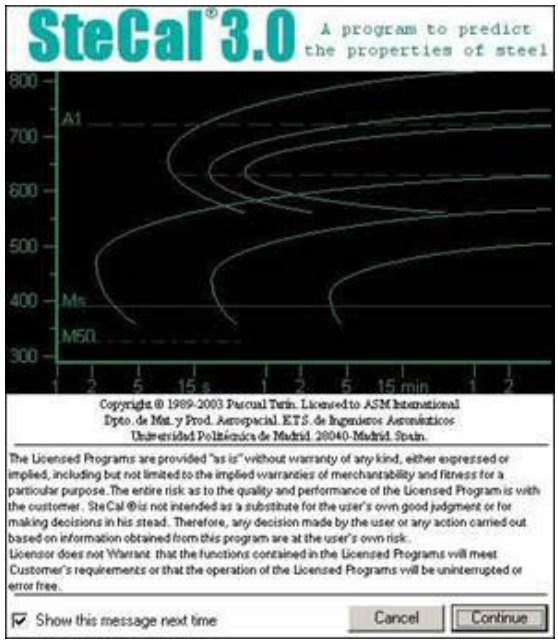


Figure 1-11: SteCal Splash Screen

2. Click **Continue** to begin using the program. To prevent this screen from appearing every time you open SteCal, uncheck **Show this message next time**.

Chapter 2: SteCal Basics

2.1 Viewing Sample Data Provided

SteCal comes with sample data files for 15 common grades of steel. The files are located in the Program Files folder and are named according to the Society of Automotive Engineering-American Iron and Steel Institute (SAE-AISI) system or Unified Numbering System (UNS) for designating carbon and alloy steels. To open a sample steel data file:

1. Select **File** ð **Open Steel Data** from the menu bar.
2. Navigate to the SteCal Program Files folder (see Step 4 of the procedure in Section 1.3, *Installing SteCal*, to determine where the program files are installed).
3. On the dialog shown in Figure 2-1, double-click a file or click it once and click **Open**. It is not possible to open more than one file at a time.

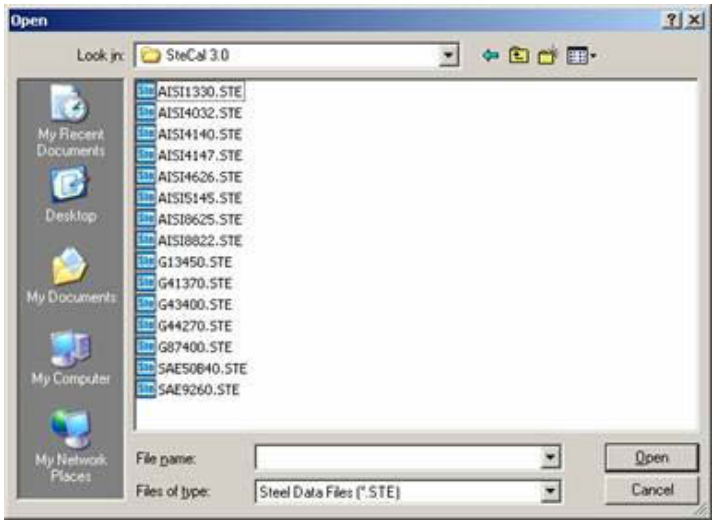


Figure 2-1: File Open Dialog

It is possible to have more than one set of data open at one time in the program, but only one set is considered the active steel data. Each open file is listed on the steel list, as shown in Figure 2-2.

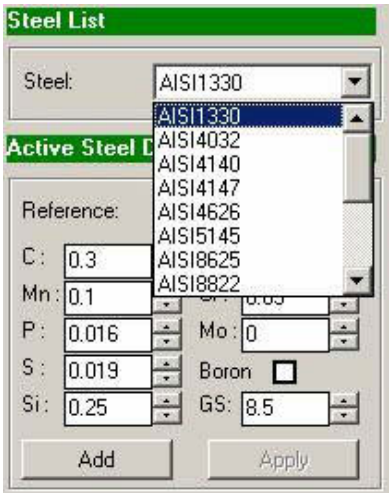


Figure 2-2: Steel List

Use the scroll bar or "up" and "down" keys to select a steel reference.

Note: Only open files appear on the steel list.

2.2 Steel Data

Composition and Grain Size Allowable Limits

SteCal allows you to enter the alloy contents of the following elements:

- Ø Carbon*
- Ø Manganese*
- Ø Phosphorus*
- Ø Sulfur*
- Ø Silicon*
- Ø Nickel
- Ø Chromium
- Ø Molybdenum

Only the elements with asterisks are required to complete the calculations. Austenitic grain size (defined according to American Society of Testing and Materials [ASTM] standards) is also required. The permitted and recommended limits are shown in Table 2-1.

Steel Data	Permitted Lower Limit	Recommended Lower Limit	Recommended Upper Limit	Permitted Upper Limit
Carbon Content (C)	0.1	0.15	0.65	0.70
Manganese Content (Mn)	0	0	2.0	2.7
Phosphorus Content (P)	0	0	0.1	0.1
Sulfur Content (S)	0	0	0.3	0.3
Silicon Content (Si)	0	0	1.0	2.0
Nickel Content (Ni)	0	0	4.0	5.0
Chromium Content (Cr)	0	0	1.5	2.5
Molybdenum Content (Mo)	0	0	0.5	1.0
Boron Content (B)	---	No	Yes	---
Grain Size (GS)	1	4	10	15

Table 2-1: Permitted and Recommended Limits of Steel Data (Contents: Weight %)

Using values within the recommended limits will provide for the least possibility of error in the calculations. Errors may occur, however, if numerous elements are close to the upper or lower limits of the specified margins. This is not normal with low-alloy steels.

Boron Content

SteCal takes boron content into account only when sufficient non-combined boron is present (>0.002%) and can affect hardenability; in this case, the steel is deoxidized and all boron has been dissolved in the austenitizing. Lin [Ref. 1] has evaluated the non-combined boron (or "boron potential") as %B – 0.8 × (%N – 0.3 × % Ti). If the boron potential is less than 0.002%, the effects on hardenability may be less than was calculated.

Effect of Other Alloying Elements

For obvious reasons, it is impossible for the calculations to take into account the effects of alloying elements that are not entered in the composition. For some elements, however, the effects can be approximated. For example:

- Ø The effect of possible tungsten content can be evaluated, to almost all effects, by adding half of the tungsten content [Ref. 2] to the molybdenum content.
- Ø The effect of copper content can be evaluated, to many effects, by adding half of the copper content to the nickel content [Ref. 3].

- Ø The effect of vanadium is not included in the calculation methods included in the program, because its effect on hardenability and temperability, for example, depends on the extent of carbide solution obtained in the austenitizing process. Incomplete solution may even diminish hardenability and as-quenched hardness. Nevertheless, the effect of vanadium can be evaluated, so far as its influence on tempering is concerned (if the steel has been correctly and completely austenized), by adding approximately double the vanadium content to the molybdenum content [Ref. 3].
- Ø Such aspects as the upper critical point temperature in heating (and, consequently, effects on austenitizing temperature) can also be considered. To take these into account it is necessary to add the following terms [Ref. 4]:

…. + 100 x %V + 400 x %Al + 400 x %Ti

Entering Steel Data

The fields for entering steel data are shown in Figure 2-3.

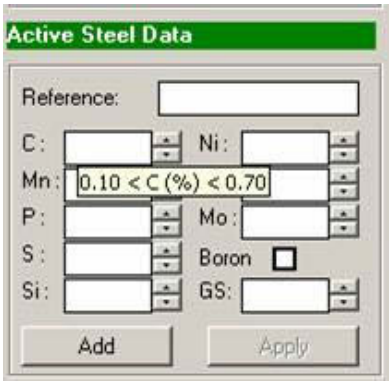


Figure 2-3: Active Steel Data Window

As shown, a "Tool Tip" displays the *permitted* lower and upper limits for the selected field. Data must be initially entered using the keyboard. The values can be changed within the *recommended* limits using the "up" and "down" arrows. The arrows may not be used for a particular field until a value is first entered via the keyboard. The arrows increase and decrease the steel data values in the following increments:

- Ø C, Mn, Si, Ni, Cr, and Mo: 0.01%
- Ø P and S: 0.001%
- Ø GS: 0.5 ASTM

Note: The values may be entered in exponential form, e.g., 2E-3.

You may move between fields using either the **Tab** key or the mouse.

After the valid steel data is entered, the code figures will appear in the lower portion of the steel data window, as shown in Figure 2-4.

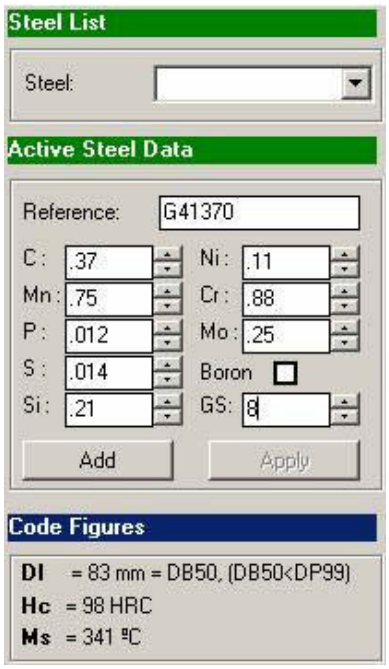


Figure 2-4: Active Steel Data with Code Figures

Notes: No calculations can be carried out unless all steel data are within the permitted limits. If you enter a value outside of the permitted limits, clicking **Add** or requesting results or graphics, may prompt the warning shown in Figure 2-5 to appear.

Figure 2-5: Invalid Data Error Dialog

You may also be warned if you enter data outside the recommended limits (see Figure 2-6), but you may continue with the calculations by clicking **OK**. (See Section 2.5, *Changing Program Options*, to select whether such warnings appear.)

Figure 2-6: Not Recommended Data Warning Dialog

Chapter 3, *Generating Results and Graphics*, explains how to display data tables and curves based on the data entered in the steel data window.

2.3 Saving and Reopening Steel Data

Using the Steel List

The steel list stores in memory different steel data *from the current SteCal session*. The steel list also includes data from any saved files opened during the current session. Data stored on the steel list are not available once the SteCal program is closed, unless it is saved as an .ste file (see the next section, *Saving and Reopening Steel Data Files*).

Steel data included on the steel list are put in order by their reference, so there cannot be two steel data on the list with the same reference. In order to be added to the steel list, data must have the adequate format (all fields are numeric) and be within the permitted limits.

To store data in the steel list:

1. Enter a name in the **Reference** field and click the **Add** button (see Figure 2-4).
2. If the **Reference** field is empty, the dialog shown in Figure 2-7 will appear. Enter the reference name and click **OK**.

Figure 2-7: Prompt to Input a Reference

3. If a reference that already exists on the steel list is entered, and the option **Overwrite previous steel data without asking** is deactivated (see Section 2.5, *Changing Program Options*), you will be alerted that the reference already exists and asked if you want to overwrite it with the new data. The warning is shown in Figure 2-8.

Figure 2-8: Steel Reference Overwrite Warning

To view data from the current session, select it from the **Steel** dropdown menu.

Saving and Reopening Steel Data Files

Steel data saved as an .ste file can be recalled after the current SteCal session has ended, i.e., after the SteCal program is closed and reopened.

To save a set of steel data as an .ste file:

1. Enter a reference name in the **Reference** field (see Figure 2-4).
2. Select **File** ð **Save Active Steel Data** from the menu bar. You may also click the **Save** icon ( ).
3. Enter a file name in the appropriate field on the dialog shown in Figure 2-9. Click **Save**.

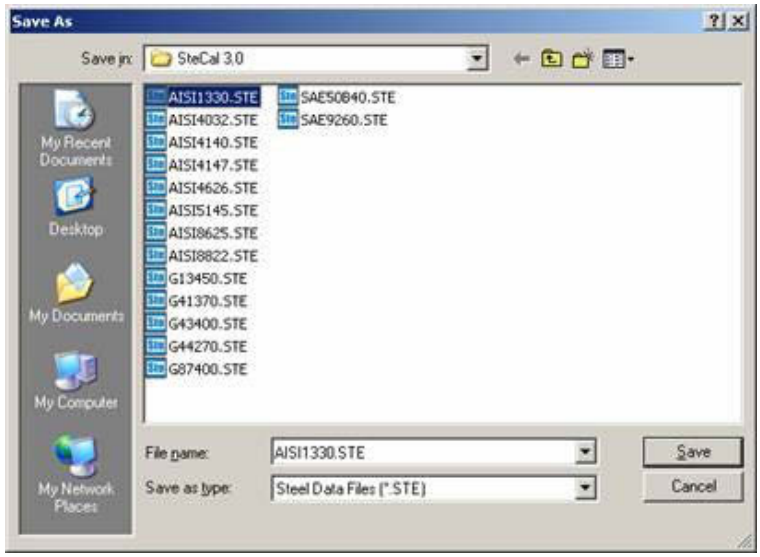


Figure 2-9: File Save As Dialog

Note: The default file storage location may not be the same as the location of the sample data files (e.g., it may be the My Documents folder). Observe the file location when saving the .ste file.

4. If a file with the entered reference name already exists, click **Yes** on the dialog shown in to overwrite it. If you click **No**, you will be allowed to enter a different name.

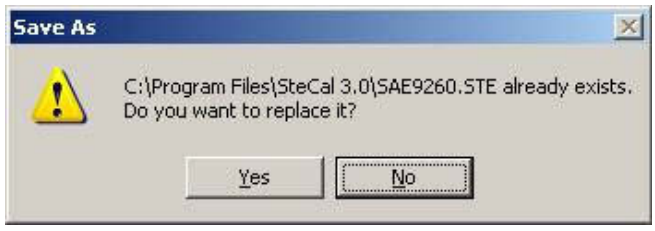


Figure 2-10: File Overwrite Warning

5. If a reference name was not entered in Step 1, you will be prompted to enter one by the dialog shown in Figure 2-7. Do so and click **OK**.
6. To save changes to the steel data, select **File** ð **Save Active Steel Data** or click the **Save** icon ( ).
7. To save changes under a *new* name, select **File** ð **Save Active Steel Data As**. Follow Steps 3 through 5.

To open an .ste file:

1. Select **File** ð **Open Steel Data** from the menu bar. You may also click the **Open** icon ( ).
2. Double-click a file or click it once and click **Open** (see Figure 2-1).

Saving Results and Graphics

Results (data tables) and graphics (data curves) may also be saved, and then reopened without the SteCal program. To save results or graphics:

1. After creating the results or graphics (see Chapter 3, *Generating Results and Graphics*), select **File** ð **Save Document**.
2. Enter an appropriate file name. Click the **Save** button. SteCal saves results as text (.txt) or rich text files (.rtf) , which can be opened, viewed, and edited in Notepad, WordPad, Word, etc. Graphics are saved as bitmap files (.bmp) , which can be opened, viewed, and edited in Paint, Photo Editor, Adobe PhotoShop, etc.

2.4 Printing Results and Graphics

To print results or graphics, select **File** ð **Print**. You may also click the **Print** icon ( ).

2.5 Changing Program Options

Units of Measure

Results and graphics may be displayed in SI or U.S. Customary units. Select **Options** ð**Units System** and select the desired system.

Note: Results and graphics were developed for this manual in SI units.

General Options

Select **Options** ð**General** and make the desired selections on the dialog shown in Figure 2-11. Click **OK** to save the selections, which will persist after the current SteCal session has ended, i.e., after the SteCal program is closed and reopened.

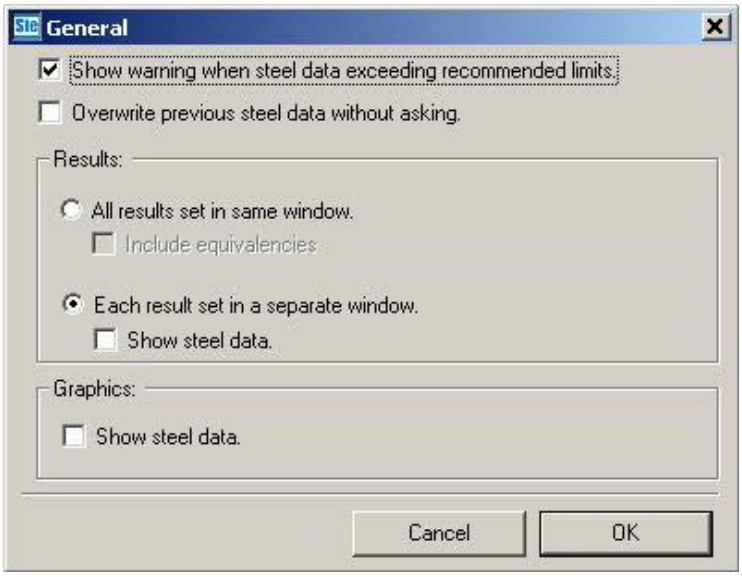


Figure 2-11: General Options

The options shown will have the following effects:

- **Show warning when steel data exceeding recommended limits:**
  A warning will be displayed when any data outside the recommended limits is entered.
- **Overwrite previous steel data without asking:**
  A warning will be displayed before previous steel data is overwritten.
- **All results set in same window:**
  All text results will be displayed in a single report, in the order in which they were requested. Steel data (reference name, composition, and grain size) will be included at the beginning of each set of results. New results will not affect previous ones.
  - **Include equivalencies:**
    The results of the equivalencies will be included in the report.
- **Each result set in a separate window:**
  Each text result will be displayed in a separate window.
  - **Show steel data:**
    Steel data will be included at the beginning of every set of text results.
- **Graphics – Show steel data:**
  Steel data will be included at the top of each graphic.

Chapter 3: Generating Results and Graphics

3.1 General

This section describes how to generate data tables and curves indicating the properties and behavior of the steel. These tables (available from the **Results** menu) and curves (**Graphics** menu) are provided in windows with representative names that are shown at the tops of the windows. The windows can be saved and modified.

A new window is automatically opened for each set of graphic results. Text results may be shown all in one window or in separate ones (see Section 2.5, *Changing Program Options*). Multiple windows may be open at once, but only the one in the foreground is considered the active document. Select a new active document by clicking it or choosing it from the **View** menu.

Once generated, you can change the text (if each result is set in a separate window) or graphic results in the active window by:

- Ø Entering new steel data and click the **Apply** button
- Ø Clicking "up" and "down" arrows

Note: SteCal was set to open results in a separate window for the screen shots in this section.

3.2 Fe-C Diagram

The Fe-C diagram data calculations are performed using the Andrews [Ref. 4] formulas, except for the carbon content, for which the eutectoid reaction is produced (pearlite content). This last is obtained using one of Aall's formulas.

To display the Fe-C diagram data, select **Results** ð **Data of Fe-C Diagram**. A window similar to the one shown in Figure 3-1 will appear.

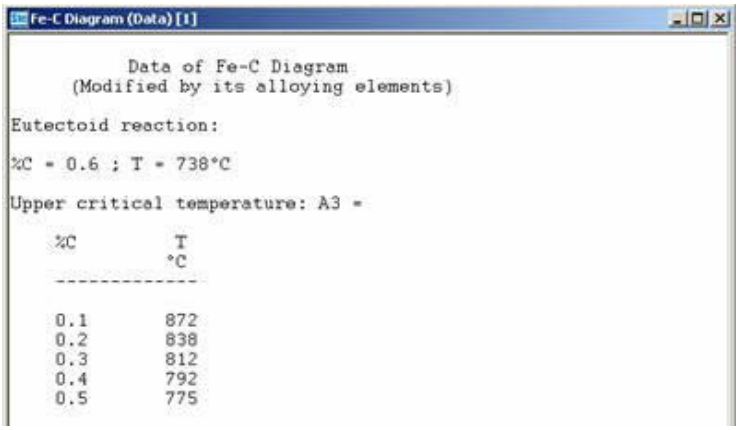


Figure 3-1: Fe-C Diagram Data

To display the Fe-C curve, select **Graphics** ð **Fe-C Diagram**. A window similar to the one shown in Figure 3-2 will appear.

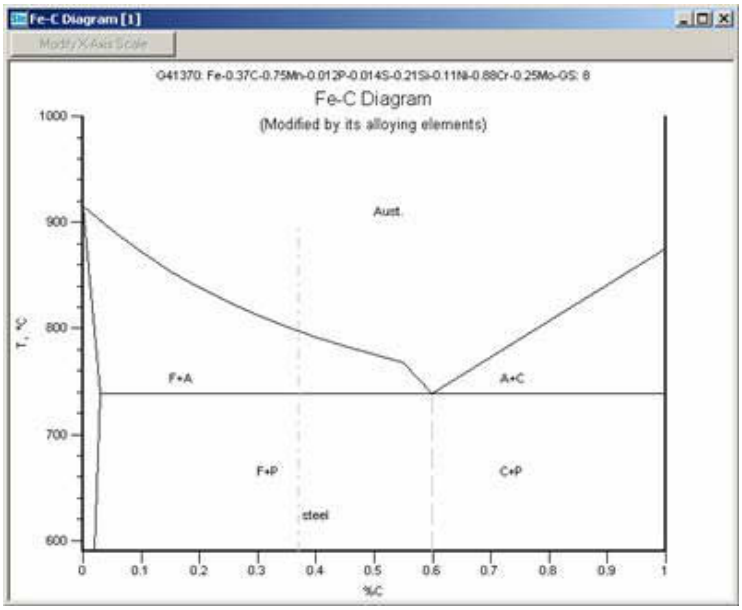


Figure 3-2: Fe-C Diagram

The carbon content of the steel being studied is shown in this diagram by a vertical line. The relative content of ferrite and pearlite of the annealed steel can be deduced from the relative position of this line.

3.3 Code Figures

Definition of Code Figures

The term *code figures* [Ref. 24] refers to three values: ideal critical diameter (DI), characteristic hardness (H_c), and the temperature at which martensite formation begins (M_s). Code figures can be calculated for a steel of given composition, and are representative parameters for that steel. These code figures (together with carbon percentage) give a better indication than the composition itself of the obtainable behavior and properties from quenching and tempering.

Additional advantages of defining steels by their code figures are:

- Ø They allow one to easily establish equivalencies between low-alloy steels that have the same code figures and carbon content, since the behavior and properties of such steels will be similar under similar heat treatments.
- Ø They are very useful when comparing two steels, with the aim of finding one steel that can be used in place of another.
- Ø They can be obtained by calculations.

When appropriate data has been entered, code figures appear at the bottom of the steel data window (see Figure 3-3).

Figure 3-3: Code Figures on Steel Data Window

Code figures can also be viewed by selecting **Results** ð **Code Figures**. A window similar to the one shown in Figure 3-4 will appear.

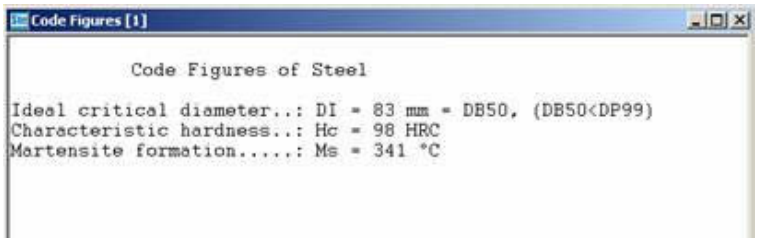


Figure 3-4: Code Figures in Separate Window

These code figures, and how SteCal obtains them, are described in more detail in the following sections.

Ideal Critical Diameter (DI)

The hardenability, or ideal critical diameter (DI), is representative of the behavior of a steel under quenching. In SteCal, hardenability is obtained by the Grossmann [Ref. 5] method, with corrections made by Siebert and Doane [Ref. 6], and with the addition of the boron influence according to the Caterpillar [Ref. 7] formula. Hollomon's [Ref. 3] model is applied to the value obtained by this procedure in order to deduce pearlitic (DP_{99} and DP_{50}) and bainitic (DB_{99} and DB_{50}) hardenabilities with 1% and 50% transformations, respectively. The martensitic hardenabilities are obtained from these values for 99% and 50% of martensite (DM_{99} and DM_{50}, respectively) using the method developed by Calvo Rodés [Ref. 8].

SteCal returns either DB_{50} or DP_{99} as the code figure value, whichever is smaller. This hardenability criterion is in line with the industrial practice of allowing up to a maximum of 50% of bainite, but no ferrite-pearlite in the quenching.

Characteristic Hardness (H_C)

The characteristic hardness (H_C) is representative of the entire response of a steel to tempering. In SteCal, characteristic hardness is obtained by Hollomon's method [Ref. 3] for high tempering temperatures.

Martensite Formation Temperature (M_S)

The temperature M_S, that represents the start of the martensitic reaction, is indicative of the susceptibility of the steel to quench cracking (when considered together with the carbon content of the steel). M_S is obtained by means of one of Andrews' [Ref. 4] formulas.

3.4 Heat Treatments

General Data

SteCal calculates the following general steel characteristics:

- Critical points: The critical points for when the steel is in equilibrium (A_1 and A_3) and when it is heated (Ac_1 and Ac_3), obtained by means of the Andrews [Ref. 4] formulas.
- Highest tempering feasible: The temperature at which austenitizing can begin, calculated according to Bain's criterion. This differs from the Andrews A_1 value, which is defined according to a different criterion.
- Austenitizing temperature: This is obtained by means of a formula that takes into account the need to increase the temperature higher than usual when carbide-forming alloying elements are present in the alloy. This is a normal industrial practice.
- Retained austenite: Indicates retained austenite that is not transformed in a normal quenching to room temperature. This is deduced from the temperature M_S, obtained by one of the Andrews [Ref. 4] formulas and from the evaluation of the martensite transformation on cooling according to Koistinen's and Marburger's method [Ref. 9].
- Susceptibility to quench-cracking: This is deduced from the temperature M_S and the carbon content of the steel, according to experimental results given by Calvo Rodés [Ref. 10].
- Hardness available by quench: The hardnesses corresponding to different martensite percentages are obtained according to the works of Hodge and Orehoski [Ref. 11]. Also included is the minimum hardness to be obtained, depending on the carbon content of the steel, as recommended by Calvo Rodés [Ref. 12].

- Ø Hardness as normalized/softest condition: These are the hardnesses obtained with a ferrite-pearlite (normalized) microstructure and with a globalized cementite (the softest condition) microstructure, according to Bain's [Ref. 13] data. They take into account the hardening effect of the alloying elements that are dissolved in the ferrite.

To view the general heat treatment data, select **Results** ð **Data for Heat Treatments** ð **General Data**. A window similar to the one shown in Figure 3-5 will open.

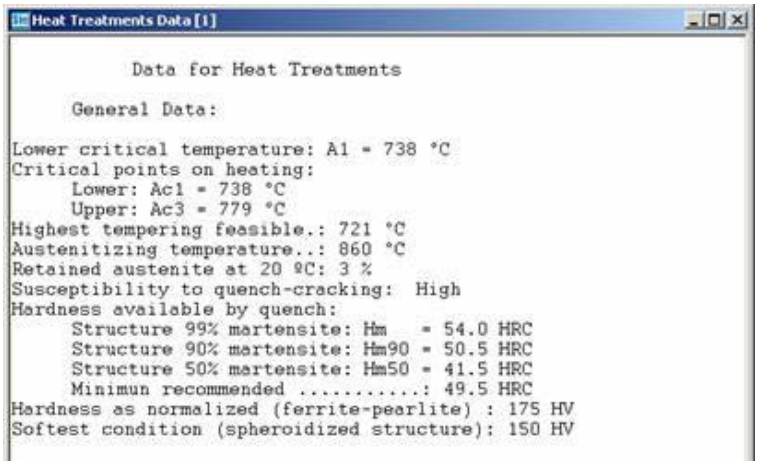


Figure 3-5: General Heat Treatment Data

TTT Diagram

SteCal calculates the following data for the time-temperature transformation (TTT) diagram:

- Ø Critical temperatures: Upper and lower critical positions in equilibrium according to Andrews [Ref. 4]
- Ø Pearlite formation/bainite formation: Data about transformation times at certain temperatures for pearlite and bainite zones, according to criteria and methods described by Haynes [Ref. 14]. The starting point for the application of these methods and criteria are the ideal critical diameter values, calculated as described in Section 3.5, and the Grossmann equivalencies [Ref. 15], with critical diameters for other quenching media. The temperature of the pearlitic zone cited is that which Haynes deduces for minimum transformation times. Likewise, the temperature defined as B_S is the highest at which any bainitic reaction can occur. Similarly, B_{50} and B_{99} are the highest temperatures at which 50% and 99% bainitic reactions can be obtained.
- Ø Martensite formation: Data that are representative of the evolution of the martensitic reaction. The temperature M_S is obtained according to Andrews [Ref. 4]. The values for M_{10}, M_{50}, M_{90}, and M_{99} indicate temperatures at which 10%, 50%, 90%, and 99%, respectively, of the martensitic reaction has been obtained. At M_{99}, the martensitic reaction can be considered complete. These four values are calculated according to the evolution of the martensitic reaction below the M_S, deduced by Koistinen and Marburger [Ref. 9].

To view the TTT diagram data, select **Results** ð **Data for Heat Treatments** ð **Data for TTT Diagram**. A window similar to the one shown in Figure 3-6 will appear.

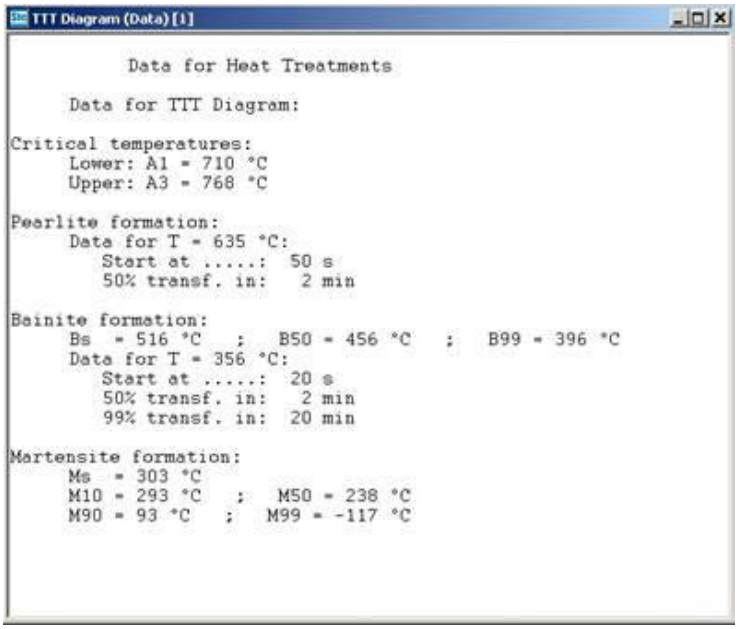


Figure 3-6: TTT Diagram Data

To view the TTT diagram, select **Graphics** ð **TTT Diagram**. A window similar to the one shown in Figure 3-7 will appear.

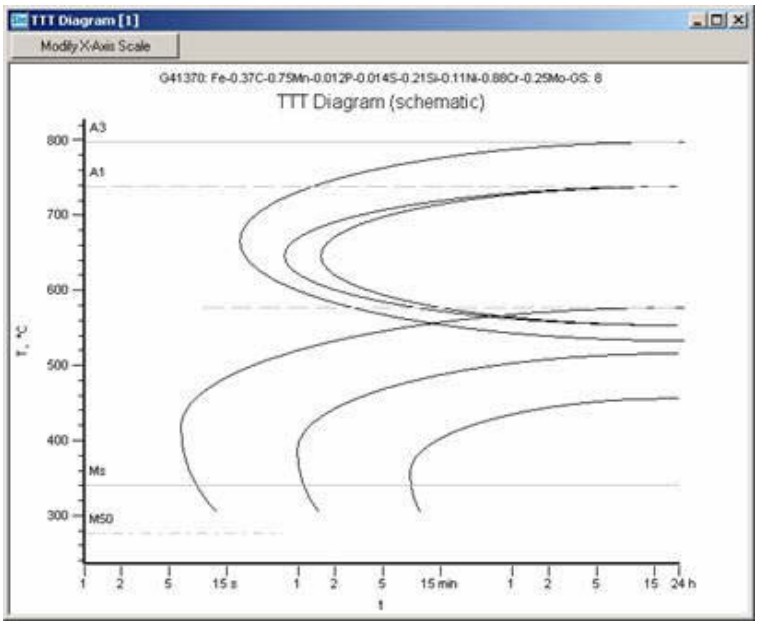


Figure 3-7: TTT Diagram

The diagram is obtained in schematic form and shows the curves corresponding to 1%, 50%, and 99% pearlitic and bainitic transformations.

The temperature axis is variable in accordance with the type of steel and, for each case, covers the range from 40 ºC below M_{50} up to 30 ºC above A_3. The previously calculated A_1, A_3, B_S, M_S, and M_{50} are also identified on this axis.

The curves corresponding to 1% and 99% pearlitic transformations are tangents to A_3 and A_1, respectively. The curve corresponding to 50% is either tangent at A_1 or situated between A_3 and A_1, depending or whether there is more or less than 50% ferrite in steel.

The time axis (on a logarithmic scale) is initially defined up to 24 hours (or 48 hours if times longer than one day have been calculated). Click the **Modify X-Axis Scale** button at the top left of the window to change the maximum time included on this axis. This option is available if the calculated minimum time is less than 24 hours, all the calculated data are included, and the curves are realistic. The program calculates the smallest time that can be used as the

maximum on the time axis for fulfilling these conditions.

The program modifies diagram esthetics when one of the times calculated is less than 1 second, or when there is interference or a considerable amount of "overlap" between the different transformation zones. These modifications improve the display and interpretation of the diagram, and also make it a truer reflection of the actual facts. This "cleaning up" is carried out automatically, as the diagram is being drawn on the screen, when any of the aforementioned causes is detected.

3.5 Ideal Critical Diameter

The six hardenabilities values, with the different ideal critical diameters (DP_{99}, DP_{50}, DB_{99}, DB_{50}, DM_{99}, DM_{50}), are calculated according to Grossmann [Ref. 5] method, with corrections made by Siebert and Doane [Ref. 6], and with the addition of the boron influence according to the Caterpillar [Ref. 7] formula.

Hollomon's model [Ref. 3] is applied to the value obtained by this procedure in order to deduce hardenabilities according to the following criteria: bainitic and pearlitic hardenabilities (see *Ideal Critical Diameter* in Section 3.3) with 1% and 50% transformation (DB_{99}, DB_{50}, DP_{99}, and DP_{50}, respectively). The martensitic hardenabilities are obtained from these values for 99% and 50% of martensite (DM_{99} and DM_{50}, respectively) using the method developed by Calvo Rodés [Ref. 8].

To view the ideal critical diameters, select **Results** ð **Ideal Critical Diameters**. A window similar to the one shown in Figure 3-8 will appear.

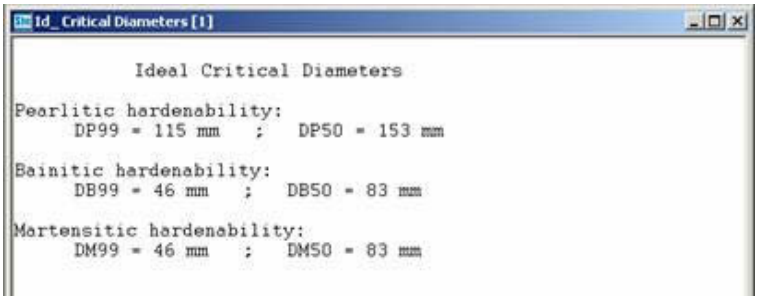


Figure 3-8: Ideal Critical Diameters

3.6 CCT Diagrams

Diagrams for continuous cooling transformations (CCT)—temperature/time, temperature/ideal critical diameter, and temperature/diameter—are based on the following calculated data:

- Ø Critical temperatures (defined in Section 3.4)
- Ø Pearlite formation/bainite formation (defined in Section 3.4)
- Ø Martensite formation (defined in Section 3.4)
- Ø Ideal critical diameters (defined in Section 3.5)

T–t Diagram

To view the temperature/time CCT diagram, select **Graphics** ð **CTT Diagram** ð **T-t Diagram**. A window similar to the one shown in Figure 3-9 will open.

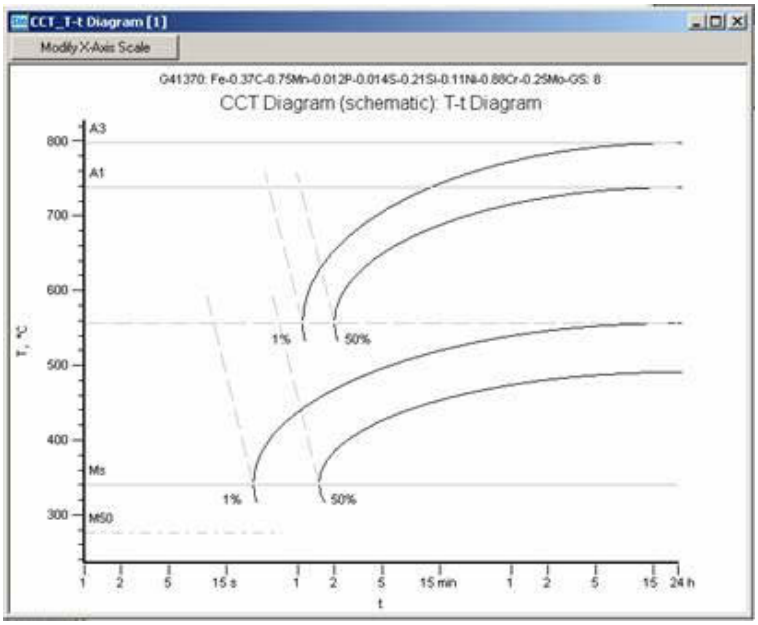


Figure 3-9: Temperature-Time CCT Diagram

The diagram is obtained in schematic form and shows the curves corresponding to 1% and 50% transformations. The axes for temperature and time fulfill the same characteristics as described earlier for the TTT diagram (in Section 3.4). The temperature axis includes A_1, A_3, B_S, M_S, M_{50} (identical to the TTT diagram), and B_S and B_{50}. These are defined by Haynes [Ref. 14] (for this case) as the maximum at which bainite can be obtained by continuous cooling.

The data necessary for drawing the diagram are obtained by deducing the cooling curve for the centers of the previously calculated ideal critical diameters from their equivalencies with positions on the Jominy test specimen or on air-cooled bars [Refs. 46, 47]. Stretches of these cooling curves are drawn (broken line) on the diagram. These superimposed curves allow deductions to be made as to the possibilities of obtaining different combinations of microconstituents by means of different cooling rates.

Click the **Modify X-Axis Scale** button at the top left of the window to change the maximum time displayed on the graph. The calculated minimum time is indicated as lower limit, as long as all the data are included in the graph and that the curves are realistic. The program does not allow a minimum time greater than 24 hours.

T–DI Diagram

To view the temperature/ideal critical diameter CCT diagram, select **Graphics** ð **CTT Diagram** ð **T-DI Diagram**. A window similar to the one shown in Figure 3-10 will open.

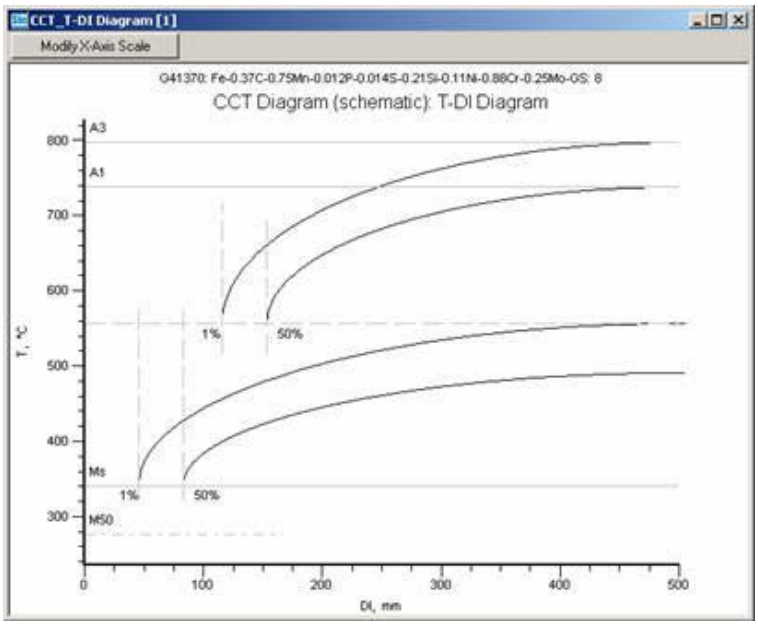


Figure 3-10: Temperature-Ideal Critical Diameter CCT Diagram

The diagram is obtained in schematic form and shows the curves corresponding to 1% and 50% transformations. The characteristics of this diagram are the same as those of the preceding one. It also incorporates superimposed, straight, vertical lines that assist in deducing the structure obtained with different diameters.

The data necessary for drawing the diagram are obtained using the calculated ideal critical diameters.

The diameter axis fulfills the same characteristics as described for the TTT diagram. The diameter axis is defined initially up to 500 mm (or 1000 mm if diameters longer than 500 mm have been calculated). The maximum may be changed as long as all the calculated data are included and the curves are realistic. The program calculates the smallest diameter that can be used as the maximum on the diameter axis for the fulfilling these conditions.

Click the **Modify X-Axis Scale** button at the top left of the window to change the maximum diameter displayed on the graph. This option is available only if the minimum value is less than 500 mm, all the data are included in the graph, and that the curves are realistic..

T–D Diagram

To view the temperature/diameter CCT diagram, select **Graphics** ð **CTT Diagram** ð **T-D Diagram**. The program prompts you to select the cooling medium for its severity of quench value H. A window similar to the one shown in Figure 3-11 will open.

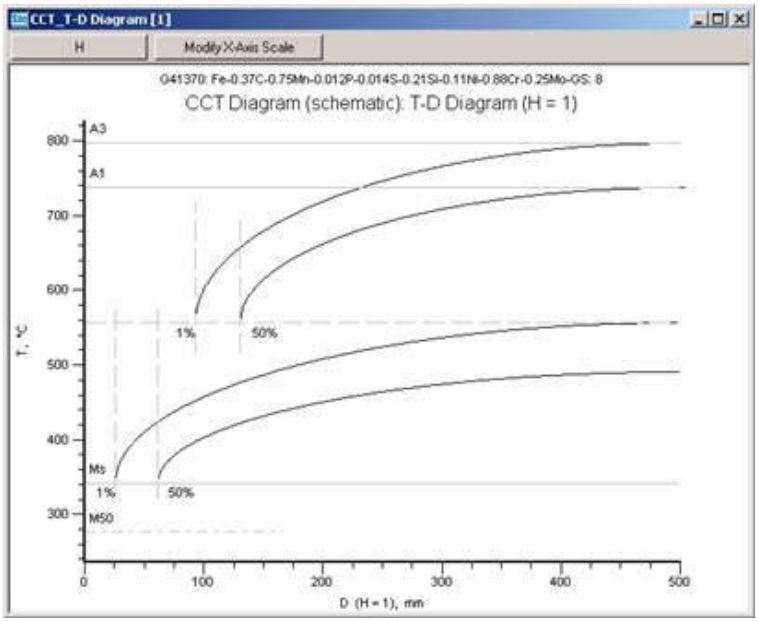


Figure 3-11: Temperature-Diameter CCT Diagram

The diagram is obtained in schematic form and shows the curves corresponding to 1% and 50% transformations. The data necessary for drawing the diagram are obtained using the calculated ideal critical diameters and their equivalencies to critical diameters in a cooling medium H, by means of the Grossmann curves [Refs. 15, 22].

The temperature axis fulfills the same characteristics as described for the TTT diagram. The diameter axis fulfills the same characteristics as described for the CCT (T-DI) diagram. The characteristics of this diagram are the same as those of the preceding one.

Click the **H** button at the top left of the window to change the cooling medium for its severity of quench.

Click the **Modify X-Axis Scale** button to change the maximum diameter displayed on the graph. This option is available as long as the minimum diameter is less than 500 mm, all the data are included in the graph, and that the curves are realistic) is indicated as the lower limit.

3.7 Hardness Tempering

The program allows calculation of the variation in hardness (on the Rockwell and Vickers scales), tensile strength (UTS), yield strength (YS), and elongation (EL) to be made in terms of the tempering temperature.

The hardness variations on the Rockwell scale for the different tempering temperatures are calculated as follows:

- Ø The Hollomon [Ref. 3] calculation method is used for complete hardening.
- Ø The Crafts [Ref. 16] method is used for incomplete hardening. Corrections, according to the Hollomon [Ref. 3] method, are applied for tempering time. In this case, the program asks for the as-quenched hardness Hq for values between 50% and 99% of martensite (Hm_{50}<Hq<Hm).

The equivalencies of the HRC hardness to the Vickers scale are calculated using the ASTM standard [Ref. 17]. The UTS, YS, and EL values are obtained from the hardness and the carbon content according to the table published by Calvo Rodés [Refs. 10, 12].

The program calculates equivalencies for temperatures between 400 and 700 ºC (750 to 1300 ºF), and shows on the screen only these values above 0 HRC. It will likewise give UTS values only if they correspond to HRC values less than 60 HRC, and YS and EL values only if they correspond to hardness values less than 45 HRC. This is because the cited author gives reliable results only in these cases.

Complete Hardening

To view the hardness tempering data for complete hardening:

1. Select **Results** ð **Hardness Tempering** ð **Complete Hardening**.
2. Enter the time (in hours) at the tempering temperature in the dialog shown in Figure 3-12. As with other data entry fields, you can view the lower and upper limits by moving the mouse over or selecting the field.

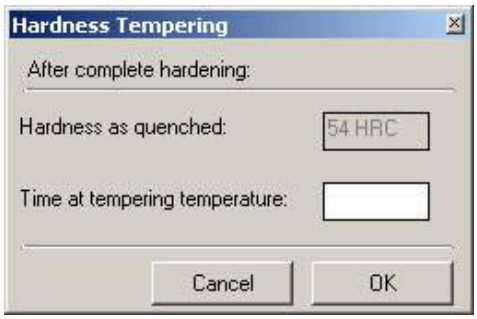
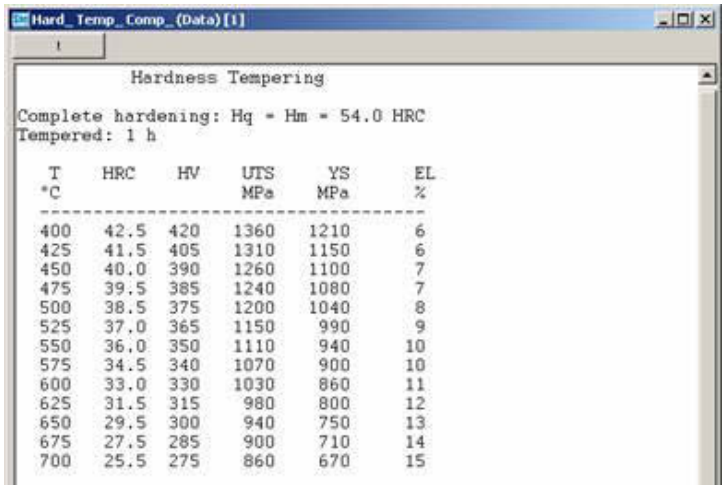


Figure 3-12: Hardness Tempering Dialog (Complete Hardening)

3. Click **OK**. A window similar to the one shown in Figure 3-13 will open.
4. Click the **t** button at the top left of the window to change the time at tempering temperature.



T °C	HRC	HV	UTS MPa	YS MPa	EL %
400	42.5	420	1360	1210	6
425	41.5	405	1310	1150	6
450	40.0	390	1260	1100	7
475	39.5	385	1240	1080	7
500	38.5	375	1200	1040	8
525	37.0	365	1150	990	9
550	36.0	350	1110	940	10
575	34.5	340	1070	900	10
600	33.0	330	1030	860	11
625	31.5	315	980	800	12
650	29.5	300	940	750	13
675	27.5	285	900	710	14
700	25.5	275	860	670	15

Figure 3-13: Hardness Tempering Data (Complete Hardening)

To view the hardness tempering curve for complete hardening:

1. Select **Graphics** ð **Hardness Tempering** ð **Complete Hardening**.
2. Enter the time (in hours) at the tempering temperature.
3. Click **OK**. A window similar to the one shown in Figure 3-14 will open, for which 25 positions have been calculated. Only the following values are drawn:
   - Ø Hardnesses between 20 and 55 HRC
   - Ø UTS and YS values between 750 and 1800 MPa (110 and 280 ksi)
   - Ø EL values less than 20%

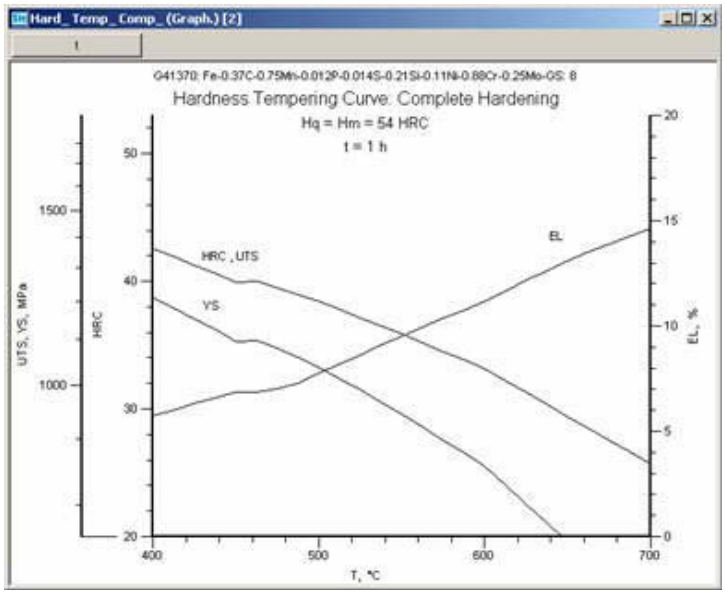


Figure 3-14: Hardness Tempering Curve (Complete Hardening)

4. Click the **t** button at the top left of the window to change the time at tempering temperature.

Incomplete Hardening

To view the hardness tempering data for incomplete hardening:

1. Select **Results** ð **Hardness Tempering** ð **Incomplete Hardening**.
2. Enter the as-quenched hardness Hq (only values between Hm_{50} and Hm) and the time at the tempering temperature in the dialog shown in Figure 3-15.

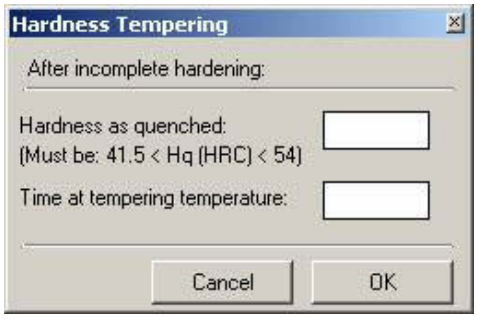


Figure 3-15: Hardness Tempering Dialog (Incomplete Hardening)

3. Click **OK**. A window similar to the one shown in Figure 3-16 will open.

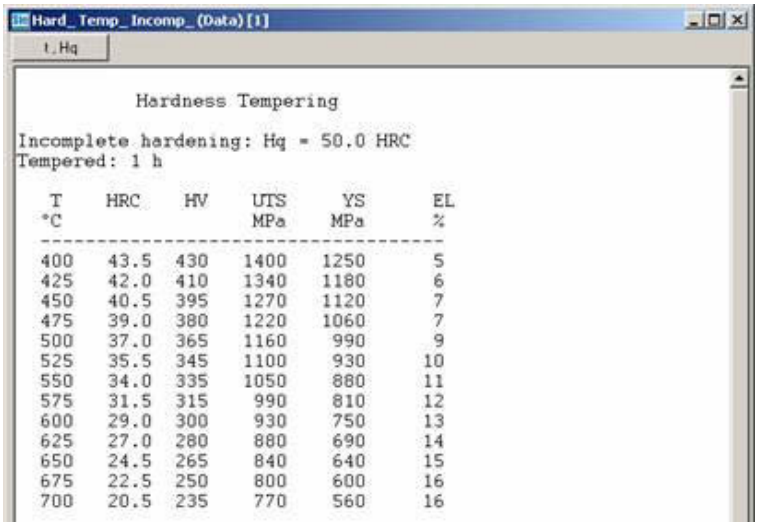


Figure 3-16: Hardness Tempering Data (Incomplete Hardening)

4. Click the **t, Hq** button at the top left of the window to change the time at tempering temperature or the as-quenched hardness (only values between Hm_{50} and Hm).

Changes in %C are allowed only if Hq stays between Hm_{50} and Hm.

To view the hardness tempering curve for incomplete hardening:

1. Select **Graphics** ð **Hardness Tempering** ð **Incomplete Hardening**.
2. Enter the as-quenched hardness Hq (only values between Hm_{50} and Hm) and time at the tempering temperature.
3. Click **OK**. A window similar to the one shown in Figure 3-14 will open, for which 25 positions have been calculated. Only the following values are drawn:
   - Ø Hardnesses between 20 and 55 HRC
   - Ø UTS and YS values between 750 and 1800 MPa (110 and 280 ksi)
   - Ø EL values less than 20%

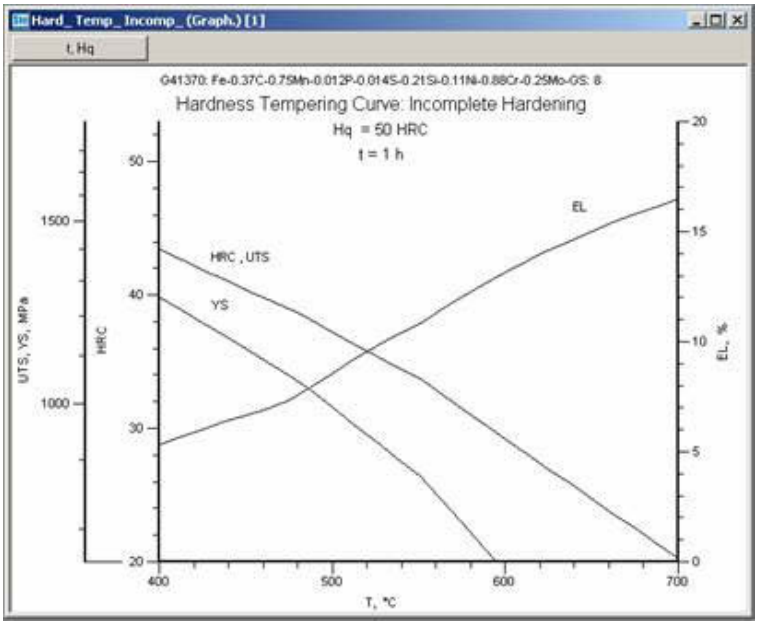


Figure 3-17: Hardness Tempering Curve (Incomplete Hardening)

4. Click the **t, Hq** button at the top left of the window to change the time at tempering temperature or the as-quenched hardness (only values between Hm_{50} and Hm).

Changes in %C are allowed only if Hq stays between Hm_{50} and Hm.

3.8 Jominy End-Quench Hardenability

SteCal calculates results for the 26 positions of Jominy distances. The hardnesses are calculated according to the Rockwell C scale, at various points on each one of the curves obtained with the Crafts [Ref. 16] method. Corrections have been made to this method, to take into account the effect of boron on hardenability, according to the Caterpillar [Ref. 7] method, and the time tempering according to Hollomon [Ref. 3]. Only the values higher than 20 HRC are drawn..

Quenched Only

To view the Jominy end-quenched hardenability data for a quenched specimen, select **Results** ð **Jominy End-Quench Hardenability** ð **Specimen Quenched Only**. A window similar to the one shown in Figure 3-18 will appear. Hardness values less than 0 HRC are not given.

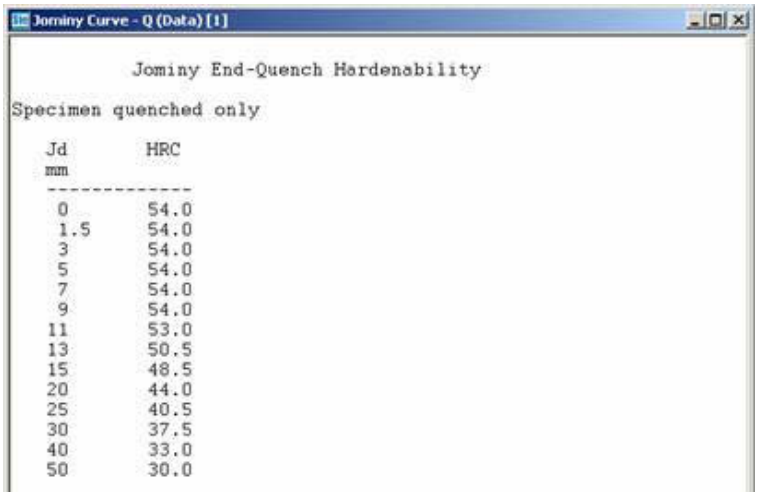


Figure 3-18: Jominy End-Quench Hardenability Data for a Quenched Specimen

To view the Jominy end-quenched hardenability curve for a quenched specimen, select **Graphics** ð **Jominy End-Quench Hardenability** ð **Specimen Quenched Only**. A window similar to the one shown in Figure 3-19 will appear. Only the values higher than 20 HRC are drawn. The curves are drawn using the results calculated for 26 positions of Jominy distances.

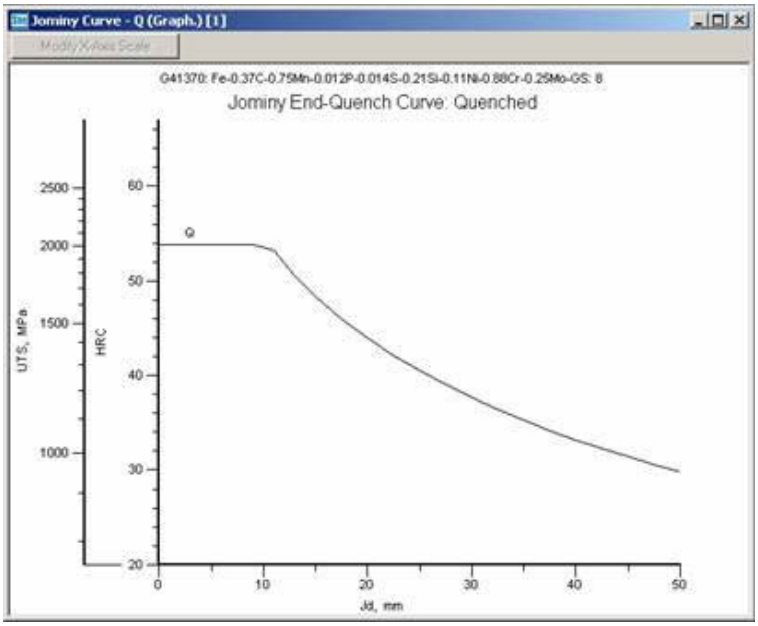


Figure 3-19: Jominy End-Quench Hardenability Curve for a Quenched Specimen

Quenched and Tempered

To view the Jominy end-quenched hardenability data for a specimen that has been quenched and tempered:

1. Select **Results** ð **Jominy End-Quench Hardenability** ð **Specimen Quenched and Q+ Tempered**.
2. Enter the tempering temperature (ºC or ºF) and time at tempering temperature (h) in the dialog shown in Figure 3-20.

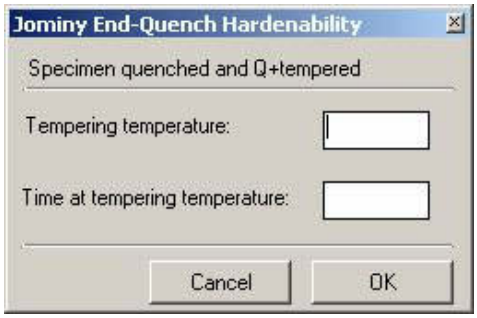


Figure 3-20: Jominy End-Quench Hardenability Dialog

3. Click **OK**. A window similar to the one shown in Figure 3-21 will appear.

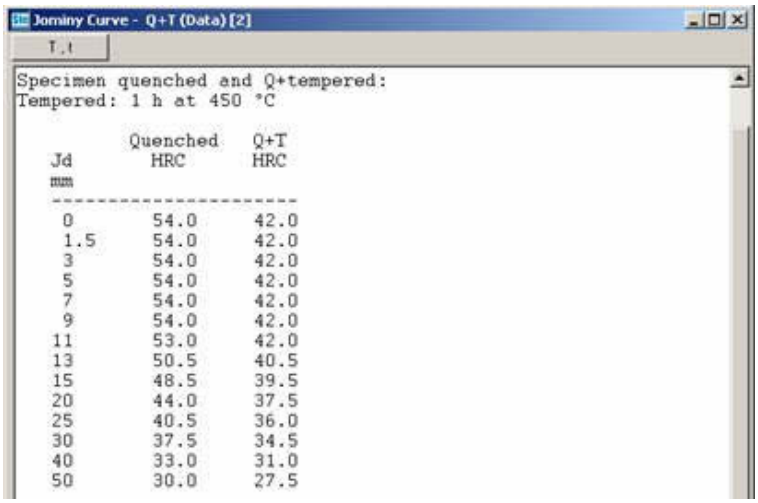


Figure 3-21: Jominy End-Quench Hardenability Data for a Quenched and Tempered Specimen

4. Click the **T, t** button at the top left of the window to change either value.

To view the Jominy end-quenched hardenability curve for a specimen that has been quenched and tempered:

1. Select **Graphics** ð **Jominy End-Quench Hardenability** ð **Specimen Quenched and Q+ Tempered**.
2. When prompted, enter the tempering temperature and time at tempering temperature (h). Click **OK**. A window similar to the one shown in Figure 3-22 will appear. The curves are drawn using the results calculated for the 26 positions of Jominy distances.

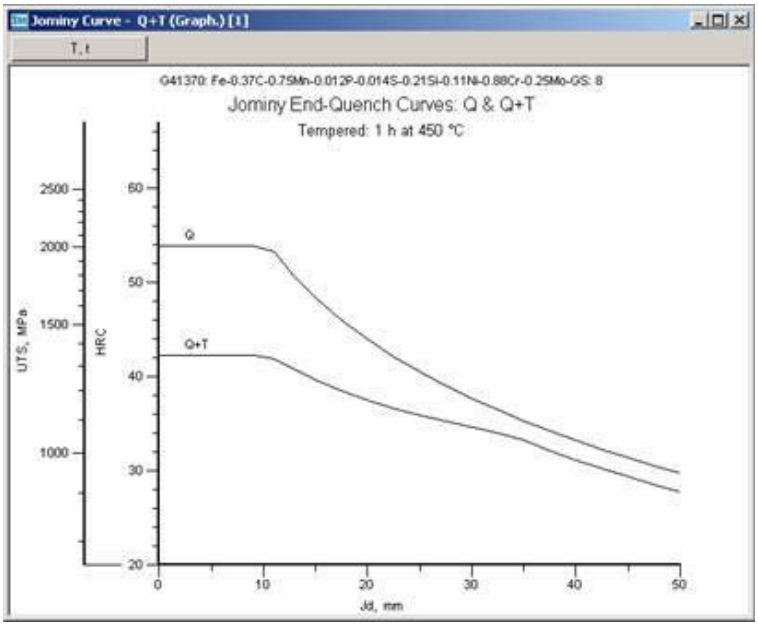


Figure 3-22: Jominy End-Quench Hardenability Curve for a Quenched and Tempered Specimen

3. Click the **T, t** button at the top left of the window to change either value.

3.9 Hardness Distribution in Round Bars

Hardness distribution in round bars is calculated for the 21 positions in the radius of the section of the bar. First, the Jominy test specimen position, which has a similar cooling, is calculated for each one of these positions using the Lamont [Ref. 18] curves. Then the hardness of each position is calculated according to the Crafts [Ref. 16] method.

In certain cases, the calculations are not possible due to the lack of equivalencies for some bar positions on the Lamont curves with positions on the Jominy test specimen (e.g., for diameters >125 mm and H > 0.5, the Lamont curves do not give an equivalence for the center of the bar). In such cases, the program will give "---" as result instead of a hardness value and the curves will be shown as incomplete.

Note: In some cases (e.g., low hardenability steels and bars with small diameter), because of the morphology of the curves obtained (which should be, in a certain way, similar to the Jominy curves), the equivalence between bar positions and Jominy test specimen positions will not be drawn correctly. This is because there are anomalies in those Lamont curves corresponding to $0.3 < r/R < 0.6$ and $r/R = 1$ and small diameters.

Quenched Only

To view the hardness distribution data for a round bar that has been quenched only:

1. Select **Results** ð **Hardness Distribution in Round Bars** ð **Round Bar Quenched Only**.
2. Enter the diameter of the round bar (mm or in) and the severity of the quench (1/in) in the dialog shown in Figure 3-23.

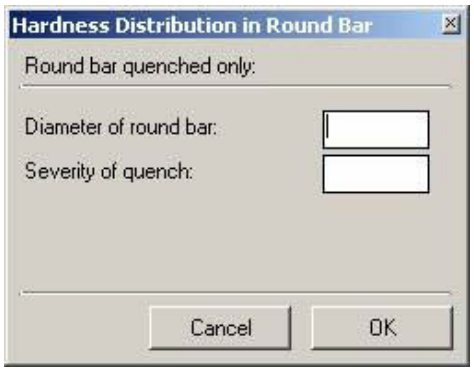


Figure 3-23: Hardness Distribution Dialog for Quenched Round Bar

3. Click **OK**. A window similar to the one shown in Figure 3-24 will appear. The hardnesses (which are calculated for several positions along the length of the cross-sectional radius of the bar) are shown for all HRC values greater than 0 HRC.

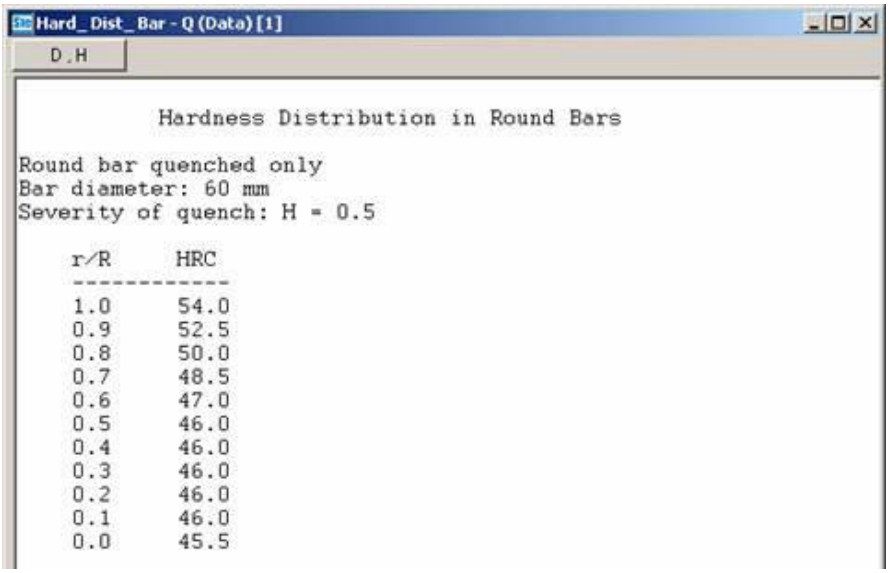


Figure 3-24: Hardness Distribution Data for Quenched Round Bar

4. Click the **D, H** button at the top left of the window to change either value.

To view the hardness distribution curve for a round bar that has been quenched only:

1. Select **Graphics** ð **Hardness Distribution in Round Bars: U Curve** ð **Round Bar Quenched Only**.
2. Enter the round bar diameter (mm or in) and quench severity (1/in). Click **OK**. A window similar to the one shown in Figure 3-25 will appear. The curves are drawn using the results calculated for the 21 positions in the radius of the section of the bar. Only the values higher than 20 HRC are drawn.

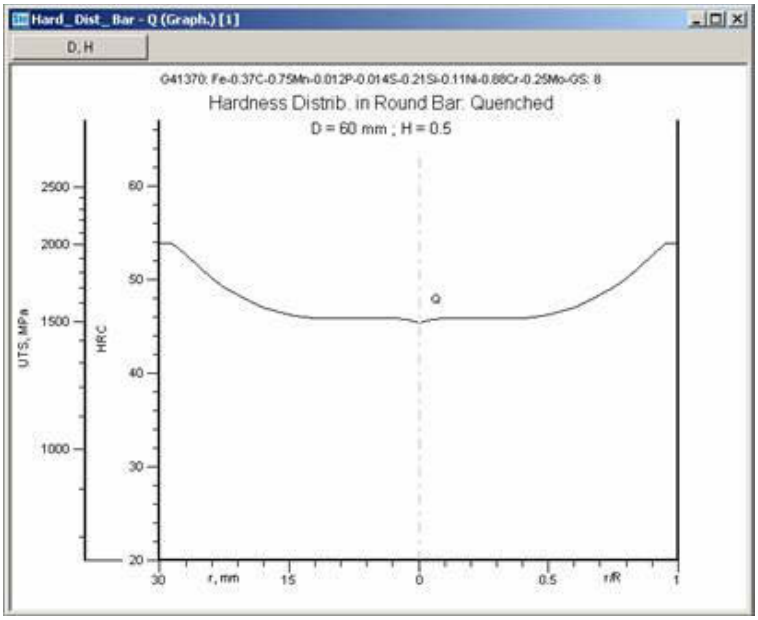


Figure 3-25: Hardness Distribution Curve for Quenched Round Bar

3. Click the **D, H** button at the top left of the window to change either value.

Quenched and Tempered

To view the hardness distribution data for a round bar that has been quenched and tempered:

1. Select **Results** ð **Hardness Distribution in Round Bars** ð **Round Bar Quenched and Q+ Tempered**.
2. Enter the round bar diameter (mm or in), quench severity (1/in), tempering temperature (ºC or ºF), and time at tempering temperature (h) in the dialog shown in Figure 3-26.

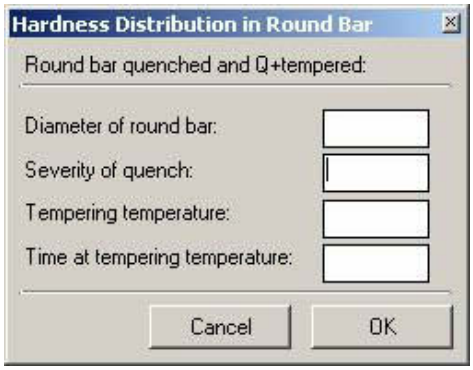


Figure 3-26: Hardness Distribution Dialog for Quenched and Tempered Round Bar

3. Click **OK**. A window similar to the one shown in Figure 3-27 will appear. The hardnesses (which are calculated for several positions along the length of the cross-sectional radius of the bar) are shown for all HRC values greater than 0.

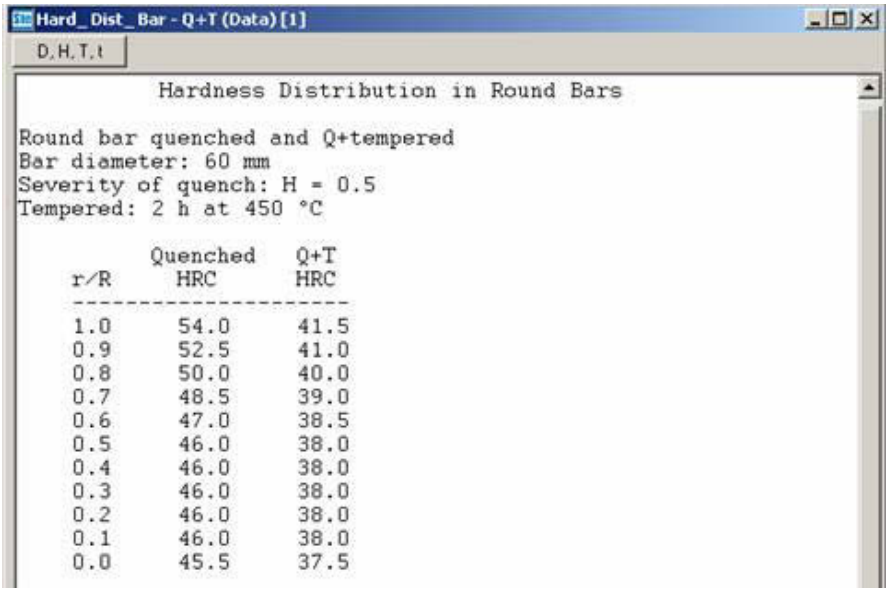


Figure 3-27: Hardness Distribution Data for Quenched and Tempered Round Bar

4. Click the **D, H, T, t** button at the top left of the window to change any of those values.

To view the hardness distribution curve for a round bar that has been quenched and tempered:

1. Select **Graphics** ð **Hardness Distribution in Round Bars: U Curve** ð **Round Bar Quenched and Q+ Tempered**.
2. Enter the round bar diameter (mm or in), quench severity (1/in), tempering temperature (ºC or ºF), and time at tempering temperature (h).
3. Click **OK**. A window similar to the one shown in Figure 3-28 will appear. The curves are drawn using the results calculated for the 21 positions in the radius of the section of the bar. Only the values higher than 20 HRC are drawn.

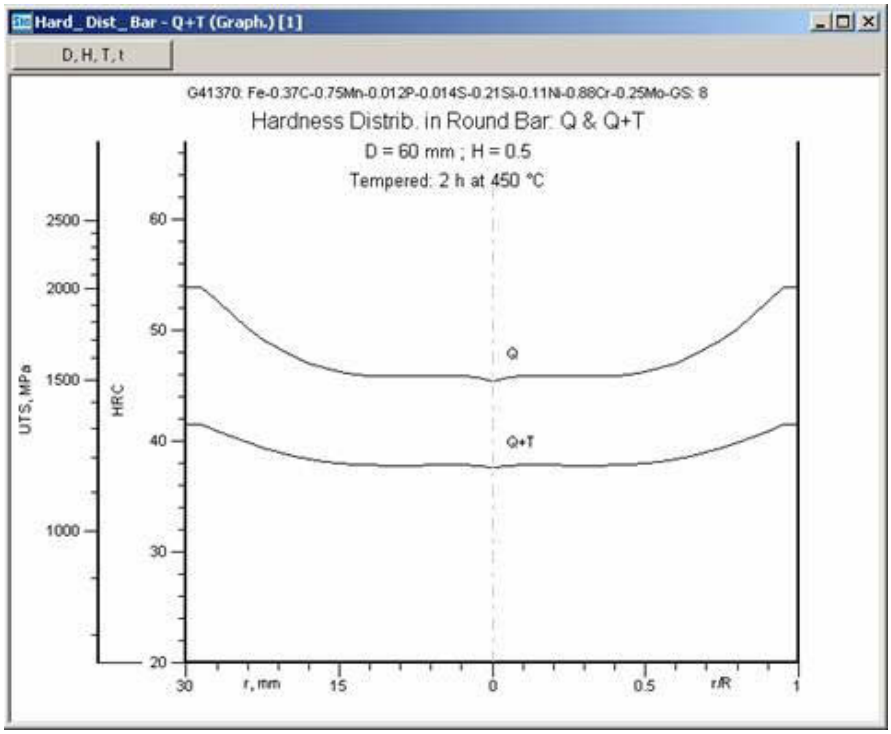


Figure 3-28: Hardness Distribution Curve for Quenched and Tempered Round Bar

4. Click the **D, H, T, t** button at the top left of the window to change any of those values.

Chapter 4: Equivalencies

This section explains how SteCal can be used to calculate the following:

- Ø Equivalencies between ideal critical diameter, quench severity, and diameter
- Ø Equivalent round
- Ø Equivalencies between Jominy test positions and ideal critical diameters
- Ø Equivalencies between Rockwell hardness, Vickers hardness, ultimate tensile strength, tensile yield strength, and elongation

Steel data are not required to perform equivalencies (only %C is required to obtain YS and EL values from HRC, HV, or UTS).

4.1 DI Û H Û D Equivalencies

The equivalencies between DI, H and D are calculated using the Grossmann curves [Refs. 15, 22]. To convert a value:

1. Select **Equivalencies ð DI Û H Û D**.
2. Select **Critical Diameter (DI)**, **Severity of Quench (H)**, or **Critical Diameter (D)** from the **Search for** dropdown, shown in Figure 4-1.

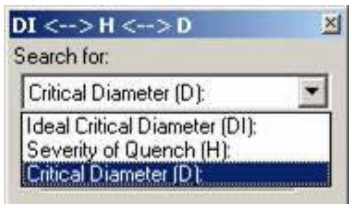


Figure 4-1: DI Û H Û D Equivalencies Dropdown Menu

3. Enter the requested values. The data entry fields will vary depending on the **Search for** selection, as shown in Figure 4-2, Figure 4-3, and Figure 4-4.

In a separate window are shown several H values. Another window shows the six different ideal critical diameters, cited in Section 3.5, if steel data required to complete the calculations have been introduced.

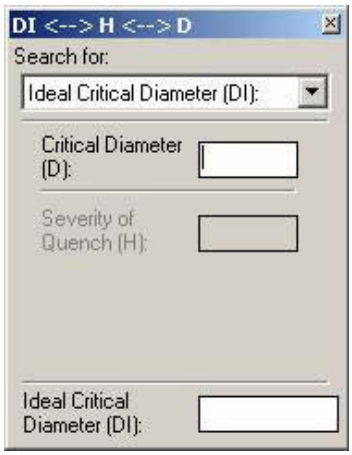


Figure 4-2: Ideal Critical Diameter Equivalencies Dialog

Figure 4-3: Severity of Quench Equivalencies Dialog

Figure 4-4: Critical Diameter Equivalencies Dialog

4. Press the **Enter** key on the keyboard to view the calculated value.

4.2 Equivalent Round

The diameter of a bar of infinite length (equivalent round)—that has a similar cooling rate to that a given piece (plate and square, rectangular, hexagonal or circular section)—is obtained using the graphs for the cooling rates of the Jominy test specimen positions and of oil-and-water-quenched plates and bars, as compiled by Calvo Rodés [Ref.12].

To calculate the equivalent diameter:

1. Select **Equivalencies ð Equivalent Diameter** from the menu bar.
2. Make a selection from the **Shape** dropdown, shown in Figure 4-5.

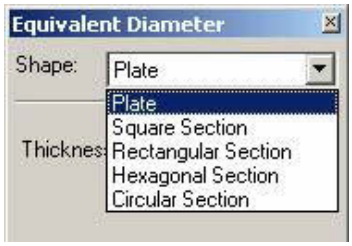


Figure 4-5: Equivalent Diameter Shape Dropdown Menu

3. Enter the requested values. The fields that will appear will vary depending on the **Shape** selection, as shown in Figure 4-6 through Figure 4-10.

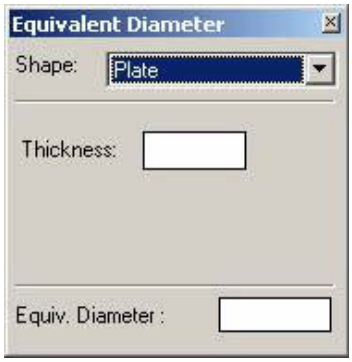


Figure 4-6: Plate Shape Equivalencies Dialog

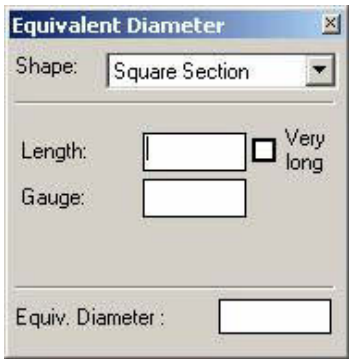


Figure 4-7: Square Shape Equivalencies Dialog

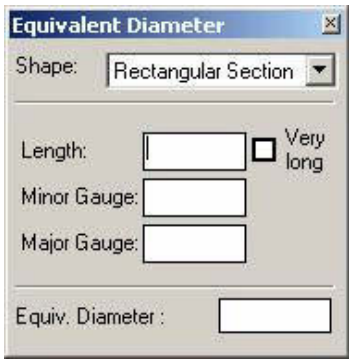


Figure 4-8: Rectangular Shape Equivalencies Dialog

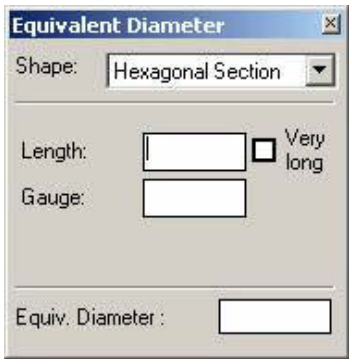


Figure 4-9: Hexagonal Shape Equivalencies Dialog

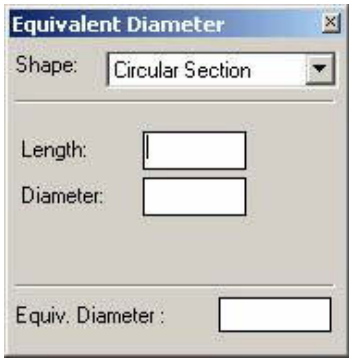


Figure 4-10: Circular Shape Equivalencies Dialog

4. Press the **Enter** key on the keyboard to view the calculated value.

4.3 J_d Û DI Equivalencies

The equivalencies (with regard to similar cooling) between Jominy test specimen positions and ideal critical diameters, are performed on the basis of the equivalence derived from the Lamont [Ref. 18] curves as revised by Carney [Ref. 21].

To calculate the equivalencies:

1. Select **Equivalencies ð J_d Û DI** from the menu bar.
2. Enter either the Jominy distance or ideal critical diameter in the appropriate field (see Figure 4-11).

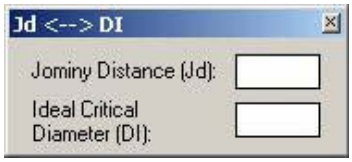


Figure 4-11: J_d Û DI Equivalencies Dialog

3. Press the **Enter** key on the keyboard to view the value not entered.

4.4 HRC Û HV Û UTS Û YSÛ EL Equivalencies

Equivalencies between the HRC and Vickers hardnesses is performed using ASTM Standard [Ref. 17].

Equivalencies between the HRC and UTS is performed according to the table published by Calvo Rodés [Refs. 10, 12].

The UTS values are calculated only if they correspond to hardnesses values less than 60 HRC or 700 HV.

The YS and EL values are calculated only if a valid %C value is present in the Active Steel Data window. They are obtained from the hardness and the carbon content according to the table published by Calvo Rodés [Refs. 10, 12].

It will likewise give UTS values only if they correspond to HRC values less than 60 HRC or less than 695 HV , and YS and EL values only if they correspond to hardness values less than 45 HRC or 450 HV, and UTS value less than 1475 MPa (210 ksi). This is because the cited author gives reliable results only in these cases.

The YS and EL values are calculated only if they correspond to hardness values less than 45 HRC, 450 HV or 1470 MPa.

To calculate the equivalencies:

1. Select **Equivalencies ð HRC Û HV Û UTS Û YS Û EL** from the menu bar.
2. Enter *only one* of the values in the appropriate field (see Figure 4-12).

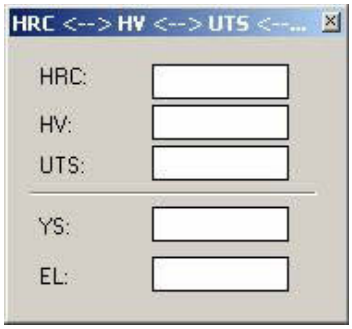


Figure 4-12: HRC Û HV Û UTS Û YS Û EL Equivalencies Dialog

3. Press the **Enter** key on the keyboard to view the values not entered.

Appendix 1: Abbreviations

The following abbreviations are used in the program and manual, and units of measurement for the data and parameters and calculated properties.

%X	X element content of steel, expressed as percentage in weight
°C	Degree Celsius (centigrade). All calculated results are rounded to the nearest degree.
°F	Degree Fahrenheit. All calculated results are rounded to the nearest degree.
A_1	Lower critical temperature (in °C or °F) at equilibrium
A_3	Upper critical temperature (in °C or °F) at equilibrium
A	Austenite (in Fe-C diagram)
Ac_1	Lower critical temperature (in °C or °F) in heating
Ac_3	Upper critical temperature (in °C or °F) in heating
AISI	American Iron and Steel Institute
Al	Aluminum
ASTM	American Society for Testing and Materials
Aust	Austenite
B	Boron
B_{50}	The maximum temperature (in °C or °F) at which 50% of the bainitic reaction can be obtained (Haynes [Ref. 14]). This is higher in isothermal transformations than in continuous cooling transformations.
B_{99}	The maximum temperature (in °C or °F) at which the bainitic reaction can be completed (Haynes [Ref. 14]). This is higher in isothermal transformations than in continuous cooling transformations.
B_S	The maximum temperature (in °C or °F) at which the bainitic reaction can be obtained (Haynes [Ref. 14]). This is higher in isothermal transformations than in continuous cooling transformations.
C	Carbon Cementite (in Fe-C diagram)
CCT diagram	Continuous cooling transformation diagram; can be expressed in terms of T versus t, T versus DI, or T versus D
Cr	Chromium
Cu	Copper
D	Diameter (in mm or in) of a bar Critical diameter in a quenching medium
DB_{50}	Maximum diameter (in mm or in) that can be quenched in an ideal medium to obtain a maximum of 50% of bainitic transformation (Hollomon [Ref. 3])
DB_{99}	Maximum diameter (in mm or in) that can be quenched in an ideal medium without obtaining bainitic transformation (Hollomon [Ref. 3])
DI	Ideal Critical Diameter (in mm or in)
DM_{50}	Maximum diameter (in mm or in) that can be quenched in an ideal medium to obtain a minimum of 50% of martensitic transformation (Holloman [Ref. 3])
DM_{99}	Maximum diameter (in mm or in) that can be quenched in an ideal medium to obtain a fully martensitic structure (Holloman [Ref. 3])
DP_{50}	Figure defined by Hollomon [Ref. 3]. Maximum diameter (in mm or in) that can be quenched in an ideal medium to obtain a maximum of 50% of pearlitic transformation.
DP_{99}	Maximum diameter (in mm or in) that can be quenched in an ideal medium without obtaining pearlitic transformation (Holloman [Ref. 3])
EL	Elongation; the increase in length of a tension test specimen, expressed as a percentage of the original length. All calculated results are rounded to 1%.
F	Ferrite

Fe	Iron
J_d	Jominy distance; distance (in mm or in) to end-quench in a Jominy specimen
G	Gauge (in mm or in) of a prismatic piece of a square, hexagonal, or rectangular section (MinG: minor gauge; MajG: major gauge) Thickness of a plate
GS	Austenitic grain size according to ASTM standards
h	Hours (time)
H	Severity of quench (in 1/in) of a medium (Grossmann). All calculated results are rounded to 0.1.
H_C	Characteristic hardness (in HRC), representative of temperability of steel (Holloman [Ref. 3])
Hm	Martensitic hardness; hardness (in HRC) of steel after a completely martensitic quenching. All calculated results are rounded to 0.5 HRC.
Hm_{50}	Hardness (in HRC) obtained in quench with a 50% martensitic structure. All calculated results are rounded to 0.5.
Hm_{90}	Hardness (in HRC) obtained in quench with a 90% martensitic structure. All calculated results are rounded to 0.5.
Hq	As-quenched hardness; hardness (in HRC) obtained in the quench
HRC	Hardness measured by the Rockwell hardness test using the C scale. All calculated results are rounded to 0.5 HRC.
HV	Hardness measured by the Vickers hardness test. All calculated results are rounded to 5 HV.
in	Inches. All calculated results are rounded to 0.05 in.
ksi	Kilopounds per square inch. All calculated results are rounded to 1 ksi.
L	Length (in mm or in) of a prismatic piece of any square, rectangular, hexagonal, or circular section
M_{10}	Temperature (in ^oC or ^oF) at which, in a normal quench, 10% of a martensitic transformation is obtained
M_{50}	Temperature (in ^oC or ^oF) at which, in a normal quench, 50% of a martensitic transformation is obtained
M_{90}	Temperature (in ^oC or ^oF) at which, in a normal quench, 90% of a martensitic transformation is obtained
M_{99}	Temperature (in ^oC or ^oF) at which, in a normal quench, 99% of a martensitic transformation is obtained (usually is defined as M_f)
min	Time in minutes
mm	Millimeter(s). All calculated results are rounded to 1 mm.
Mn	Manganese
M_S	Temperature (in ^oC or ^oF) at the beginning of a martensitic transformation in continuous cooling
Mo	Molybdenum
MPa	Megapascal (Meganewtons per square meter); SI unit of pressure (and stress). All calculated results are rounded to 10 MPa.
N	Nitrogen
Ni	Nickel
P	Phosphorus Pearlite (in Fe-C diagram)
Q	Quenched
Q + T	Quenched and tempered
s	Seconds (time)
S	Sulfur
SAE	Society of Automotive Engineering
Si	Silicon

t	Time
T	Temperature (in ^{o}C or ^{o}F). All calculated results are rounded to 1 degree.
Ti	Titanium
TTT diagram	Time-temperature transformation diagram of isothermal transformations
UNS	Unified Numbering System
UTS	Ultimate tensile strength (in MPa or ksi)
V	Vanadium
VL	Very long
X axis	Scale of time or diameter in CT and IT diagrams
YS	Tensile yield strength (in MPa or ksi)

Appendix 2: Tables of Allowable Limits

This appendix lists the upper and lower limits for steel data and other user-entered values.

Table A2-1: Allowable Limits of Steel Composition Data

Steel Data	Units	Permitted Lower Limit	Permitted Upper Limit	Recommended Lower Limit	Recommended Upper Limit
Carbon Content (C)	%	0.1	0.70	0.20	0.65
Manganese Content (Mn)	%	0	2.7	0	2.0
Phosphorus Content (P)	%	0	0.1	0	0.1
Sulfur Content (S)	%	0	0.3	0	0.3
Silicon Content (Si)	%	0	2.0	0	1.0
Nickel Content (Ni)	%	0	5.0	0	4.0
Chromium Content (Cr)	%	0	2.5	0	1.5
Molybdenum Content (Mo)	%	0	1.0	0	0.5
Boron Content (B)	%	---	---	No	Yes
Grain Size (GS)	ASTM	1	15	4	10

Table A2-2: Allowable Limits of Other User-Entered Data

Variable	Units	Permitted Lower Limit	Permitted Upper Limit
Critical Diameter (D)	mm	4	500
	in	0.2	20
Diameter (D)	mm	6	150
	in	0.20	6
Diameter of Round Bar (D) (Equivalency DI Û H Û D)	mm	4	490
	in	0.2	19.3
Diameter of Round Bar (D) (Hardness Distribution in Round Bars)	mm	4	250
	in	0.2	10
Ideal Critical Diameter (DI)	mm	10	500
	in	0.4	20
Ideal Diameter (DI)	mm	10	170
	in	0.4	7
Gauge (G)	mm	4	110
	in	0.20	4.50

Variable	Units	Permitted Lower Limit	Permitted Upper Limit
Severity of Quench (H) (CCT T Diagram)	1/in	Permitted: 0.02 and 0.1	
		0.3	5
Severity of Quench (H) (Equivalency DI Û H Û D: Search for D)	1/in	Permitted: 0.02, 0.1, and 0.3	
		0.3	5
Severity of Quench (H) (Equivalency DI Û H Û D: Search for DI)	1/in	Depends on D	
Severity of Quench (H) (Hardness Distribution in Round Bars)	1/in	0.3	5
Hardness as Quenched (Hq)	HRC	Depends on %C	
		Hm_{50}	Hm
HRC	HRC	20	65
HV	HV	240	800
Jominy Distance (J_d)	mm	1	50
	1/16 in	1	32
Length (L)	mm	4	110 or VL
	in	0.20	4.50 or VL
Major Gauge (MajG)	mm	4	110
	in	0.20	4.50
Minor Gauge (MinG)	mm	4	110
	in	0.20	4.50
Tempering Temperature (T)	°C	450	700
	°F	850	1300
Thickness (T)	mm	4	110
	in	0.20	4.50
Time at Tempering Temperature (t)	h	0.1	9
UTS	MPa	750	2500
	ksi	110	360

Appendix 3: Technical References

The following references were used in the program and manual:

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Appendix 4: Calculation Methods

Background

The influence of different alloying elements on the properties of steels has long been a subject of research. As research progressed, it became apparent that this influence was purely structural in low-alloy steels. In other words, the only thing the alloying elements did was to make it possible to obtain a certain kind of microstructure by means of a given heat treatment; they did not transfer their own characteristic properties to the steel. However, given the close relationship between microstructure and properties, the influence of alloy elements on the latter is obvious. Consequently, any variation in composition naturally causes a corresponding variation in properties. Alloying elements likewise affect the means of obtaining a certain microstructure, bringing about variations in properties such as hardenability and temperability, or in parameters such as the temperature at which different treatments should be performed.

In view of these facts, it was accepted that the action of one alloy element could be substituted for by that of another (although in a different proportion); in some cases to all effects, and in others only with respect to certain aspects of the behavior of the steel. Of course, the element to be substituted had to be merely a "structural action," and the so-called "substantial action," by which some characteristic property of the alloy element is transmitted to the steel, could not become evident. Thus, it became critical to develop a method to predict and to quantify the ways in which the most significant properties of a steel are affected by the actions of each of its alloying elements, along with those properties which can be obtained by means of specific heat treatments.

Some Existing Calculation Methods

During the 30's, many studies concerning the influence of alloying elements were carried out and hardenability was determined by means of the Jominy test in 1939. In 1942, Grossman [Ref. 5] quantified the influence of different alloy elements on hardenability (ideal critical diameter) and gave an empirical method for calculating it from the composition of the steel and the austenitic grain size. This same author had already, in 1939 [Ref. 22], quantified the severity of quench of the more commonly employed cooling media. He also published equivalencies between ideal critical diameters and those corresponding to different cooling media, as well as the round equivalent of pieces with different geometrical shapes.

In 1943, Field [Ref. 23] published a first method for calculating the curve for the Jominy test hardenability curve and established a number of model curves corresponding to each ideal critical diameter calculated according to the Grossman formula. In the same year, Lamont [Ref. 18] published graphs showing the relationship between the cooling rates corresponding to positions on the Jominy test specimen and those of bars of various diameters quenched in various media. With both these works, the cross-sectional hardness could be calculated along the diameter of a bar (U curve) quenched in a medium.

In 1947, Hollomon and Jaffe [Ref. 3] established a calculation method in which, depending on composition, hardenabilities with different criteria were obtained (bainitic or pearlitic, and with 1 % or 50% transformation). They also presented a method for calculating the hardness after tempering, after a complete martensitic quench. This was obtained by subtracting the softening produced by the time spent at tempering temperature from a maximum, non-real hardness which they termed "hardness characteristic H_C" (which depended on composition). They then evaluated the combined influence of these two factors (time and temperature). This method took into account the action of each element (which it had evaluated) and the possibility of adding up the effects of the different elements at each temperature. The action of some elements was quantitatively dependent on tempering temperature.

These same authors defined the hardness characteristic H_C as a representative parameter of the entire response of a steel to tempering, in the same way that the ideal critical diameter (DI) was a figure that was representative of behavior under quenching, and the temperature M_S of the start of the martensitic reaction, was representative of the susceptibility to quench cracking (together with the carbon content of the steel). They produced a formula for calculating this temperature, although this was not the first one to be published.

Three figures (DI, H_C, and M_S) were thus defined. These, together with the carbon percentage, were more representative parameters of the behavior of steel than the composition itself with respect to quench + tempering heat treatment (the normal in low-alloy steels). For this reason, Professor Calvo Rodés et al. [Ref. 24] named them "*code figures.*" The definition of these parameters enabled comparisons of applications and behavior of steels under quenching and tempering to be made quickly by comparing their code figures. It also enabled equivalencies to be established between two low-alloy steels, carbon content and the three code figures being equal, since both behavior

and properties were similar for similar treatments. These figures could be arrived at by calculations; to facilitate this task, they designed a "slide rule for steels" [Ref. 8] in which they also included the Hollomon method for predicting the effect of tempering on hardness and Grossmann's equivalencies between the different critical diameters.

In 1949, Crafts and Lamont [Ref. 16] put forward a different procedure for calculating the Jominy hardenability test curves (quenched and quenched + tempered), as a function of composition and tempering temperature (for a two-hour tempering). Unlike Field's method [Ref. 23], this was based on the evaluation of the action of each alloy element on the hardness at each position of the test specimen, and on the addition of the actions. In the same way, the method for calculating the effect of tempering on hardness of each position was incremental and enabled calculation to be made after both complete and incomplete quench. Calvo Rodés [Ref. 8] designed another "slide rule" for the application of this method.

Other methods, all of them empirical, have been published for calculating other properties or representative parameters for steels, as well as heat treatment temperatures, the hardnesses obtainable with these, and the time necessary for the occurrence of some transformations, susceptibility to quench cracking, etc. We shall mention [Refs. 4, 14, 25] those which we consider most relevant to our interests and which were used in our SteCal Program. Calculating the properties of steels with the greatest possible reliability continues to be of interest, as demonstrated by the following examples:

- In 1952, Grossmann [Ref. 26] himself collected six different works about the molybdenum factor for the calculation of ideal critical diameters. There are ten other known works [Ref. 25] in which the factors for other elements are revised.
- There are at least seven different formulas that deal with the influence of boron on hardenability [Ref. 25].
- In 1973, Tarín [Ref. 27] compiled nine formulas for calculating M_S. There are, at present, at least fourteen formulas.
- There are at least three other methods for calculating the Jominy test hardenability curve [Refs. 28-30].
- There are at least two other methods for calculating hardness-tempering [Refs. 31, 32].
- There are three other "slide rules" similar to the one designed by Calvo Rodés. Those of the Climax Molybdenum Company and the Bethlehem Steel Company are based on Field's method, and the third [Ref. 28] is based on an independent method. The three limit themselves to the calculation of hardenability and/or hardness at several Jominy distances.
- Other methods continue to be collected and revised in recent bibliographies [Refs. 33-37].

In 1977, what we believe to be the first computer-applied method for calculating steel properties [Ref. 38] was published. More recently, other programs that can be used in microprocessors [Refs. 39-42] have been reported. In 1985, we introduced a first version of the program [Ref. 43], followed by the 1986 version [Ref. 44].

ASM International published a first version (1.0) of this program SteCal in 1989 [Ref. 19], and a second version (2.0) in 1992 [Ref. 20]. Version 3.0 has the similar capabilities and uses the same calculating methods as the previous ones.

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The Materials
Information Society

Materials Park, Ohio 44073-0002

www.asminternational.org

First printing, February 2004

ISBN: 0-87170-796-9

SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America