Calculation of the Hardness Space Distribution in the As Quenched Condition of a Medium Hardening Tool Steel

G. Sánchez Sarmiento[1] *and J. Vega*[2]

1. Departamento de Física, Facultad de Ingeniería, Universidad de Buenos Aires, Av. Paseo Colón 850. (1063) Buenos Aires, Argentina
2 . Universidad Católica de Córdoba and SUDOSILO SA, Cno. San Carlos Km 4,5. (5000) Córdoba, Argentina

ABSTRACT: The calculation of the hardness profile is a powerful tool for the selection of the right steel for a given purpose. Computer programs INC-PHATRAN and INDUCTER-B were formerly developed by the authors for the calculation of hardness profiles after heat treatment processes of low alloy and carbon steels. The first one simulates quenching as well as through hardening operations, and the second one models electromagnetic induction heat treatments processes. These codes make use of the SAE Standard J406 in order to obtain the hardness profile, with enhanced regression coefficients recently obtained by the authors.

The present work broadens the field of application of this method, allowing to apply it for low hardenability tool steels such as the ASTM O1 Tool Steel.

The method used for the calculation of the hardness profile is here summarized, and an example of application is described, which shows good correspondence between the calculated and measured values.

Introduction

Heat treating engineers must frequently cope with mechanical components ready for quenching, but made up from inadequate steels as a result of a poor steel selection decision. This problem seems to be more important when the components to be constructed are *tools or dies for cold working processes*, such as blanking, cutting, forming or stamping steel or other metal sheets. At this point, the design engineer has several tool steel alternatives. The most frequently selected steels are those classified into the ASTM D and O Steel Groups.

Unfortunately, it is not uncommon to see die designers and producers that apply the wrong idea that the so-called *tool steels* (all of them) will be hardening through the full section independently of its size and shape. Normally, this happens because the hardenability concepts are very well known and applied in a daily basis when constructional steels and low or medium alloy steels behavior is analyzed. On the other hand, a hardenability or hardness distribution calculation is seldom performed on the steel selection step, during the project or design of a cold working tool or die.

It is not unusual to find that, after the heat treatment process of O1 Steel dies, its hardness is below the specified value or it is heterogeneous. The final result is time lost in manufacturing and processing and money lost in some expensive steel for the construction of a failing die.

The tool heat treatment shop experience shows that the problem is more serious when the die to be constructed has very different section patterns, with abrupt section changes or large dimensions. In this case, (and if a O1 Steel has been selected), the hardness will be higher in thin section areas and on the edges, while it will be lower on the heavy section areas.

Irrespectively of the application, it is certainly convenient to be able to predict this phenomenon in advance when planning the construction of the component. The existence of a computer program as a tool for the calculation of the hardness penetration in the O1 steel grade is highly convenient in order to be able to estimate the hardness pattern well in advance to the quenching step. Such a program should simulate the result for different quenching conditions and steels (such as different quenching media), different part dimensions and different steel compositions.

Computer programs INC-PHATRAN and INDUCTER-B were formerly developed by the authors[1-6] for the calculation of hardness profiles after heat treatment processes of low alloy and carbon steels. The first one simulates quenching as well as through hardening operations, and the second one models electromagnetic induction heat treatments processes. These codes make use of the SAE Standard J406 [7] in order to obtain the hardness profile, with enhanced regression coefficients recently obtained by the authors[8]. Another model for stainless steels, named TRATINOX, was also developed [9].

The present work broadens the field of application of this method, allowing to apply it for low hardenability tool steels such as the ASTM O1 Tool Steel. An ASTM O1 steel cylindrical sample of 100 mm in diameter and 300 mm in length, was used to measure the temperature variation during quenching and the obtained hardness distribution through a transverse section.

The entire process was simulated, obtaining satisfactory agreement between the experimental hardness measurements and the values calculated by the Code. The hardness profile was also calculated for different sample diameters, which allows visualizing the behavior of the ASTM O1 steel and its response for different sizes.

The method used for the calculation of hardness profile in the INC-PHATRAN Program is here summarized, the experimental procedure is described, and the numerical simulation procedure is exposed.

1. Program INC-PHATRAN

INC-PHATRAN (**IN**verse **C**onduction coupled with **PHA**se **TRAN**sformation) is a program[1] that can be employed to simulate a wide variety of heat treatment processes, having plane geometry as well as axisymmetrical ones. It may also be used to ascertain the heat transfer coefficients, provided a record of temperatures at different positions in the component is available. The program has already been presented at several international conferences[2,3,6] and is currently being used by industrial applications in the USA, Argentina, and Colombia.

The model is based on a numerical optimization algorithm which includes a module responsible for calculating on time and space the temperature distribution and its coupled microstructural evolution. In the present model, the transformation from austenite to ferrite and pearlite is governed by the appropriate TTT curve and also by the Avrami's approximation. Whereas the temperature distribution in a two dimension domain with axial symmetry is calculated using a finite element approximation, the time variation is approached using a Crank-Nicholson finite difference scheme. The temperature evolution at one or several positions in the component, as measured by thermocouples, is used as input for the program in order to calculate the time variation of the heat transfer coefficients, together with the temperature and distribution of phases variations throughout the component.

The procedure to predict the hardness distribution of a heat treated steel specimen taking into account the influence of its chemical composition, is based on the assumption that the hardness is a direct function of the thermal history undergone during the quenching process. The methodology proposed is outlined below:

1. The hardenability of a Jominy probe, with the same chemical composition of the steel specimen to be treated, is calculated according to SAE Standard J406 [7] with enhanced coefficients [8], in the case that measured values was not available.

2. The space and time distribution of the temperature within the Jominy probe during the quenching test coupled with the phase change transformation process is obtained according to the procedure outlined above.

3. A similar calculation, considering the specific heat treating process (quenching, induction heating) is carried out for the probe.

4. After solution of these two thermal problems, cooling curves corresponding to any nodal point of the Jominy probe and of the steel specimen are available. To assign a hardness value to a specimen nodal point, its cooling curve is compared to all the cooling curves of the Jominy points. Once the Jominy point with the closest cooling curve is identified, its hardness is assigned to the specimen point. In this way, the hardness of the Jominy probe is mapped into the steel bar. On using these hardness nodal values, hardness distribution contours for the component can be produced.

2. Experimental procedure

A cylindrical sample of 100 mm diameter and 300 mm length made of ASTM O1 steel was used. Two flexible thermocouples of 3 mm diameter were inserted into the sample, attached to the bottom of two 4 mm diameter and 150 mm deep holes drilled from one of the bases of the cylinder, at 10 and 50 mm from the surface respectively (see figure 1).

The thermocouples were connected to a computer for the data-acquisition process, performing temperature readings from both of them at a frequency of 3 values per second. The readings were saved in a file and introduced into the Program INC-PHATRAN. The data were also used to construct the corresponding cooling curves.

The chemical composition of the steel and the sample are shown in the table below.

The sample was austenitized at 820 °C in a Controlled Atmosphere Furnace, to avoid decarburization and or scaling of it. Once the temperature of the part was completely homogeneous, it was quenched in 50 a m/min agitated oil, at a temperature of 70 °C. Afterwards, the cylinder was sectioned at a distance of 140 mm from the base, and the hardness measurements were made from the surface to the center of the section.

		C	Mn	Si	Cr	V	W	Ni
Specification	Max.	1,00	1,40	0,50	0,60	0,30	0,60	0,30
	Min.	0,85	1,00	--	0,40	--	0,40	--
Sample		**0,70**	**1,01**	**0,28**	**0,60**	**0,12**	**0,51**	**0**

Figure 2 shows a picture of the cylindrical sample, the thermocouples inserted in it and the facilities used for the experiments.

The calculation was carried out applying the parameters given by the SAE J406, correcting the value corresponding to the C content which lies outside the range recommended by the Standard.

Figure 3 shows the experimental Jominy curve measured on a probe made with the same steel of the sample.

Figure 4 shows both the hardness profiles calculated against that measured experimentally in the sample of 100 mm in diameter with the composition given in the previous table.

Figure 5 shows the same experimental hardness profile against the calculated based on the Jominy curve obtained by the Code based on the chemical composition of the table.

As can be seen, the results obtained with the Jominy curve calculated from the chemical composition and the results obtained with the Jominy curve measured experimentally (from a probe machined from the same steel used for the sample), are quite similar. Both curves show a discrepancy of around 2 mm. at the 55 HRC level if they are compared against the measured hardness penetration in a sample of 50 mm in radius, as one can see in figures 4 and 5. Such difference means an error of 4 % in determining the hardness penetration, which could be considered rather exact information during the design step of a steel tool and allow making a better selection of the potential applications as well as the process parameters.

As the two options are available in the program, the calculation can be made with both sources of data, but sufficient precision is obtained with the hardenability curve predicted from the composition, and the experimental measurements could be avoided.

Fig. 6, 7 and 8, show the results obtained after making the calculation for different part sizes. The sensibility of the program to predict the conditions under which, problems of low or heterogeneous hardness will occur, are shown here. Figure 6 shows a part that has been through hardened, while Figure 8 shows a part that has a very shallow hardness penetration. An intermediate situation, with a hardness penetration between the others, is shown in figure 7.

As can be seen from the results, it must be taken into account that parts of ASTM O1 of more than 100 mm in diameter will not harden up to a satisfactory depth for some applications and will develop high residual stresses in it.

For example, if an electroerosion machining operation is carried out after the heat Treatment process to make holes or cut another smaller piece from the original, some problems could arise. The hardness pattern itself suggests that the residual stress level will be very high in parts of approximate 100 mm in diameter. This is a dangerous situation in the case of the electroerosion operations described above, where the parts could even crack under the liberation of such stresses during the cutting or electro-machining operation.

It is also evident that, if it was planned to cut smaller pieces from a blank with section of approximate 100 mm in diameter, the hardness in the resulting parts will be heterogeneous. If this electro-machining operation is mandatory, a steel with a higher Hardenability should be selected, and a stress relieving operation (at not less than 500 ºC) is strongly recommended.

Conclusions

1. It was shown in this work, that the computer model presented has enough sensibility to predict the behavior of the O1 steel, when dimensions and composition of the sample and quenching conditions are changed.
2. Improvements to the program are possible by adjusting the C Hardenability factor for over 0,7 % C, which is the original range of validity given by the SAE J406.

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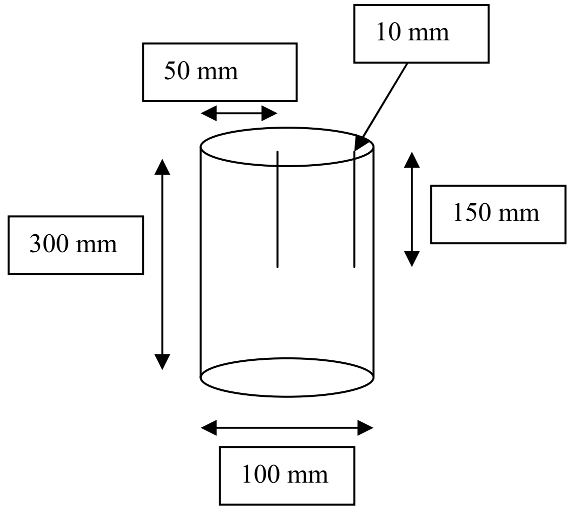


Figure 1.- Dimensions of the sample and location of the holes for the thermocouples.

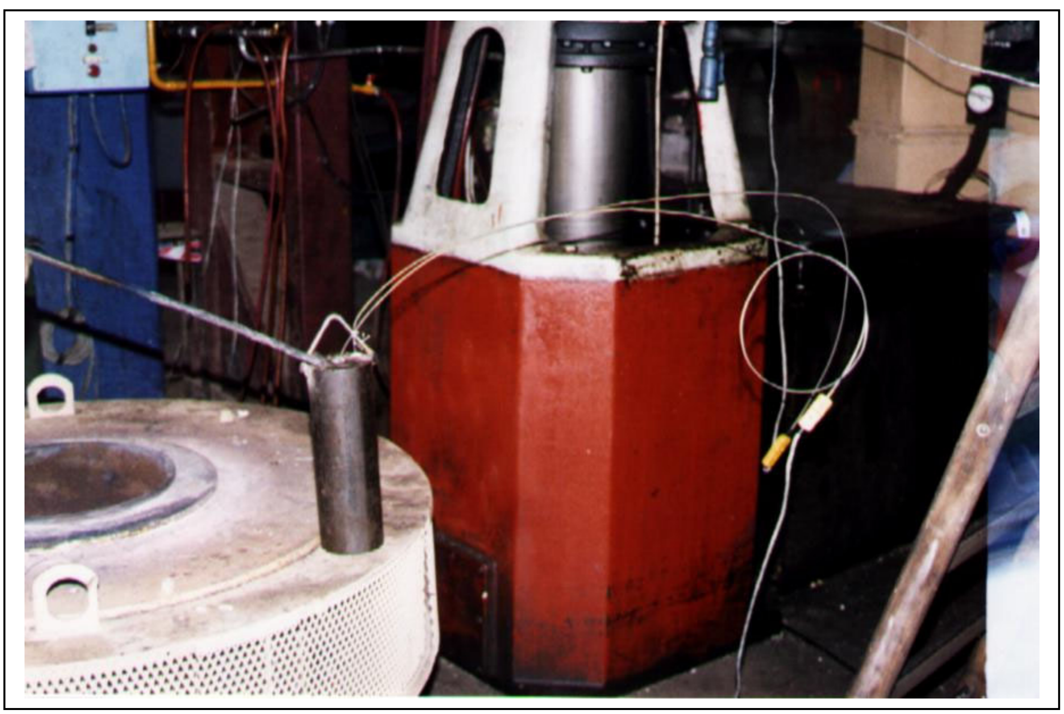
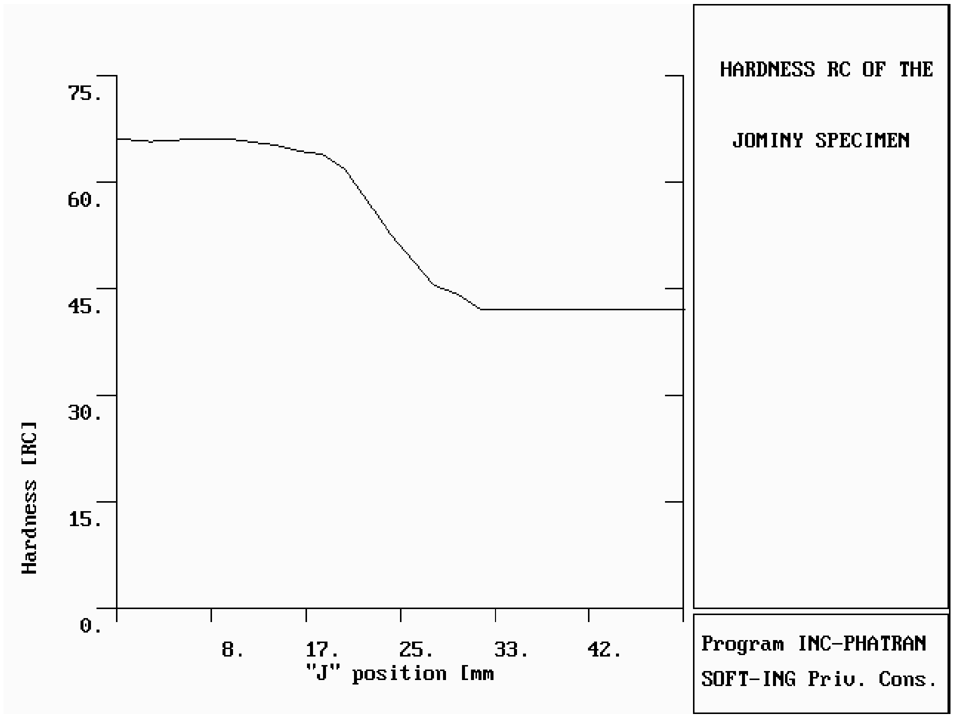


Figure 2.- Set up of the experiment, showing the thermocouples inserted in the sample and the facilities used.



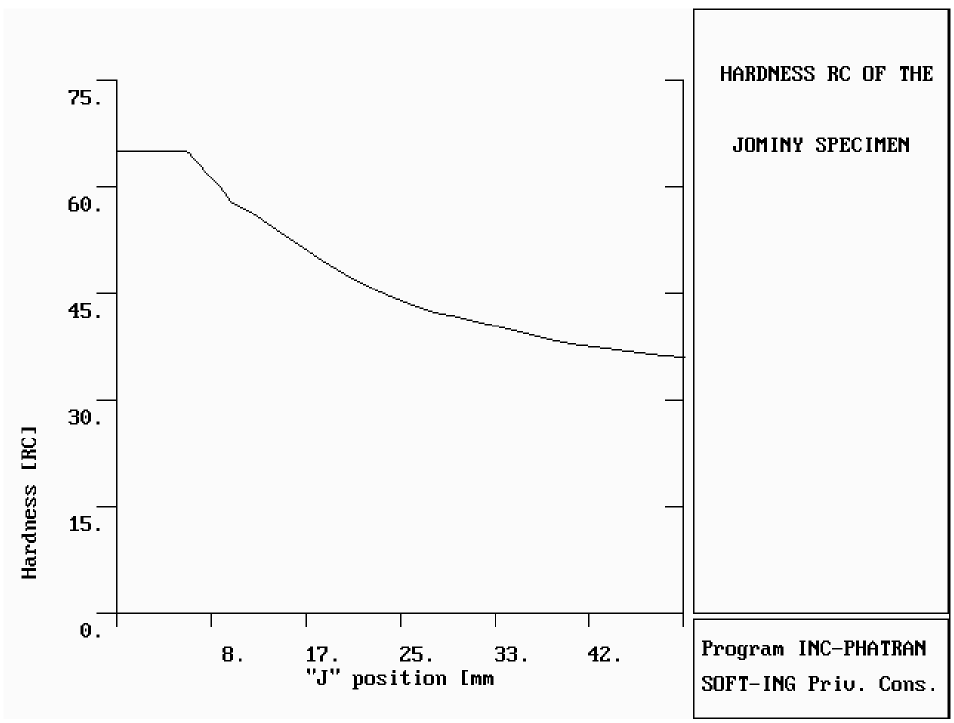


Figure 3.- Jominy curve of the steel analyzed. Above (a): measured. Below (b): obtained from the chemical composition according to SAE Standard J406.

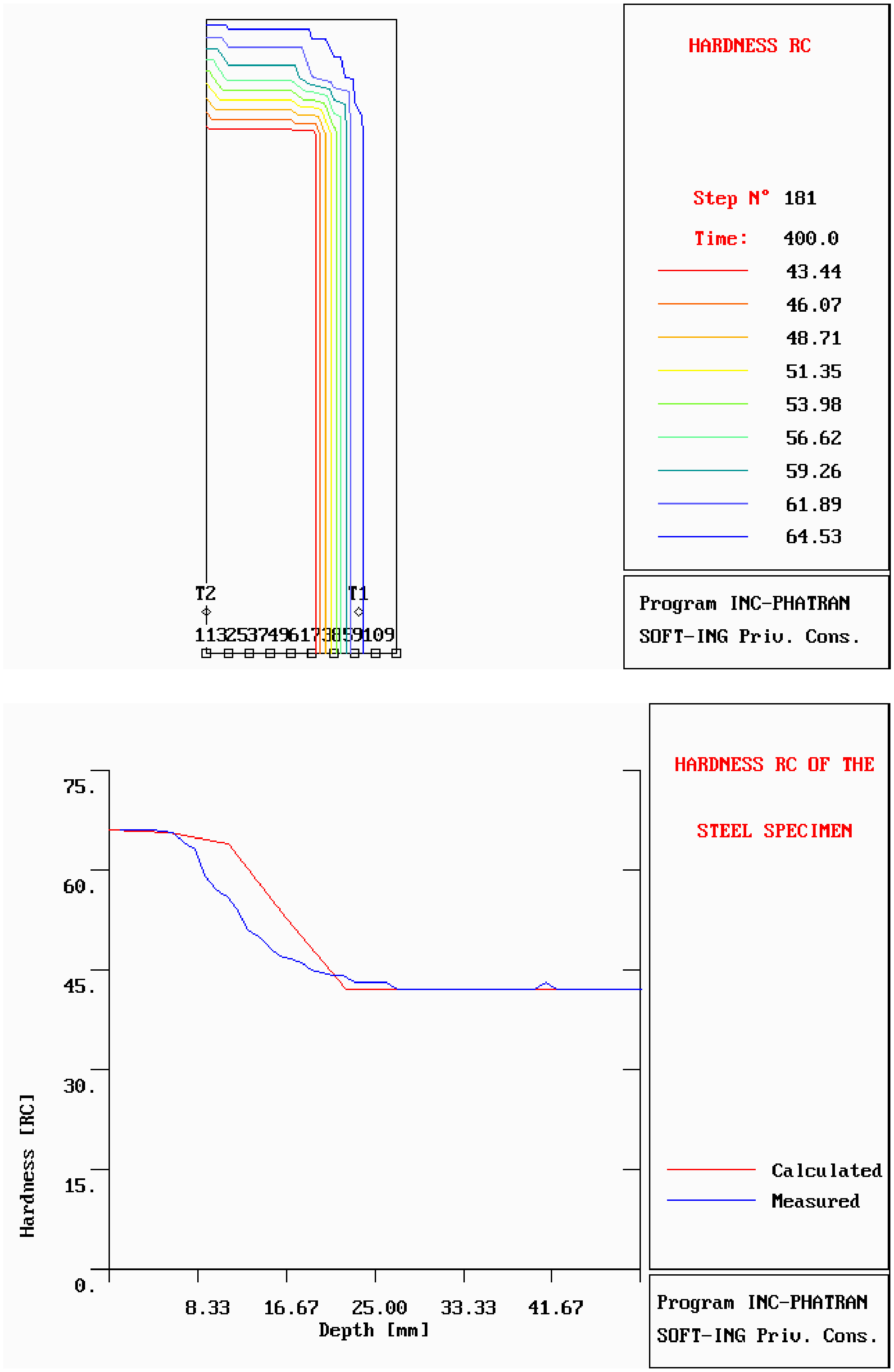


Figure 4.- Hardness profiles in the 100 mm diameter sample. Comparison between experimental measurements and the calculated values from the measured Jominy curve of figure 3-a.

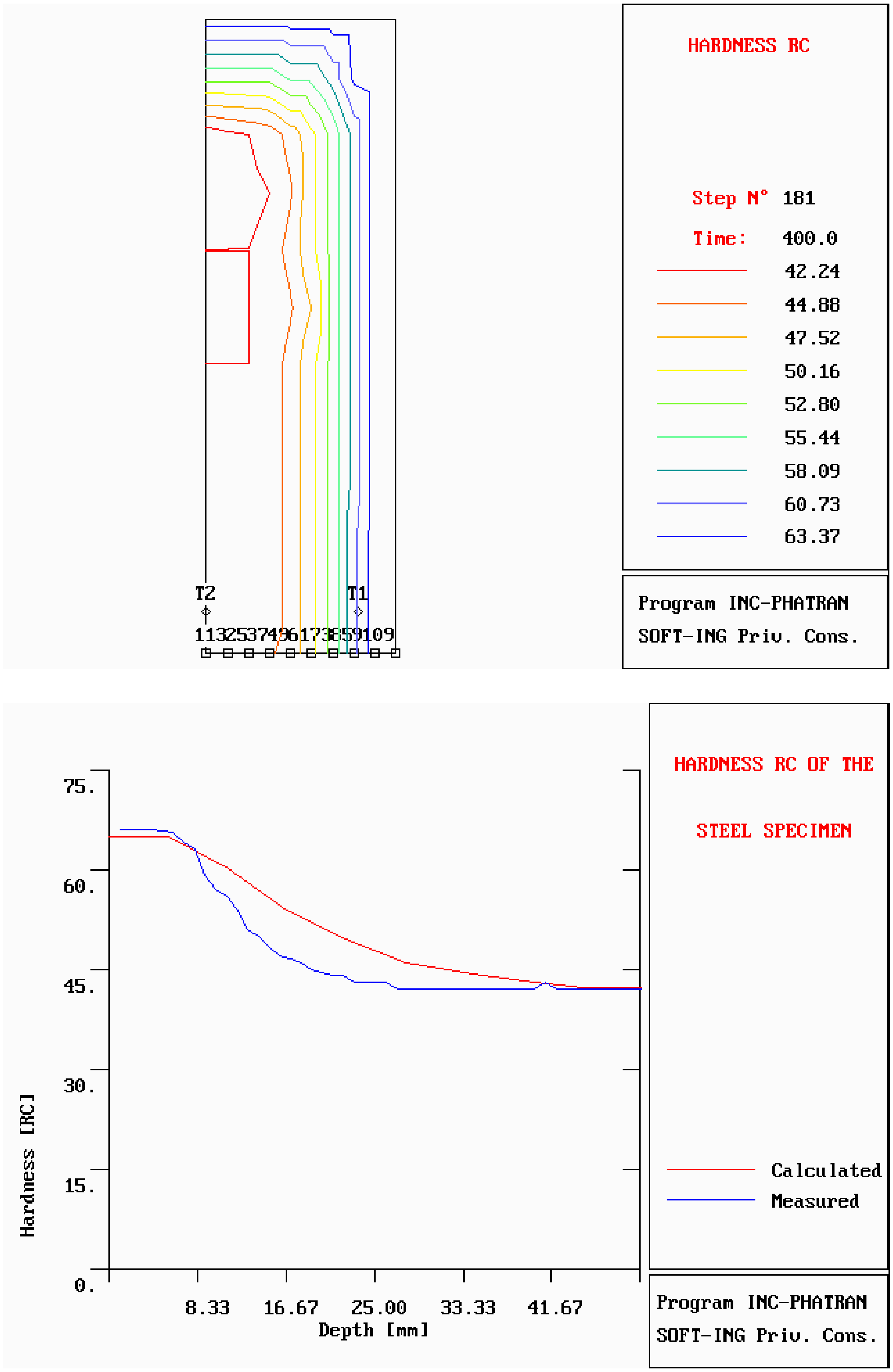


Figure 5.- Hardness profiles in the 100 mm diameter sample. Comparison between experimental measurements and the calculated values with the Jominy curve obtained from the chemical composition using the SAE Standard J406 (figure 3-b).

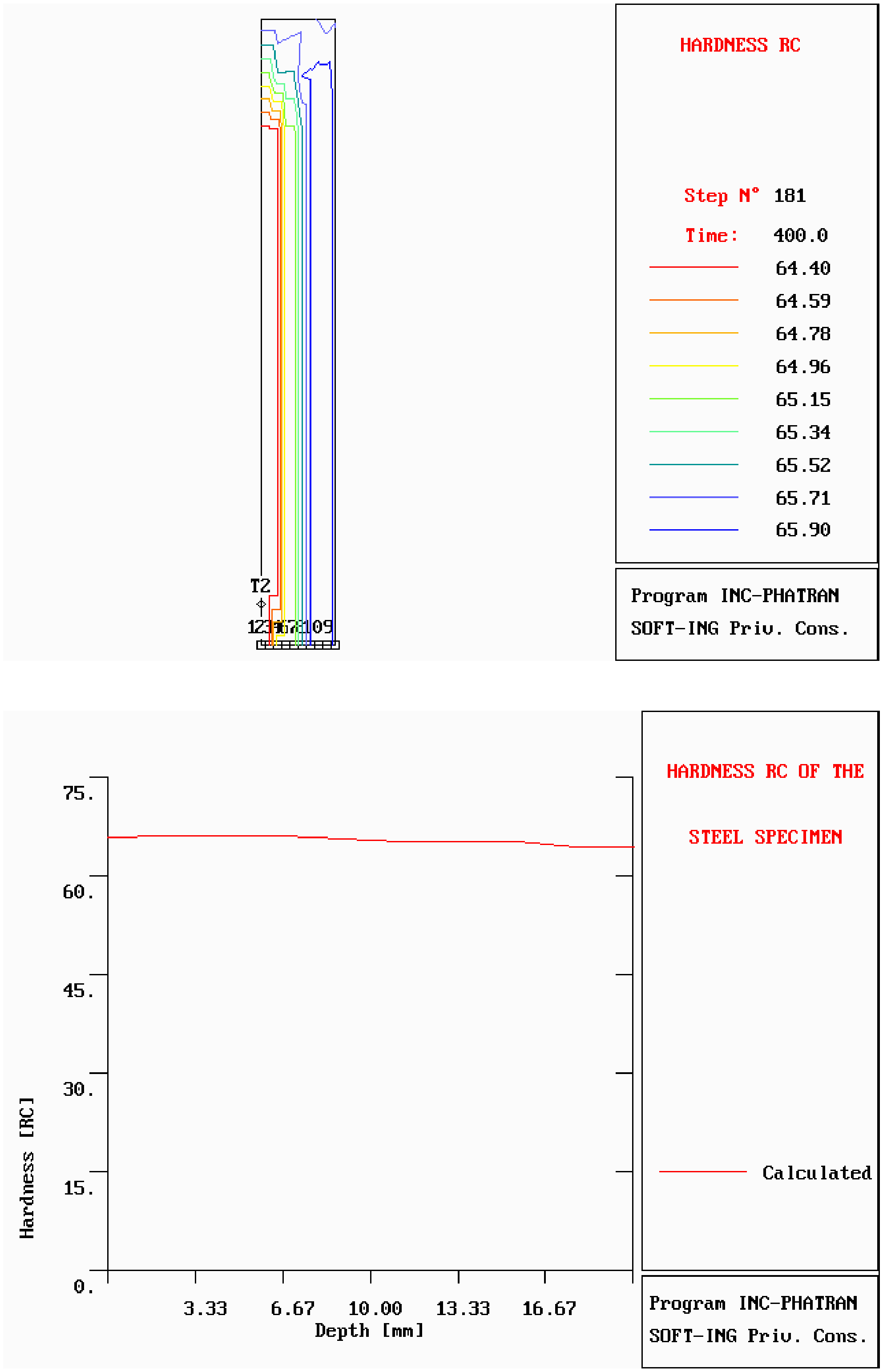


Figure 6.- Hardness profile calculated for a 40 mm diameter sample.

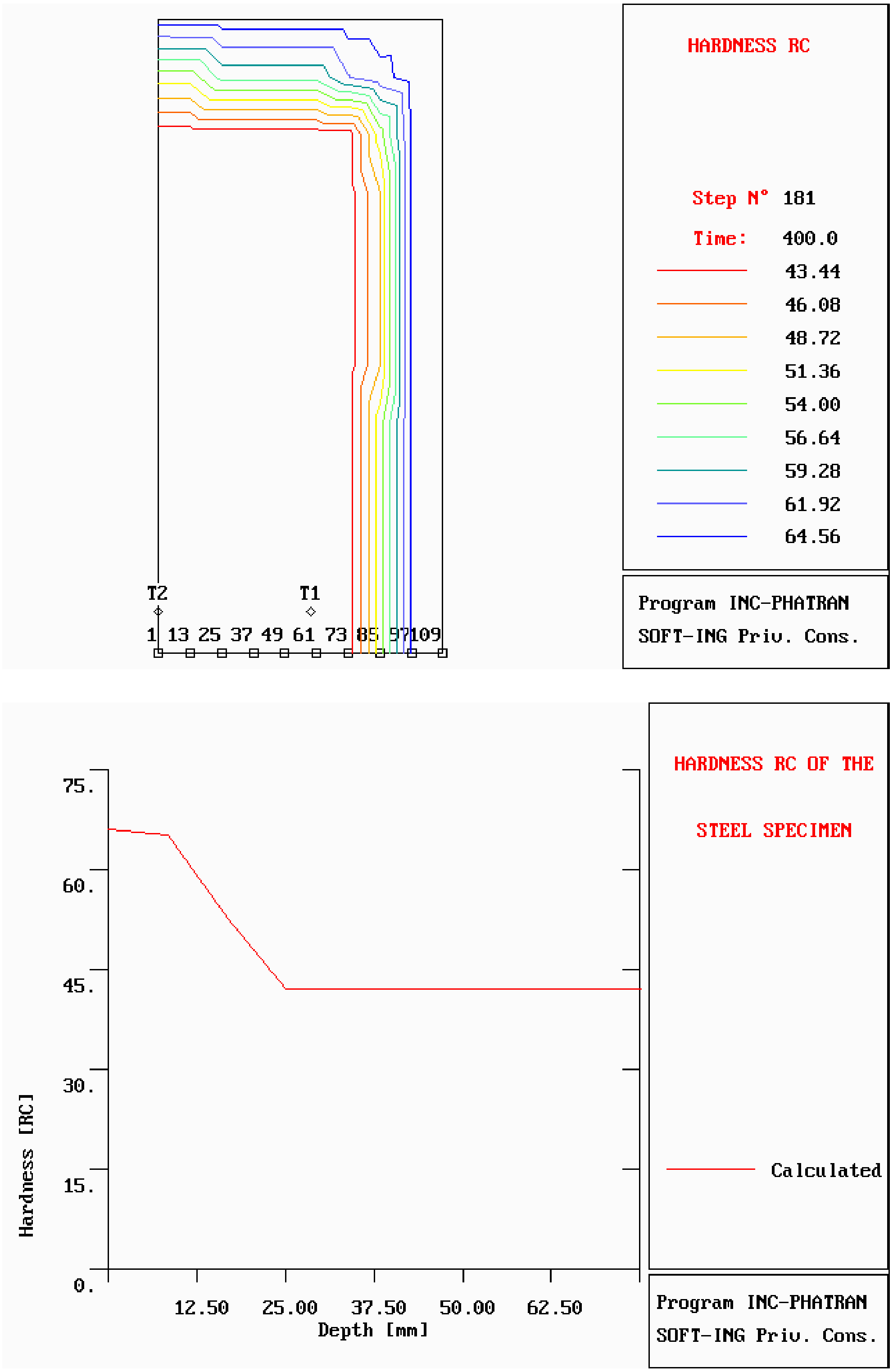


Figure 7.- Hardness profile calculated for a 150 mm diameter sample.

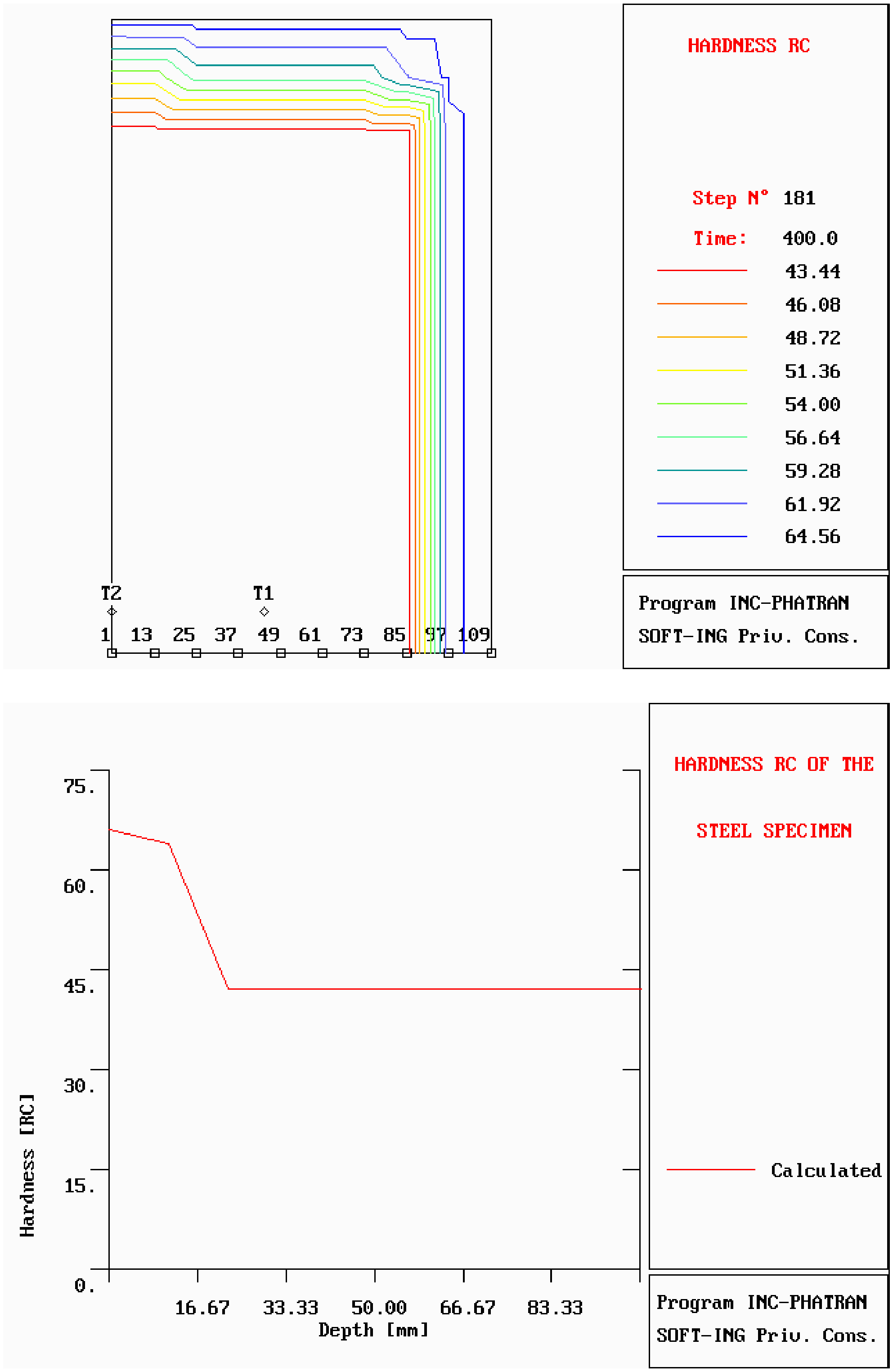


Figure 8.- Hardness profile calculated for a 200 mm diameter sample.