Original Article

Analysis of the effect of immersion rate on the distortion and residual stresses in quenched SAE 5160 steel using FEM

R.D. López-García a,*, F.A. García-Pastor b, A. Maldonado-Reyes a, M.A. Jiménez-Gómez a, J.A. Rodríguez-García c

a Tecnológico Nacional de México, Instituto Tecnológico de Ciudad Victoria, Blvd. Emilio Portes Gil No. 1301, Pte. Cd. Victoria, Tamps, Mexico
b Cinvestav Unidad Saltillo, Av. Industria Metalúrgica No. 1062, Parque Industrial, Ramos Arizpe, Coahuila, Mexico
c Universidad Politecnica de Victoria, Av. Nuevas Tecnologías 5902, Parque Científico y Tecnológico de Tamaulipas, Cd Victoria, Tamps, Mexico

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ABSTRACT

Distortions and residual stresses are common engineering problems present in thermal processes at high temperatures, not only because they lower the quality of the thermally treated components, but also if these stresses are of sufficient magnitude, may cause cracks and fractures to the material during cooling. This investigation focuses on determining the trustworthiness of a mathematical model used in DEFORM-3D software to evaluate the effect of immersion rate on the mechanical properties, distortion and residual stresses formed during the thermal treatment for hardening of SAE 5160 steel used to make leaf springs. The austenitizing temperature used was 920 °C, austenite grain size (AGS) of 10 ASTM, and different immersion rates were studied. The kinetics of phase transformations were calculated using JMatPro software, and they were validated by quench dilatometry. Results showed that the distribution of distortion and residual stresses could be minimized in certain defined ranges of immersion speeds.

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1. Introduction

Thermal treatments commonly involve heating stages, isotherms and cooling at a variable rate, the last stage is responsible for both; the microstructure, and the final mechanical properties of the thermally treated components. Quenching is one of the most used heat treatments in the automotive industry to increase the mechanical properties of steels such as strength and hardness. On the other hand, quenching process involves physical, mechanical, and metallurgical phenomena that are difficult to control and to predict, not only causing a decrease in the possibility of obtaining the
desired mechanical properties, but also affecting the dimensional accuracy of the treated components [1,2]. Quenching process in steels induces the generation of residual stresses which may be thermally generated because of high temperature gradients within the component and austenite-martensite phase transformations. The magnitude of these stresses depends on the chemical composition and in an even greater level, on the cooling rate [3–6].

When the steel cools down from the austenitic temperature at a slow cooling rate, microstructures are obtained that favors the appearance of a low level of residual stresses. However, in order to obtain high mechanical properties, higher cooling rates are necessary, ones that suppress the formation of phases such as ferrite, pearlite or bainite. For these conditions, the predominant phase is the martensite phase, which will generate a greater magnitude of internal stresses that can be undesirable during the life of a piece or component.

Phase transformations in solid state result on some volumetric deformations and transformation plasticity. The first one is presented by the change of volume with transformation per unit of volume and the deformation plasticity. The transformation plasticity includes the deformations produced by the interaction between the phase transformations and the current stress fields. In hardening by quenching, the microstructure of the steel, the deformations and the residual stresses change constantly by the temperature. If at any point of the component the strength limit of the material is exceeded, a non-uniform plastic flow will occur, it will result in the presence of residual stresses in the component, depending on the magnitude; besides, they will be at tension or compression, and they can be beneficial or detrimental to the component. If the residual stresses of the component surface are in compression, it will benefit to the material; otherwise, if the stress is under tension, it could cause problems in the fatigue properties of the component [7,8].

It is difficult to improve all the mechanical properties by simple cooling by quenching, these could vary depending on the conditions of the process. Among the main variables to consider are the quenching medium, the temperature of the liquid bath, the characteristics of the cooled component, agitation of the liquid medium, the austenitic grain size before quenching, the immersion direction and the immersion rate. Therefore, the relationships that exist among these define the final mechanical properties, the magnitude of the distortion, the surface condition and the residual stresses in the cooled component. A large number of variables that are related to establishing optimal conditions during cooling down show the importance of having optimal control during the quenching parts and components, in order to reduce production losses during the manufacturing of steel components with reliable service properties.

Mudasiru et al. studied the effect of the immersion velocity on the mechanical properties and microstructure of low carbon steels, finding that the immersion rate has variable effects on mechanical properties such as yield strength, Young's modulus, hardness and tensile strength to this kind of steels [9]. While Adedayo et al. researched the effect of immersion velocity in mechanical properties during water quenching for a steel with 0.3% C, finding a relationship between the increase in mechanical properties and the increase in immersion rates [10]. Likewise, recent studies using mathematical models indicated that the cooling rate in a piece of steel with low carbon contents is mostly influenced by variables such as the cooling time or dimensions of the piece, rather than the immersion rate [11]. Because quenching is a multi-physical process that involves a complicated interaction of couplings between different physical events such as: heat transfer, phase transformations and the evolution of internal stress, there is no analytical solution to the governing equations, particularly considering the three-dimensional cases and transitory states [12]. Consequently, the use of numerical simulation with thermal-mechanical-metallurgical coupling is essential to achieve a better understanding of the effects of quenching heat treatment on the quality of the cooled parts, allowing for the evaluation of properties that cannot be measured experimentally. Some researchers [7,13–18] have proposed several numerical simulations using finite element method (FEM) to solve this problem.

In this work, the effect of the immersion rate on the generation of residual stresses, the kinetics of phase transformations, the mechanical properties and the distortion generated in medium-carbon steel parts cooled in an oil bath that are used in the automotive industry to manufacture leaf springs were assessed using a numerical FEM approach based on experimental data. JMatPro was used to calculate kinetics of phases transformations, which were later refined using quench dilatometry. A fully coupled three-dimensional FEM model with the previously calculated heat transfer coefficient (HTC) was developed using the commercial software Deform-3D.

1.1. Modeling

Several mathematical models, with different precisions and complexities, have been developed in the last two decades. These models are based on the solution of a series of differential equations, which involves the application of finite element methods (FEM), and are the most widely used for the prediction of distortion, residual stresses and mechanical properties [19–23]. The simulation of finite elements in the quenching heat treatment processes includes three main phenomena which govern the interactions among the different physical aspects and are influenced by each other, so they must be coupled during the simulation process. These are heat transfer, phase transformations, and the generation of residual stresses plus deformations [24–27].

The mathematical model shown here, considers the thermal interactions, the microstructural evolution and the internal stress present. The properties of the variables of each element will be a function of the temperature, so it is possible to obtain information concerning to the effect of the immersion rate in the liquid bath, about residual stresses and the distortion of these components. Since the temperature is different along the piece at the same moment in time, due to the immersion conditions that are typical of the quenching process, the temperature gradients will be different throughout the piece. At each step in time, the temperature distribution will depend on the quenching severity in the cooling medium, the thermal conductivity, the heat capacity and the latent heat in the phase transformations. Convective heat transfer is a
function of the surface temperature distribution of the pieces and depends on the severity of the cooling. Modeling the phases transformations are considered through the evolution of a phase volume fraction during solid-state transformation as a function of time, corresponding to the cooling curve. The internal stress points are calculated using an elasto-plastic analysis that assumes small deformations.

1.1.1. Modeling the heat transfer

The effectiveness of the quenching heat treatment depends on the characteristics of the heat transfer in the piece and the cooling medium. The exact prediction of the thermal evolution of the cooled component is vital for the purposes of the simulation and this precision can only be achieved through understanding the present heat transfer phenomena.

Quenching can be defined as a transient heat conduction problem with heat transfer mechanisms by means of convection and radiation boundary conditions with internal heat source and sink. The ruling equation for this problem has been formulated by Fourier’s law [28] Eq. (1):

\[ q = -k \nabla T \]

(1)

where \( q \) is the heat flux, \( k \) is the thermal conductivity and \( \nabla T \) is the gradient of the temperature field inside the material.

According to Fourier’s law, the heat conduction equation of the transient problem with the phase-transformation latent heat can be determined by using conservation of energy in a rectangular coordinate system, Eq. (2):

\[ \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q = \left( \frac{\partial T}{\partial t} \right) \rho C_p \]

(2)

where \( k \) is the thermal conductivity, \( T \) is the quenching piece temperature, \( q \) is the heat generation rate from the steel phase transformations, \( \rho \) is the material density, \( C_p \) is the specific heat capacity at a constant pressure, \( t \) is the time and \( (x, y, z) \) are the rectangular coordinates.

The rate of heat transmission by convection and radiation between the surface of the piece, and the cooling medium can be calculated by Newton’s cooling equation [29], Eq. (3):

\[ Q = h A \Delta T \]

(3)

where \( Q \) is the heat flux density, \( h \) is the heat transfer coefficient (which is determined by the convection and radiation mechanisms), \( A \) is the surface area of the piece, and \( \Delta T \) is the temperature difference between the piece surface and the quenching medium.

1.1.2. Modeling of phase transformation

Since phase transformations strongly influence thermal and mechanical behavior, they should be considered in simulations of mathematical models. The first step is to determine the temperature ranges in which the phase transformations are presented and which are limited by the critical temperatures. These temperatures can be calculated using the Time-Temperature-Transformation (TTT) diagrams, or by using analytical expressions.

A TTT diagram describes the relationship between the beginning and end of transformation and the transformed volume fraction during the isothermal process at different temperatures. The isothermal kinetic equation, namely Johnson–Mehl equation [30], is elementary in the numerical simulation of thermal processes, although it cannot be directly applied to calculate the volume fraction during non-isothermal processes. Due to the strict limitation of Johnson–Mehl equation, Avrami [31] proposed an empirical equation which has been widely used in these processes Eq. (4):

\[ f = 1 - \exp(-bt^n) \]

(4)

where \( f \) is the volume fraction of the new phase, \( t \) is the isothermal time duration, \( b \) is a constant dependent on the temperature, composition of parent phase and the grain size, and \( n \) is a constant dependent on the type of phase transformation and which ranges from 1 to 4. Coefficients \( n \) and \( b \) at different temperatures, are usually calculated from the TTT diagrams obtained experimentally by Eqs. (5) and (6):

\[ n = \frac{\ln(\ln(1 - f_1) - \ln(1 - f_2))}{\ln t_2 - \ln t_1} \]

(5)

\[ b = -\frac{\ln(1 - f_1)}{t_2^n} \]

(6)

\( b \) depends on the temperature according to the Arrhenius equation given by Eq. (7):

\[ b = b_0 \exp \left( \frac{-Q}{RT} \right) \]

(7)

where \( b_0 \) is the frequency factor, \( Q \) is the activation energy for transformation, \( R \) is the gas constant and \( T \) is the absolute temperature.

In the case of martensite transformation, there is a stage of nucleation and growth; however, the growth rate is so high that the volume of transformation is almost totally controlled by nucleation, as a result, its transformation kinetics is not influenced by the cooling speed. It means that it cannot be described by Avrami’s equation. Therefore, the amount of martensite formed is often calculated as a function of temperature using the equation established by Koistinen and Marburger [32] Eq. (8):

\[ V = 1 - \exp \left[ -\alpha (M_s - T) \right] \]

(8)

where \( V \) is the martensite transformed volume fraction, \( T \) is the temperature, \( M_s \) is the martensitic transformation beginning temperature and \( \alpha \) is a constant that indicates the transformation rate and depends on the steel composition. For carbon steels lower than 1.1% C, \( \alpha = 0.011 \).

However, it is important to notice that there is a critical cooling rate to obtain the martensitic transformation, which is a function of the chemical composition of the steel, and it can be obtained through the TTT and CCT diagrams.
1.1.3. Modeling the mechanical interactions

The presence of mechanical stresses during the cooling stage in heat treatment is a widely studied subject. However, the mechanisms that rule their formation continue to be an important challenge in cooling processes such as quenching.

The formation of residual stresses during quenching can occur because of several mechanisms: differences between temperature gradients, phase transformations or the combination of both of them. The first one is a consequence of high thermal gradients formed between the surface and the core of the piece. Since the surface cools faster than the core, the piece contraction begins on the surface, causing the appearance of residual stresses of “tension” type, while, in the core, in order to balance the state of residual stresses “compressions” are formed. The second one begins as soon as the martensite transformation is formed on the surface. The deformation caused by phase transformations due to thermal expansion and transformations caused by plasticity cause residual stresses, that on the surface of the piece to change to compression; which is the reason why the core of the piece reacts to balance the stress. The last changes of the magnitude and type of residual stresses begin as soon as the phase transformations occur in the piece heart. At this moment, the piece surface is completely transformed and cooled [33].

Material models that have been proposed for the simulation of quenching can be classified into three major categories: elasto-plastic constitutive models, elasto-viscoplastic constitutive models, and unified plasticity models. Almost all the constitutive equations for the simulation of quenching are based on the decomposition of the deformation tensor. Assuming that steel behaves like a thermo-elasto-plastic material, the total strain rate on the steel during quenching for this study has been expressed in terms of elastic, plastic, thermal, transformation and transformational plasticity strain terms, according to Eq. (9):

\[ \dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^e + \dot{\varepsilon}_{ij}^p + \dot{\varepsilon}_{ij}^h + \dot{\varepsilon}_{ij}^{pt} + \dot{\varepsilon}_{ij}^{tr} \]  

(9)

In which: \( \dot{\varepsilon}_{ij}^e, \dot{\varepsilon}_{ij}^p, \dot{\varepsilon}_{ij}^h, \dot{\varepsilon}_{ij}^{pt}, \dot{\varepsilon}_{ij}^{tr} \) are the elastic, plastic, thermal, phase transformation and transformational strain by plasticity strain rates, respectively.

To describe the elastic-plastic mechanical behavior of the material during the quenching process, a yield functional \( \phi \) uses temperature, Cauchy stress \( (\sigma_{ij}) \), volume fraction and plastic history of phases \( (\xi_k, \kappa_k) \) as state variables are defined Eq. (10):

\[ \phi = \phi \left( T, \sigma_{ij}, \xi_k, \kappa_k \right) \]  

(10)

Considering the small strain Von Mises plasticity, the associated Prandtl–Reuss flow rule and isotropic linear hardening (a special hardening rule which takes effect of phase transformation on flow stress into account) is suggested. It should be considered that effective plastic strain \( \dot{\varepsilon}^{pF} \) cannot be used as a strain hardening parameter during phase transformations because of the plastic deformation accumulated in the austenitic phase will be totally or partially lost due to the reconstruction of the lattice-work structure. Thus, a new strain hardening parameter \( (\kappa_k) \) that tracks the history of the plastic deformation for each phase is defined and updated using Eq. (11):

\[ \kappa_k (t + \Delta t) = \int_{t}^{t + \Delta t} \left( \frac{d\sigma_{ij}}{dt} - \frac{1}{\xi_k} \frac{d\xi_k}{dt} \dot{\varepsilon}_{ij} (t) \right) dt \]  

(11)

where \( (\kappa_k) \) is the related strain hardening parameter for \( (k^{th}) \), the microstructural constituent. Subsequently, a new variable is calculated to flow stress for phase mixtures, in which a new state variable and a linear rule of mixtures are used, Eq. (12):

\[ \sigma_{ij} = \sum_{k=1}^{N} \xi_k \bar{\sigma}_{ij}^k + \sum_{k=1}^{N} \xi_k H_k \kappa_k = \sigma_{ij} + \sum_{k=1}^{N} \xi_k H_k \kappa_k \]  

(12)

where \( \sigma_{ij} \) is the yield strength and \( H \) is the plastic hardening modulus.

Once the concepts of yield functional, flow rule and hardening rule have been established, Eq. (9), could be calculated by summing up the strain rates due to different physical origins, as indicated in Eqs. (13)–(17):

\[ \dot{\varepsilon}_{ij}^e = \frac{1}{E} \left[ (1 + \nu) \sigma_{ij} - \delta_{ij} \nu \sigma_{kk} \right] \]  

(13)

\[ \dot{\varepsilon}_{ij}^p = d\lambda \frac{\partial \bar{\phi}}{\partial \sigma_{ij}} \]  

(14)

\[ \dot{\varepsilon}_{ij}^{th} = \sum_{k=1}^{P} \xi_k \int_{0}^{T} \alpha_k dT \]  

(15)

\[ \dot{\varepsilon}_{ij}^{pt} = \sum_{k=1}^{P} \frac{1}{3} \delta_{ij} \Delta_k \xi_k \]  

(16)

\[ \dot{\varepsilon}_{ij}^{tr} = \frac{3}{2} K_k \xi_k \left( 1 - \xi_k \right) S_{ij} \]  

(17)

where \( E, \nu, \sigma_{ij}, d\lambda, \alpha_k, \Delta_k, K_k, S_{ij} \) are elastic modulus, Poisson’s ratio, Cauchy stress tensor, plastic multiplier, temperature-dependent thermal expansion coefficient for phase \( k \), structural dilatation due to decomposition of austenite to the \( k^{th} \) phase, TRIP constant and stress deviator, respectively.

2. Experimental procedure

First of all, a 5160 steel material with the chemical composition indicated in Table 1, was austenitized at 920°C in an electric muffle type furnace at a heating rate of 5 °C s⁻¹, soaked at that temperature for 300 s to obtain an austenitic grain size of ASTM 10, and quenched in industrial oil at 60°C. Fig. 1 shows the flow chart of the data acquisition systems. The cooling bath consists of a hexagonal based tank with a height of 1500 mm, and a width of 300 mm. Flat steel samples with dimensions of 500 mm long, 60 mm wide and 10 mm thick were used in the immersion tests. The computational domain that represents this piece is presented in Fig. 2. The flat samples to be quenched were placed in a rectangular device,
Table 1 – Chemical composition of steel.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>(wt%)</td>
<td>0.6</td>
<td>0.87</td>
<td>0.96</td>
<td>0.25</td>
<td>0.22</td>
<td>0.14</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Fig. 1 – The flow chart used to obtain the cooling curves for specimens with different immersion rates using a data acquisition system.

Fig. 2 – Geometry used in the simulation showing dipping trajectories in a vertical direction $\hat{z}$.

Table 2 – Variation of heat transfer coefficients with temperatures using in FEM.

| Temp (°C) | 25  | 150 | 200 | 240 | 250 | 280 | 300 | 400 | 500 | 600 | 700 | 800 | 920 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| HTC (W/m² K) | 0.1 | 0.2 | 1.4 | 1.2 | 1.0 | 0.9 | 0.7 | 1.3 | 1.3 | 1.2 | 1.0 | 0.6 | 0.2 |

and fixed only by the ends, avoiding a greater area of contact. The velocity of immersion of the flat samples in the liquid bath was controlled by a NEMA 23 stepper motor and control software. The flat steel samples were instrumented with a K-type thermocouple fixed on the surface of their central part, and temperature records changes were obtained by a 10-channed data acquisition module as well as an analysis software. The flat samples were submerged for 90s. The immersion rates used for cooling flat samples in the quench bath were 10, 20, 60, 100 and 140 mm s⁻¹. The thermal data was recorded using a computerized acquisition system. The heat transfer coefficient (HTC) used is illustrated in Table 2. The hardness of the tempered samples were evaluated using a hardness tester (Rockwell TIME model TH 500) and a diamond tip indenter with a load of 150 kg. After the quenching operation, the samples were machined to standard specifications for tensile testing, using a Shimadzu universal testing machine, the strain rate during the stress tests used was 3 s⁻¹. The martensite volume fraction has been measured using common metallography techniques. JMatPro software was used to calculate the phase transformation kinetics and martensite linear expansion. Afterwards, these calculations were validated by a dilatometer, this equipment is the quenching/deformation dilatometer (L78 RITA Linseis Messgeräte,
Germany) to measure the changes in length during heating and cooling samples. Induction heating and helium cooling were used in the experimental setup, with a cylindrical sample (10 mm long and 3 mm thick) instrumented with a k-type thermocouple recording 1000 data points per second. Finally, the TTT diagram was constructed and the critical cooling rate was determined for this type of steels using an austenitic grain size of ASTM 10.

2.1. **3D FEM simulation**

Deform-3D version 10.2.1 software was used for the finite element simulation of the quenching heat treatment of a steel piece with the geometry shown in Fig. 2, which represents a three-dimensional model of the central part of a leaf spring component with 33,000 elements and 4718 nodes. The model considers thermal interactions, microstructural evolu-
tion and elastic–plastic deformation. The boundary conditions and thermo-physical quantities of the model are mentioned below. Thermal conductivity, yield stress and Young’s modulus, were obtained from JMatPro database. Specific heat, enthalpy and flow stress were obtained of the available literature, while transformation kinetics were determined through quenching/deformation dilatometer. The initial temperature was set to 920 °C for all the nodes, and all the elements were assumed to be made up of 100% homogeneous austenite with a defined grain size (ASTM 10). Distortion and residual stresses generated during those previous processes were considered at the beginning of the simulation, and were found to be negligible.

In order to analyze the effect of immersion rate during quenching on the distortion and residual stresses, the piece was dipped in the Z direction of the coordinate axis shown in Fig. 2. The Deform-3D code has the capacity to introduce a solid object into a pool at a given speed. Basically, this is done by sequentially switching on the oil cooling boundary condition throughout the surface of the object, as if it were immersed in a pool.

The element properties were computed in the form of a sum of the contributions of the individual fractions of phases present in the element at the particular step in time. All phase transformations from austenite to ferrite, pearlite, bainite and martensite, were considered in each modeling, which were assigned an independent set of material data properties. The simulated hardness distribution was computed from individual phase hardness values. The properties of individual phases were obtained using JMatPro, with the initial conditions, consisting in an austenitic temperature of 920 °C and an austenitic grain size of ASTM 10. Thermal and mechanical properties such as specific heat capacity at a constant pressure (C_p), thermal conductivity (k), enthalpy (H), Young’s modulus (E), linear expansion and yield stress (S_y) of the material, were defined as dependent on the current phase, as shown in Fig. 3. The density (ρ) and Poisson ratio (ν) were set as 7.67 × 10^3 kg m^-3 and 0.3, respectively.

3. Results and discussion

The results were obtained from the experimental tests and the simulation of the components quenching process used as a Leaf Spring at the suspension systems of heavy trucks, using Deform-3D software. The complex coupling of thermal, mechanical and phase transformations were thoroughly analyzed.

3.1. Thermal analysis

Fig. 4 shows the experimental cooling curve (continuous line) obtained by thermocouples placed on the surface of the cooled component from a temperature of 920 °C to room temperature, in a liquid oil medium at 60 °C. After obtaining the cooling profile, approximations of the heat transfer coefficient (HTC) were made by Deform-3D until an excellent adjustment of the simulated cooling curve (line with circles) was achieved. The prediction of the calculated cooling profiles shows good agreements with those obtained by experiments with the difference between the calculated and experimentally measured temperature of 3.57%.

Fig. 5a shows the calculated cooling curves of the surface of the component by different cooling rates studied for SAE
5160 steel, and for an austenitic grain size ASTM 10. We can see that as the immersion velocity increased, the time to complete cooling decreased, showing that the extraction of heat under these conditions was favored at high speeds. After an immersion speed of 60 mm s$^{-1}$, the behavior of the cooling curve does not show important changes in thermal evolution. Fig. 5b represents the behavior of the heat transfer coefficient (HTC), obtained through the cooling curves of the studied components for different immersion speeds Fig. 5a. Once the cooling profile was obtained, HTC approximations were carried out in Deform-3D until the cooling curve presented an excellent agreement. We can see that for all cases a similar behavior is presented having different ranges of the HTC. First, the HTC increases during cooling and reaches a maximum at a temperature of approximately 500 °C, then the HTC decreases to a temperature close to 390 °C, finally during the transformation of the martensite, the HTC increases to a temperature of approximately 200 °C. After this point, the release rate of the latent heat starts to decrease and so does the HTC. Clearly, the shape of this drop in the HTC curve depends on the properties of both, the oil and the steel.

Fig. 6 shows the cooling speeds obtained by the studied different immersion rates. The maximum cooling speeds obtained were 23 and 37 °C s$^{-1}$ for the immersion rates of 10 and 140 mm s$^{-1}$ respectively. The total cooling time is lower when the immersion rate is higher than 60 mm s$^{-1}$. The above is desirable because there is less time for the formation of high temperature gradients, which favors the generation of thermal stress in the component.

During the cooling of quenched components, it is desirable that the temperature changes at the component occur uniformly on the surface and the core of the part. However, due to the complex interaction of the various thermal, physical and mechanical phenomena present during the quenching process, control is complicated and high temperature gradients might occur at different points in the piece, generating a non-homogeneous distribution of mechanical properties. These thermal gradients give place concentration of stress, distortion, and the formation of residual stresses responsible of the formation of cracks and fractures in quenched parts.

Fig. 7 shows the maximum and minimum temperature gradients during time of simulation for the components cooled at different immersion rates. The curves presented are the result of the measurements of all the nodes in the mesh corresponding to the component studied. We can observe that the higher temperature gradients of >600 °C correspond to the slowest immersion rate studied (10 mm s$^{-1}$), and these temperature gradients remain for spaces of more than 20 s while by an immersion rate of >60 mm s$^{-1}$ the times are shorter and the temperature gradients are lower. Prolonged times with high temperature gradients in the component could generate higher thermal stress and more macroscopic distortion in the part.

### 3.2. Phase transformation and mechanical properties

Fig. 8 shows the TTT diagram in which the beginning and end of the bainite transformation is presented for the SAE 5160 steel with an austenitic grain size of (AGS 10). The results obtained for this figure have been calculated using the software JMatPro (continuous line and dashed line) and have been validated through quench dilatometry studies (points). It can be seen that the JMatPro software has shown an excellent agreement at the beginning (B$_{S}$) and the end (B$_{F}$) of the bainite transformation according to the reaction temperatures studied by dilatometry. According to this figure, bainite transformation beginning curve is very close to time 0 of the graph, indicating that the cooling time necessary to suppress the bainite phase and obtain fully martensite must be extremely fast, increasing the possibility of the appearance of cracks, fractures, and the generation of residual stresses due to high temperature gradients. However, according to the prediction by JMatPro, for larger grain sizes AGS 8 and 5 the time is increased and the critical cooling rate required to avoid the formation of bainite decreases, Fig. 9.

Fig. 10 shows the evolution of the fraction of martensite transformed as a function of time for the five immersion rates.
studied. It shows that, for all immersion rates, percentages of martensite transformation were close to 80% volume. However, the immersion rate influences the necessary time to reach this percentage. For immersion rates of 60 mm s\(^{-1}\) and above all, the time required is 60 s, whereas, for the lowest immersion rates studied, the time to reach these percentages is 80 s. These results show that slower immersion rates will favor the appearance of a greater level of residual stresses due to a martensite transformation slow speed. The accumulation of stresses present in the material will be added to stresses formed during martensitic transformation, causing a decrease in the dimensional accuracy of the pieces, and if the residual stress exceeds the yield stress, cracks or fractures in the material may occur.

This is evident when the microstructural results of the phase distribution at the end of cooling are compared. It is observed that for the slower immersion speeds Fig. 11a the bainite is present in a greater percentage than for the higher immersion rates where the austenite-martensite transformation is almost complete Fig. 11b.
Additionally, a type of fracture failure was observed exclusively in the quenched pieces for immersion speeds of 10 mm s\(^{-1}\). Fig. 12a shows the morphology obtained in the cross-section of the quenched pieces at this immersion speed, showing a type of intergranular fracture, caused by the conditions of the process, an inhomogeneous distribution of the temperature in the component and mainly to the accumulation of stresses in very specific areas of the piece that were able to overcome their yield stress. For immersion speeds of 20 mm s\(^{-1}\) and higher, no evidence of fracture failure in the quenched pieces was observed. Fig. 12b shows the morphology obtained for these immersion conditions.

The hardness profiles for the steel studied, and for the different immersion rates are shown in Fig. 13. The behavior of the hardness is directly related to the martensitic transformation volume. The higher hardness levels reached correspond to higher immersion rates that are close to 57 HRC. Similarly, the hardness is directly related with the martensite transformation, at higher immersion rate, greater hardness is reached.

In addition to the previously described behavior of the transformed martensite fraction and the hardness evolution (HRC), Figs. 10 and 13, there are other important differences during cooling related to immersion rate.

The martensite volume fraction and hardness (HRC), was calculated using the post-processor incorporated in Deform-3D, in the results shown below, the dispersion of the martensite and hardness are analyzed in a more complete way through histograms representing the accumulated data of the 4718 nodes that make up the mesh of the simulated complete component and it is presented in Fig. 14 for a cooling time of 70 s for the different immersion speeds studied.

Fig. 14a–e shows the distribution of martensite, and Fig. 14f–j indicates the distribution of hardness. The results show that the distribution of the martensite fraction transformed and the hardness in the tempered component present a more homogeneous distribution at higher immersion rates (140 mm s\(^{-1}\)). On the other hand, slower immersion rates in Fig. 14a, b and f, g, which correspond to martensite transformation and hardness respectively, show that a significant number of elements that form the mesh are not transformed yet, since the temperature of these nodes is above the \(M_s\) for the times studied. This means that a higher immersion rate is more efficient for obtaining a better distribution of martensite and hardness in the component, contributing to a lower concentration of residual stresses and distortion in the piece. Additionally, Fig. 15a–e and f–j represents the central part of the simulated piece in Deform-3D, where the distribution of martensite and hardness respectively are shown by screenshot. This figure complements the results shown in Fig. 14, where it becomes clear that slower immersion speeds cause austenite-martensite transformation and hardness to have a heterogeneous distribution throughout the piece, due to a non-uniform temperature in the component during cooling.

Fig. 16 shows hardness (HRC) simulated and calculated for the different immersion rates studied. We can see a good fit between the results simulated and those measured experimentally, providing the certainty of the results obtained using the Deform-3D.
Fig. 14 – Histograms, a–e) the martensite volume fraction and f–j) HRC hardness, at the mash nodes for different immersion rates. The quenching time was 70 s.
The ultimate tensile stress (UTS) and yield stress (YS) were simulated and calculated, and the results obtained are shown in Fig. 17. We can see that the hardness, UTS and YS are strongly influenced by the immersion rate, increasing at higher immersion rates.

**3.3. Analysis of stress and deformation**

Fig. 18 shows the evolution of the effective stresses on the surface of the samples simulated in Deform-3D. It can be clearly observed that the immersion velocity present a prominent effect in the increase of distribution and magnitude of effective stresses at the end of the cooling when the immersion rate is slower. According to the simulation, these stresses were presents along the X-axis of the component, in some cases exceeding 180 MPa for the speed of 10 mm s\(^{-1}\).

Fig. 19 shows the longitudinal stress along the ZX axis corresponding to Fig. 2. The results are the average obtained in each node of the mesh by the tempered component and for two immersion rates studied. We can see that for the slowest immersion rate of 10 mm s\(^{-1}\), the formation of this stress appears after 30 s of cooling and increases swiftly, reaching levels of stress near 120 MPa (tension type) for a time of 40 s, all this being a consequence of the high temperature gradients formed by these immersion rates as shown in Fig. 7. Meanwhile, for an immersion rate of 140 mm s\(^{-1}\) the stress only reaches values of 40 MPa (compression type) for a time of 40 s.

From the results of the analysis of effective stress generated on the surface and core of the component, a comparative study was carried out on the effect of the immersion rate on the magnitude of stresses, and the degree of distortion (displacement) obtained in the component for different immersion rates.

The lower part of Fig. 20 shows the evolution of the effective stresses and the displacement of the component, while the

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**Fig. 15** – Comparison of martensite volume fraction and hardness distributions in the cross-section of the simulated components in Deform-3D, a–e) martensite and f–j) hardness. The quenching time was 70 s.

**Fig. 16** – Comparison of the hardness calculated and measured for different immersion rates in SAE 5160 steel.

**Fig. 17** – Comparison of the ultimate tensile strength (UTS) and yield stress (YS) for different immersion rates in SAE 5160 steel.

**Fig. 18** – Distribution of residual stresses after quenching, obtained in DEFORM-3D for different immersion rate, a) 10, b) 20, c) 60, d) 100 and e) 140 mm s\(^{-1}\).
upper part represents the relationship between the cooling curve and the volume fraction of martensite, both depending on the time of study, for the immersion rates of 10 and 140 mm s⁻¹.

The lower part of Fig. 20a corresponds to the immersion rate of 10 mm s⁻¹, and we can see that at a time of 39 s the transformation of the martensite begins and the residual stresses formed in the component reaches values close to 600 MPa. The above is due mainly to the thermal contraction of the material (σth) and high temperature gradients between the surface and core of the piece.

The displacement of the component at this time was 1.1 mm. During the time interval from 39 to 76 s, a combination of thermal origin stress (σth) and phase transformations (σtr) is presented. The stress reached is in order of 390 MPa and the displacement is 1.7 mm. After 76 s of cooling, the stress formed is exclusively generated by phase transformations (σtr), and both, the stress and the displacement do not present notable changes. The lower part of Fig. 20b corresponds to the immersion rate of 140 mm s⁻¹. In this case, the stress that is thermal in origin (σth) due to thermal contraction during cooling is presented in the component from the beginning of the test to 30 s when the martensitic transformation begins. For this condition, the stresses generated in the component is in the order of 320 MPa and the displacement of the piece is 0.1 mm. For the time interval from 30 to 64 s; the stress formed is a combination of thermal origin stress (σth) and phase transformations (σtr). The stress decreases to zero and the displacement of the piece remains at 0.1 mm. After 64 s, the stress and the deformation remained constant in the ranges obtained in the previous interval time.

It is clear that thermal stress has a greater influence on the formation of residual stresses than the one caused by martensitic transformation, with higher immersion speeds favoring the decreasing of the stress and the distortion of the component.

Fig. 21 shows the total displacement of the component measured along the Y-axis in the cross section at different points of the part and for a studied immersion rate of 10 and
140 mm s\(^{-1}\). We note that for an immersion rate of 10 mm s\(^{-1}\) there is significant displacement in the middle of the component, close to 3 mm, and at the end, the distortion is close to 0.5 mm. On the other hand, for the highest immersion rate of 140 mm s\(^{-1}\), the distortion of the component is below 0.5 mm along the entire component. The influence of the immersion rate on the displacement of the component is remarkable, the least distortion occurring at high immersion rates in the studied cases.

4. Conclusions

A finite element mathematical model was developed in Deform-3D, fully coupled to study the thermal, physical and mechanical phenomena that occur during the quenching heat treatment in a SAE 5160 steel, obtaining an excellent agreement of the simulated results and those obtained experimentally. The kinetics of transformation were calculated using quenching dilatometry to obtain the data pertaining to the thermal evolution of the component. The heat transfer coefficient (HTC) as a function of temperature, as well as the data of the mechanical tests to determine strength and hardness were considered in the simulation model.

The results of the simulation showed that the immersion rate in the liquid bath for the tempered pieces has an important effect on the mechanical properties, the formation of residual stresses and the distortion or displacement of the component. The thermal origin stress has greater influence on the distortion of the component than the stress because of the martensitic transformation. The high temperature gradients formed are the main cause. The stress and the distortion are reduced when increasing the immersion rate of the flat samples in the liquid bath, in which, at the highest immersion rate studied, the stresses were significantly reduced and the displacement was in levels below 0.3 mm. The analysis of the distortion in the complete component showed greater distortion in the middle of the component when slow immersion rates were used. Dispersion analysis using histograms showed that immersion rates of 60 mm s\(^{-1}\) and higher, favored a better distribution of the martensite fraction and hardness during cooling. While lower immersion rates presented zones in the material with little transformation and other areas with a martensite volume that was very untransformed; causing the formation of high residual stresses in specific areas of the piece and a macroscopic distortion of the part. The development and application of the mathematical model in this study has great relevance for industries that use thermal treatments for the design of equipment and its operation, the prediction of mechanical properties, the improvement in the dimensional precision of pieces, and the prevention of failure due to fractures in quenched components.

Conflicts of interest

The authors declare no conflicts of interest.

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