# DIMENSIONAL CHANGE PREDICTION IN AUSTEMPERED DUCTILE IRON PARTS USING FUZZY MODELLING

A. L. DAI PRA[†], M.D. ECHEVERRÍA[‡], A. SCANDURRA[†] , O. MONCADA[‡] and J. SIKORA[*]

*Facultad de Ingeniería, UNMDP, Juan B. Justo 4302, (7600) Mar del Plata, Argentina*
*† Artificial Intelligence Research Group.*
*‡ Mechanical Technology Research Group*
**Head Metallurgy Division INTEMA(UNMDP) – CONICET*
*jsikora@fi.mdp.edu.ar*

*Abstract*— **This work focuses on the development of a model to help in the qualitative and quantitative estimation of the changes in linear dimensions of austempered ductile iron (ADI) parts during the heat treatment cycles.**

**The model was developed by applying fuzzy concepts using experimental data of dimensional changes taken from a large number of actual parts. It is able to predict the changes expected to take place on selected linear dimensions of ADI parts. Each part is characterised by ten input variables, which include data about chemical composition, heat treatment process and part size.**

**The model is considered a useful tool to help in the estimation of dimensional change in ADI actual parts and it is being used in the design of new components**.

*Keywords*— **ADI, Dimensional Change, Fuzzy Modelling**

## I. INTRODUCTION

Most metallic actual parts suffer dimensional changes as consequence of the heat treatment cycles carried out to adjust final microstructure and mechanical properties.

The quantitative variation of some specific linear dimensions, referred as "Dimensional Change" (DC), must be taken into account to enable the final piece dimension to be within the required tolerance. The information available in the literature allows to predict DC for homogeneous materials extensively used in the industry, as for example some standardised steels (Metals Handbook, 1981). Austempered Ductile Iron (ADI) is an emerging material and many factors affect the magnitude and repeatability of DC. To the best of the authors knowledge the information about this topic is scarce and imprecise yet.

Taking into account that the machinability rating of any ADI part is significantly lower than the same ductile iron piece in the as-cast condition, it is important to reach a good prediction of DC in order to allow the machining operations can be done before heat treatment, availing better conditions and involving lower cost.

Some studies about the qualitative influence of the processing variables on DC have been reported in the literature. Dodd and Gundlach (1984), Keough (1991) and Bahmani *et al*. (1997) have studied the influence of the prior microstructure on DC. Gundlach *et al*. (1985) and Hornung and Hawke (1984) have considered also the effect of austenitising and austempering temperatures. Moncada and Sikora (1996) got quantitative data about the individual influence of some variables making systematic measurements on test samples and actual parts, studying also the anisotropy of DC. Recently, Echeverría *et al.* (2001) have studied the magnitude and dispersion of DC and its influence on the fabrication steps in ADI actual parts, making a comparison with a quenched and tempered SAE 4140 steel, both with similar mechanical properties.

Echeverría *et al*. (2001) and Sosa *et al.* (2001) have reported that ADI parts (gears) with the same external diameters but different thickness, made with the same alloy and identical heat treatment cycles, presented different DC on those diameters. They stated that when these parts are mounted on machine components, the DC can cause variations on the allowance or interference, producing deficiencies in service. In some of the mentioned studies (Gundlach *et al*., 1985; Moncada and Sikora, 1996) it has been determined that the DC can range from noticeable positive (+0.7% expansion), to slight negative values (-0.05% contraction).

The reported studies take into account the individual effect of some variables on DC. Most of these variables exert influence on phase transformations and therefore on DC. Nevertheless, the simultaneous effect that the variables altogether can exert on DC is very complex to know.

The Metallurgy Division of INTEMA has extensive experience in the industrial application of ADI (Sikora *et al*., 1991; Martínez *et al*., 2002). Many different actual parts and test samples produced at commercial foundries were austempered and analysed. The metallurgical and mechanical characteristics of those parts, as well as the DC produced during the ADI heat treatment, were systematically determined and the results were accumulated in a database.

Artificial Intelligence techniques were employed to develop an Expert System in an attempt to improve the knowledge on ADI. This Expert System allows to establish the optimal heat treatment variables for a given ADI actual part taking into account the required mechanical properties (Dai Pra *et al*., 1996, 1998). The success of this interdisciplinary effort and the availability of the mentioned database encouraged the research groups to use the novel fuzzy modelling in order to estimate DC.

The fuzzy modelling, based in the Zadeh fuzzy concepts (Zadeh, 1965), is considered an appropriate methodology to model and to predict results in industrial processes on the basis of some existing experimental data (Guillaume, 2001; Chen *et al*., 2002: RaBbach and Lehnert, 1999: Klawonn and Kruse, 1997). This methodology has been developed during the last years and is suitable for a wide range of engineering applications, particularly for the treatment of complex relational systems. Fuzzy modelling exploit the tolerance to imprecision, uncertainty and partial truth to achieve tractability, robustness and solutions at low computational cost (Pedrycz, 1995).

The objective of this work is to develop a fuzzy model in order to help in the qualitative and quantitative estimation of the linear dimensional changes of ADI parts, considering the simultaneous effect of material, part size and processing variables. The model is based only on actual DC measurements.

## II. METHODS

### A. Materials

Ductile iron "Y" blocks of 0.5; 1 and 3 inches, according to ASTM A395 (12.7; 25.4 and 76.2 mm), as well as a large number of actual parts were cast in commercial foundries by using medium frequency induction furnaces. Pig iron, foundry returns, steel scrap and ferroalloys, were used as raw materials. The melts were nodularised using Fe-Si-Mg and inoculated with Fe-Si. The chemical compositions for all the melts were in the following ranges: C: 3.10-3.65 %, Si: 2.44-3.18 %, Mn: 0.11-0.5 %, Cu: 0.04-1.19 %, Ni: 0-1.43 %, Mo: 0-0.28 %, Mg: 0.025-0.045%, S: less than 0.03%, P: less than 0.04%.

### B. Tests samples and actual parts

Cylindrical and prismatic bars, having dimensions of 10 mm in thickness and 100 to 200 mm in length, were machined from the "Y" blocks, and were used as test samples.

More than twenty types of actual parts were used. They include plate cams, stepped clamps, pipes, different kinds of reducing internal and crown gears, crankshafts, mill blades, eccentrics, wheel axes, worm wheels, threading tools, plow shares, etc, having linear dimensions ranging within 4 to 800 mm. Fig.1 shows some of these parts. At lest ten parts of each type were employed to carry out the measurements of each specific linear dimension used in this work.

Most parts are being produced in serial manufacturing, so, in some cases similar parts were cast from different melts.

The test samples and actual parts were chemically and metallographically characterised, accurately measured and heat treated.

In some cases the prior matrix microstructures were adjusted by previous ferritising and normalising heat treatments, in order to obtain fully ferritic and fully pearlitic matrices, respectively. The amounts (percent) of ferrite and pearlite were determined by using conventional metallographic techniques.

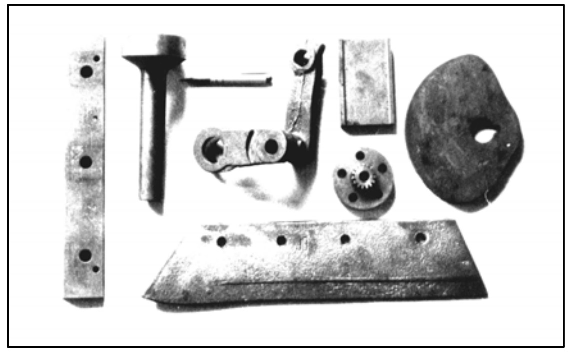

Figure 1. Some ADI parts

### C. ADI Heat treatments

Test samples and actual parts were heat treated following diverse thermal cycles, in order to obtain different ADI grades (Grades 1 to 5 ASTM 897-90).

The range of temperatures and holding times, for the austenitising and austempering steps, were the following: Austenitising temperature, 840 to 950 °C; Austenitising time, 60 to 120 minutes; Austempering temperature, 240 to 370 °C; and Austempering time, 60 to 120 minutes.

### D. Dimensional Metrology

Several linear dimensions *(dim)* of test samples and actual parts used in the present study, were carefully measured in order to determine the DC accordingly to the following formula:

$$DC = 100\ (dim_f - dim_i)\ /\ dim_i \qquad (1)$$

where $dim_i$ and $dim_f$ are the measured values of a given linear dimension, before and after the heat treatment process, respectively. It is important to note that the DC values are indicated in percent.

In most cases different linear dimensions were considered for the same part. As an example, for the case of a mill blade, Fig. 2 shows three different specific linear dimensions, "L, t and w" where the DC was determined.

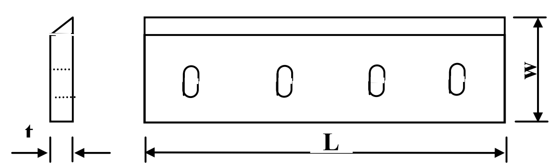


Figure 2. Example of different linear dimensions of an ADI part.

A coordinate measuring machine, with a linear displacement accuracy of ±(2,5+4L/1000) μm was used. In most cases fine finishing was carried out in the zones where the corresponding linear dimension was measured, to improve the accuracy. These zones were protected with metallic foils or chips, to avoid deleterious surface effects during the heat treatment.

## III. DEVELOPMENT OF THE FUZZY MODEL

### A. General concepts

A fuzzy model is a rule set. In the present case the rules are, accordingly to the Takagi-Sugeno style (Takagi and Sugeno, 1985; Grauel and Mackemberg, 1997), of the form:

$$\textit{Rule } j\text{: if } x_1 \text{ is } c_1^{(j)} \text{ and } x_2 \text{ is } c_2^{(j)} \text{ and ... and } x_n \text{ is } c_n^{(j)} \text{ then } y^{(j)} \text{ is } f_j(x_1^{(j)} \ldots x_n^{(j)}) \quad (2)$$

where $j$ is the number of rule, $x_1, x_2, \ldots, x_n$ are the input variables and $y$ is the output variable. Each rule allows to describe fuzzy areas of the workspace through functions $f_j(x_1 \ldots x_n)$. The characteristic of these fuzzy areas is that the membership of a datum to the area is not necessarily 'yes or no', or 'true or false'. It is a real number in the range [0,1] defined by a membership function $\mu_i$. Therefore, the fuzzy areas can be overlapped, belonging a datum to one and another area, as it is shown in Fig. 3.

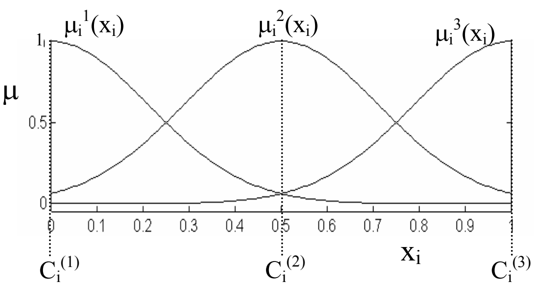


Figure 3. Membership functions

The $c_i$ values in Fig. 3 correspond to prototypical data that characterise the area. The terms "$x_i$ *is* $c_i^{(j)}$" in Eq. 2 indicate the evaluation of a membership function $\mu_i^{(j)}(x_i)$, being in this case:

$$\mu_i^{(j)}(x_i) = e^{\frac{-(x_i - c_i)^2}{2\sigma^2}} \quad (3)$$

The determination of an output value ($Y$) is obtained through the average weight of the $f_j$ functions as:

$$Y = \frac{\sum_{j=1}^{r} \alpha_j f_j(x_1, \ldots, x_n)}{\sum_{j=1}^{r} \alpha_j} \quad (4)$$

where $r$ is the total number of rules, and the $\alpha_j$ values correspond to the weight of the $j$ rule in a multi-dimensional area, defined by the conjunction of the $\mu_i^{(j)}$ in the $j$ rule, computed through the product of the $\mu_i^{(j)}$ (Fig. 4).

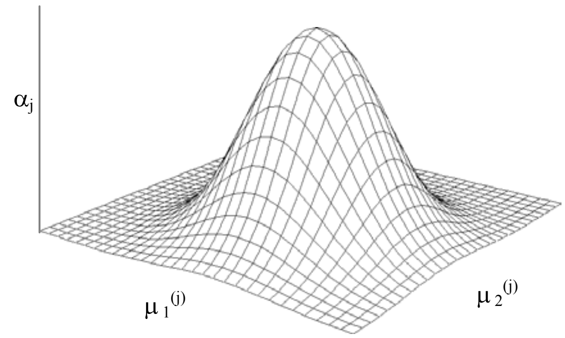


Figure 4. Conjunction of two membership functions for two variables

In order to define each rule it is necessary to determine the multi-dimensional fuzzy areas composed by the input-output variables. A fuzzy clustering method is used to find the $c_i^{(j)}$ values and to define the $\mu_i^{(j)}$ membership functions.

The Subtractive Clustering algorithm (Chiu, 1994), provided by the Fuzzy Logic Toolbox for Matlab® (Jang and Gulley, 1995), was selected. This algorithm assumes each data point as a potential cluster centre, based on the density of surrounding data points. The algorithm selects the data point with the highest potential as the first cluster centre. Then, it destroys the potential of data points near to the first cluster centre and searches a new highest potential data. The process is repeated until a potential limit. The measure of the density is calculated as:

$$D_k = \sum_{j=1}^{n} \exp\left( - \frac{\left\| X_k - X_j \right\|}{(r_a/2)^2} \right) \quad (5)$$

Where ||.|| is a vectorial norm representing the euclidian distance between two vectors, X = [$x_1, x_2, \ldots, x_n, y$] corresponds to input-output data and $r_a$ determines the amplitudes of the cluster.

### B. Model for test samples

In a first step only the test samples (cylindrical and prismatic bars taken from the "Y" Blocks) were used to build a preliminary and simplified fuzzy model. The objective of this preliminary model was to analyse if the predictions given by the model were in accordance with the tendencies reported in the literature, taking into account that most of these tendencies were found using similar test samples. In this model the attention was only focused on the influence of the following input variables:

- *Ta:* Austempering temperature
- *Pearlite%:* prior matrix microstructure, (expressed in % of pearlite) present before the ADI heat treatment.
- *Y_ block:* size of the "Y" block (in inches).

The rules obtained to build the model were the following:

*If Ta is 360 and Pearlite% is 0 and Y_block is 0.5 then* $DC_1$ *is -0.001 Ta -0.305 Y_block +0.481*

*If Ta is 360 and Pearlite% is 85 and Y_block is 1 then* $DC_2$ *is 0.004 Pearlite% - 0.052 Y_block - 0.225*

*If Ta is 340 and Pearlite% is 15 and Y_block is 3 then* $DC_3$ *is - 0.001 Ta + 0.001 Pearlite% - 0.272 Y_ block + 1.14*

*If Ta is 280 and Pearlite% is 70 and Y_block is 1 then* $DC_2$ *is 0.006 Pearlite% - 0.073 Y_block - 0.628*

### C. Model for actual parts

A second model was build using data taken from all the actual parts studied, which involved different heat treatments, diverse chemical compositions and different shapes and sizes. The model focused on the evaluation of the expected DC produced on each specific linear dimension of each actual part.

The parts should be characterised by the following input variables:

- $T_\gamma$: Austenitising temperature (°C)
- $t_\gamma$: Austenitising holding time (minutes)
- $T_a$: Austempering temperature (°C)
- $t_a$: Austempering holding time (minutes)
- *dim:* linear dimension of a given part (mm).
- *Mn:* manganese (weight percent)
- *Cu:* copper (weight percent)
- *Ni:* nickel (weight percent)
- *Mo:* molibdenum (weight percent)
- *Si:* silicon (weight percent)

It is important to point out that in many cases, due to the irregularity in shape and size of the parts, the undercooling in different zones varies significantly. Therefore, a noticeable matrix heterogeneity is expected, making difficult to quantify accurately the amount of the microconstituents present before the ADI heat treatment.

Accordingly to empirical observations, the influence of these effects on the DC is greater for small dimensions than for the big ones. Then, a new variable called *dim** was defined in order to adjust the model. It has six numerical values (or codes), in an approximated logarithmic integer scale of the original *dim* variable, as indicates Fig. 5. Then, it is possible to adjust the linear dimension considering indirectly the undercooling effects on the microstructure, and therefore on the DC, taking values in the range of real numbers since *dim** is finally a fuzzy variable. This classification allows to improve the model taking into account the part size effect.

Some details about the considerations taken into account for the selection of the model parameters were previously analysed (Dai Pra, 2003).

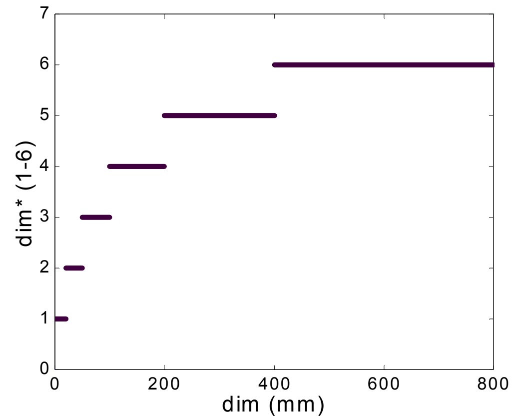


Figure 5. Relationship between *dim* and *dim**.

## IV. RESULTS AND DISCUSSION

### A. Prediction of DC for test samples

Figures 6 to 8 show results, through surface graphs, about the influence of the studied variables on the DC.

Figure 6 shows the influence of the austempering temperatures and the size of the "Y" blocks on the DC, for test samples having fully pearlitic matrices. It is shown that the smaller the size of the "Y" block, the higher the value of DC. It is also shown that the higher the austempering temperature, the lower the DC. These results are in coincidence with those reported by Hornung and Hawke (1984), Gundlach *et al.* (1985), and Moncada and Sikora (1996)

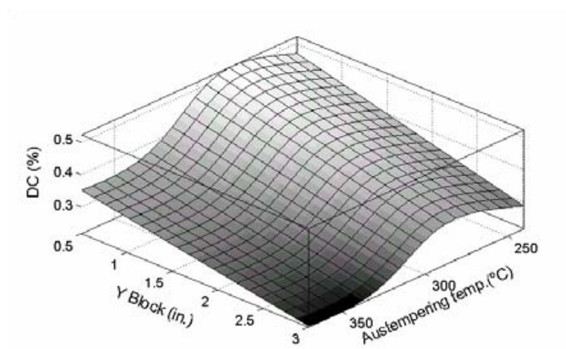


Figure 6. Influence of austempering temperature and "Y" block size on the DC for fully pearlitic matrices

Figure 7 shows a similar tendency for ferritic matrices. Nevertheless, it is important to point out that the DC values are consistently smaller than those measured for pearlitic matrices and they are negative values for the higher austempering temperatures.

Figure 8 confirms the tendencies mentioned before for the case of alloys with different ferrite and pearlite contents, showing that test samples with fully ferritic matrices can have slightly negative DC values, i.e. a contraction for the higher austempering temperatures. This is also in agreement with other reported results (Moncada and Sikora, 1996; Echeverría *et al*. 2001).

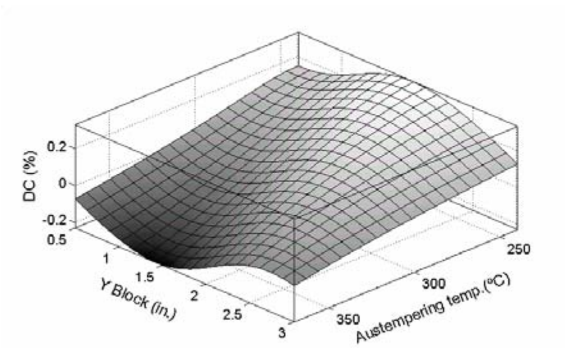


Figure 7. Influence of austempering temperature and "Y" block size on the DC for fully ferritic matrices

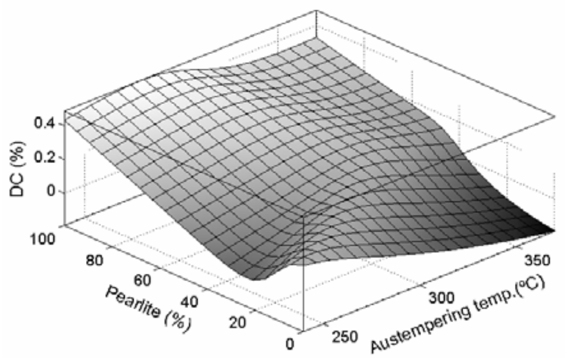


Figure 8. Influence of matrix microconstituents and austempering temperature on the DC

Despite of the coincidence between the predictions given by the model and other reported values, it is clear that practical limitations remained present in this model for test samples, due to: a) It has not considered the chemical composition, b) The previous matrix microstructures were selected in order to obtain controlled amounts of ferrite and pearlite, c) The shape and size of the samples are restricted to small prismatic and cylindrical bars.

**B. Prediction of DC for actual parts**

Figures 9 to 14 show some results given by the extended model. They allow to analyse the combined effect of the most important variables on DC at the industrial practise, and to help in the interpretation of the results given by the model (note that in the caption of each figure the values of the other variables are indicated).

Figure 9 shows the expected values of DC as a function of the austempering temperatures and *dim**. It can be seen that the tendency regarding the influence of the temperature is in coincidence with previous results showed in Fig. 6 and Fig. 7 (for the case of test samples), as well as with data reported by other authors (Moncada and Sikora, 1996; Echeverría *et al*., 2001).

The relationship between *dim** and DC is not obvious. It means that the lowest values of DC are waited for the largest dimensions. It is possible to speculate that the larger the part, the higher the amount of ferrite present in the matrix.

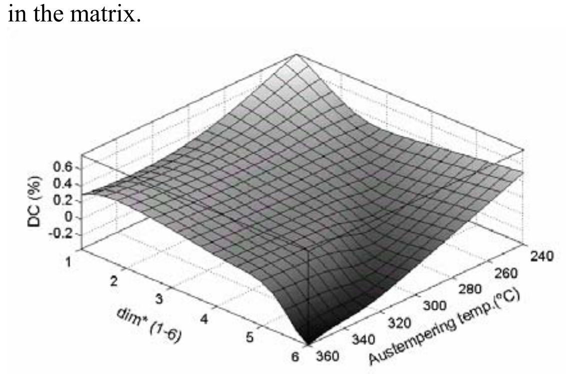


Figure 9. Influence of austempering temperature and *dim** on the DC for $T_\gamma$: 900, $t_\gamma$: 120, $t_a$: 100, Mn: 0.25, Cu: 0.5, Ni: 0.4, Mo: 0.21, Si: 2.8.

The influences of the main alloying elements on DC are shown in Fig. 10 to 12. Figure 10 shows that DC increases when the amount of Mn and/or Mo increase. Figure 11 shows a similar tendency for Cu, while the influence of Ni is light and variable. Figure 12 indicates that DC decreases when the amount of Si increases, but this effect disappears when Cu is present.

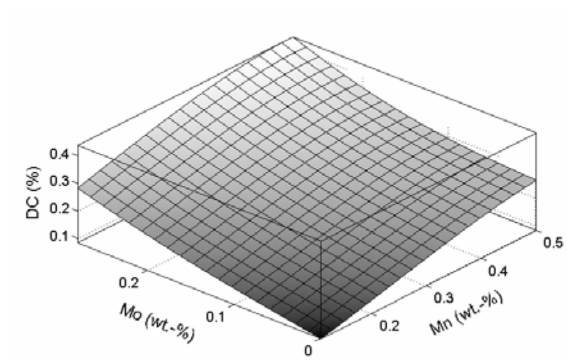


Figure 10. Influence of Mn and Mo on the DC for $T_\gamma$: 900, $t_\gamma$: 100, $T_a$: 330, $t_a$: 105, *dim**: 2, *Cu*: 0.515, *Ni*: 0.415, *Si*: 2.7.

The general knowledge indicates that Mn, Mo and Cu are alloying elements with a strong pearlitising effect, while Ni has a lower pearlitising tendency. On the other hand, Si is an effective graphitiser which promotes the precipitation of ferrite. Taking into account these metallurgical concepts, it is possible to attribute the variation of DC to the amounts of pearlite and ferrite present in the matrix before the ADI heat treatment, and therefore to the chemical composition of the alloy.

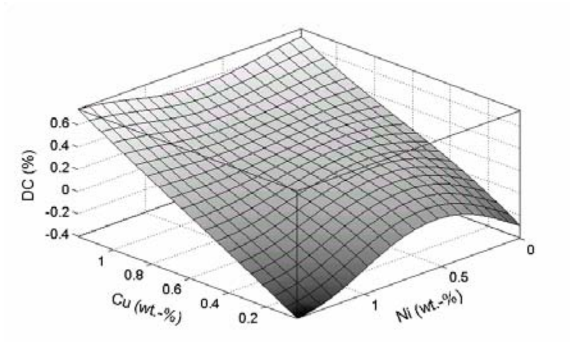


Figure 11. Influence of Cu and Ni on the DC for : $T_{\gamma}$: 910 , $t_{\gamma}$: 120, $T_a$: 320, $t_a$: 120, *dim**: 1, *Mn*: 0.2, *Mo*: 0.18, *Si*: 2.8.

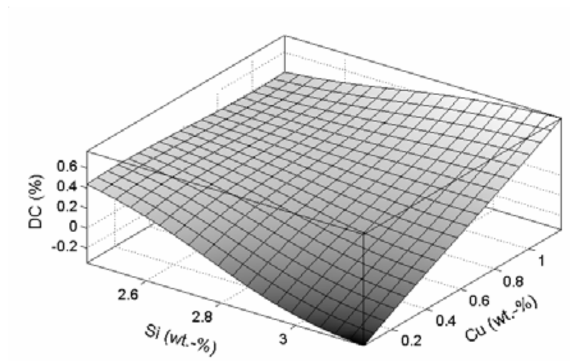


Figure 12. Influence of Cu and Si on the DC for $T_{\gamma}$: 910, $t_{\gamma}$: 110, $T_a$: 320, $t_a$: 120, *dim**: 1.5, *Mn*: 0.21, *Ni*: 0.15, *Mo*: 0.18.

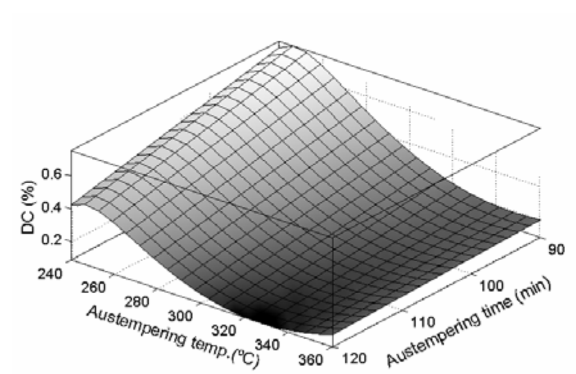


Figure 13. Influence of austempering temperature and holding time on the DC for $T_{\gamma}$: 910, $t_{\gamma}$: 120, *dim**: 2, *Mn*: 0.4, *Cu*: 0.4, *Ni*: 0.3, *Mo*: 0.14, *Si*: 3.

Figure 13 shows that when the austempering holding time increases DC decreases when low austempering temperatures are used. Figure 14 indicates that DC slightly increases when the austenitising temperature increases, as it was already reported (Moncada and Sikora, 1996). This figure also shows that the larger the value of *dim**, the smaller the DC.

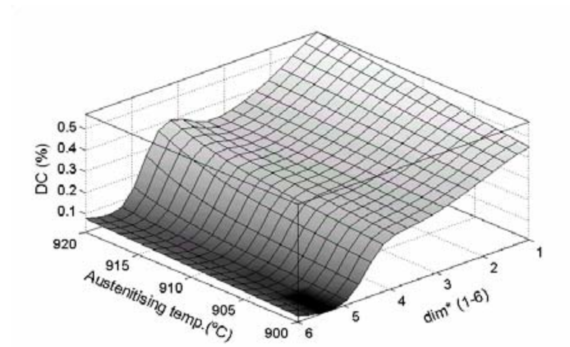


Figure 14. Influence of austenitising temperature and dim* on the DC for $t_{\gamma}$: 120, $T_a$: 280, $t_a$: 100, *Mn*: 0.2, *Cu*: 0.315, *Ni*: 0.115, *Mo*: 0.14, *Si*: 2.71.

Figure 15 allows the validation of the model considering the differences among calculated and actual DC values on several cases. The continuous line joins values of actual DC measurements ordered by its magnitude, and the points indicated as '+' are the corresponding output DC values calculated by the model. The approximation is satisfactory considering that the output values are inside the observed dispersion ranges.

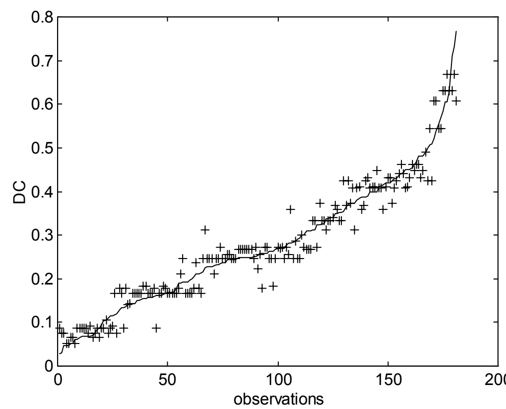


Figure 15. Difference among calculated and actual DC values.

As an example, Table 1 reports the average of the DC values given by the model for the three linear dimensions of several mill blades, as that schematized in Fig. 1, which were heat treated to obtain ADI Grade 4. The chemical composition of the melt, expressed as weight percent was: Mn=0,27; Cu=0,47; Ni=0,66; Mo=0,12 and Si=2,95. The thermal cycle involved the following heat treatment variables*: Tγ=920°C; tγ =180 min; Ta=270ºC and ta=90 min.* It is shown that the DC values predicted by the model are inside the dispersion range of the experimental data.

Table 1. Average DC% values in mill blades

| Linear dimension *(dim)* | Experimental DC dispersion range [%] | Output DC value from model[%] |
|---|---|---|
| L = 290 mm | 0,289 – 0,315 | 0,306 |
| W = 62 mm | 0,312 – 0,330 | 0,316 |
| t = 18 mm | 0,465 – 0,502 | 0,480 |

A careful analysis of a large amount of predictions provided by the extended model allows to conclude that many of them are in agreement with the tendencies reported in the literature and/or established by the preliminary model developed by using only test samples.

Moreover of the coincidences with other studies, the main goal of this model is that it gives novel predictions never considered before, for example, the influence of the main alloying elements on DC.

The model can be improved and extended by the addition of new experimental data. The zones that seem to have illogical values in some graphs are attributed to the absence of sufficient training data, or to the combination of variables without technical interest. This is the case for the values of DC smaller than 0.15% negative indicated in Fig. 11, for low contents of Cu combined with high amounts of Ni.

In summary, the model in the present state is considered a useful tool. It is being used to help in the qualitative and quantitative estimation of DC in the design of new components, including the case of thin wall ADI parts (Sosa *et al.*, 2001; Martínez *et al*. 2002).

## V. CONCLUSIONS

- The present study confirms the aptitude of fuzzy modelling as an appropriate methodology to model complex relational systems of industrial processes, in this case the prediction of DC in ADI on the basis of existing experimental data.
- The results obtained in a first simplified model, using only data taken from test samples, showed good agreement with the information reported in the literature. This model considered the influence of the austempering temperature, the matrix microstructure and the size of the “Y” blocks.
- A second and extended model was developed by using data taken from a large number of actual parts. This new model considered the influence of the austenitising and austempering temperatures and holding times, as well as the chemical composition and the part size. The model gives novel predictions, which were never considered before. The results are in good agreement with actual data, taking into account that the calculated values are inside the actual observed dimensional change ranges.
- A simplified analysis of the results given by the model shows that DC increases when the amount of pearlitisers elements, such as Cu, Mn and/or Mo, increase. On the other hand, DC decreases when the level of Si, the austempering temperature, the austempering holding time and the value of the linear dimension, increase.
- The model is considered a useful tool for the estimation of DC in actual ADI parts and it is being used in the design of new components.

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