Influence of the Dimensional Change, and Its Dispersion, on the Fabrication Size Tolerances of Austempered Ductile Iron (ADI) Parts: Comparison with SAE 4140 Steel

María D. ECHEVERRÍA, Osvaldo J. MONCADA and Jorge A. SIKORA

INTEMA, Faculty of Engineering, National University of Mar del Plata, Juan B. Justo 4302, (7600) Mar del Plata, Argentina.
E-mail: jsikora@fi.mdp.edu.ar.

(Received on April 17, 2000; accepted in final form on September 22, 2000)

To accurately satisfy the size tolerance of metallic parts, it is necessary to take into account the dimensional change (DC) caused by heat treatment, and the dispersion (ΔDC) of the DC values. The information available on this topic for ADI is very scarce.

The present work aims to determine DC and ΔDC on ADI and SAE 4140 steel parts and to analyze its influence on the size tolerances. Ductile iron and SAE 4140 steel specimens were used to compare DC and ΔDC caused by austempering, and quenching and tempering heat treatments. DC and ΔDC were also measured for several industrial parts of different ADI grades, having different chemical compositions, shapes and sizes.

The results show that in average ADI suffer greater DC than SAE 4140 steel parts of similar mechanical properties, but, on the other hand, ΔDC is always lower for ADI than for steel.

A more accurate prediction of the DC is then possible on ADI than on steels. This would allow the use of less strict machining tolerances, under better machinability conditions, when final operations can be done before heat treatment, producing series of ADI parts. This represents a technical and economical advantage for ADI in comparison with steel.

The influence that the previous microstructure, the austempering temperature and the piece anisotropy, exert on the DC of ADI were also studied. The effects identified in this work are in agreement with previously reported results.

KEY WORDS: dimensional change; dispersion of dimensional change; ADI and SAE 4140 steel; fabrication and machining tolerances; fabrication steps.

1. Introduction

The dimensional change (DC) caused by heat treatment of ductile iron and steel parts, is an important factor that must be taken into account to enable the final piece dimensions to be within the required size tolerance.

There is information in handbooks that allows to predict accurately DC of some steels.¹⁾ This is not the case for Austempered Ductile Iron (ADI). DC in ADI is difficult to predict because many variables affect its magnitude, and the available information is very scarce.²⁻⁴⁾ By the other hand, the machinability rating of ADI is lower than that of as-cast ductile iron,^{5,6)} and in consequence longer cutting time and higher cost must be considered if machining is to be done after heat treatment.

In a previous work, the authors of the present article pointed out the principal factors affecting DC , and gave quantitative information about its values for different ADI grades.⁷⁾ Complementary, the DC of many ADI industrial parts developed by the research group was systematically measured, and the results were introduced in a data base

which helps in the prediction of DC of new ADI pieces.

To define correctly the fabrication sequence of an ADI part, to be produced in a serial process, and to accurately establish its machining tolerance, it is necessary to take into account the dispersion of the DC values.

In fact, if the final machining of a piece is carried out before heat treatment, the predicted DC must be compensated by adjusting the nominal size (X), reaching the nominal machining size (X_m).

As it is indicated in **Fig. 1-a**), for $DC > 0$ it results:

$$X_m = X - DC \quad \dots\dots\dots(1)$$

In a serial production process the DC of a part can vary within a range, which amplitude is defined as the dispersion of dimensional change (ΔDC) (see **Fig. 1-b**).

In order to satisfy the size tolerance (T) (**Fig. 1-c**), the values of ΔDC must be considered to obtain the machining tolerance (T_m), indicated in **Fig. 1-d**, using the following expression:

$$T_m = T - \Delta DC \quad \dots\dots\dots(2)$$

Equation (2) means that when the smaller the value of ΔDC the larger the value of T_m , and in consequence the lower the precision requirements in the machining operations.

It is important to point out that DC only influences the magnitude of X_m , while ΔDC directly affects T_m , and in consequence the machining operation cost. For this reason it is desirable that ΔDC remains as small as possible. The influence of DC and ΔDC on the size tolerance of ADI and cast steel parts has not been analyzed in the literature, to the best of our knowledge.

Taking into account that many ADI parts could be also produced in heat treated SAE 4140 steel, because both materials cover similar fields of applications, the comparison of DC and ΔDC between them results of industrial interest.

The principal objectives of the present work are: a) To determine DC and ΔDC on ADI industrial parts, and experimental specimens of ADI and SAE 4140 steel of similar mechanical properties. b) To analyze the variables affecting DC in test specimens and industrial parts, and to compare them with other reported values.

2. Experimental Procedure

2.1. Specimens

Cylindrical bars of 11.5 mm diameter and 108 mm length were machined from "Y" blocks (ASTM A395) of ductile iron, and SAE 4140 cast steel, produced by industrial foundries by using conventional casting practices.

The chemical composition [wt%] of the ductile iron used was: C=3.40, Si=2.77, Mn=0.45, Cu=1.17, Ni=1.43, Mo=0.18, P=0.01, S=0.01, and Mg=0.04. The as-cast microstructure was predominantly pearlitic.

The chemical composition [wt%] of the cast steel was: C=0.43, Si=0.36, Mn=0.86, Cr=1.05, Mo=0.22, P=

0.027, S=0.025. It is important to point out that the steel was annealed by the steel foundry before delivery, and showed ferritic-pearlitic microstructure. Therefore, the dimensional change measured on the steel is that taking place as a result of the quenching and tempering of an annealed condition, and not of an as-cast condition.

The ductile iron specimens were heat treated to obtain two different ADI grades (grades 2 and 5 of ASTM 897-90), using the austenitizing and austempering temperatures and times indicated in **Table 1**.

The steel specimens were quenched in oil, and then tempered in order to obtain two different conditions (T1 and T2), as it is indicated in **Table 2**.

Table 3 lists the mechanical properties measured after heat treatment. The ADI grade 2 specimens have similar hardness and tensile strength than the steel with the heat treatment indicated as T1 in Table 2. A similar comparison can be done between ADI grade 5 and the steel treated according to T2.

2.2. ADI Industrial Parts

The chemical composition and predominant as cast microstructures of the industrial parts, are indicated in **Table 4**.

Four basic shapes can be recognized as follows:

- Tubes (internal gears of four different sizes) Fig. 2-a)
- Plate cams: (thin cams with similar sizes) Fig. 2-b)
- Rectangular bars: (mill blades with similar sizes) Fig. 2-c)
- Disks with hub: (thin, medium and thick) Fig. 2-d)

The austenitizing and austempering temperatures and times, used for the heat treatment of the parts, are indicated in **Table 5**.

2.3. Measuring Method

All industrial parts and specimens were carefully measured before and after heat treatment in order to determine the DC . A Coordinate Measuring Machine, with a linear displacement accuracy of $2.5 + 4L/1000 \mu\text{m}$, and a Measuring Repeatability of $4 \mu\text{m}$ was used.

The number of samples, necessary to obtain comparative results, was determined using statistical analysis. An

Fig. 1. Influence of DC and ΔDC on the piece dimensions and the machining tolerance. 1-a, correction taking into account DC ; 1-b, standard deviation ΔDC ; 1-c, size tolerance (T); 1-d, machining tolerance (T_m).

Table 1. Experimental specimens of ADI: Thermal cycles.

Material	ADI grade 2	ADI grade 5
Austenitizing	900°C - 60'	920°C - 60'
Austempering	360°C - 90'	280°C - 120'

Table 2. Experimental specimens of SAE 4140 steel: Thermal cycles.

Heat-treatment	T1	T2
Quenching	850°C - 60'	850°C - 60'
Tempering	620°C - 60'	445°C - 60'

Table 3. Mechanical properties of experimental specimens.

Propertie	ADI Grade 2	ADI Grade 5	SAE 4140 T1	SAE 4140 T2
Tensile strength σ_R [Mpa]	1133	1450	1180	1530
Hardness [HRC]	38	47	36	46

Table 4. As-cast microstructure and chemical composition of industrial parts.

PART / TIPE (*)	Microstructure	Mn	Cu	Ni	Mo	Si
Internal gears I (a)	Ferritic	0.5	<0.10	<0.10	<0.10	2.96
Internal gears II and IV (a)	Pearlitic-ferritic	0.29	0.49	0.69	0.12	3.26
Internal gears III (a)	Pearlitic-ferritic	0.27	0.47	0.66	0.18	3.17
Plate Cams (b)	Pearlitic-ferritic	0.31	0.98	1.06	0.18	2.68
Mill blades I (c)	Pearlitic-ferritic	0.36	0.82	0.50	0.14	3.06
Mill blades II (c)	Pearlitic-ferritic	0.36	0.82	0.50	0.14	3.06
Mill blades III (c)	Pearlitic-ferritic	0.27	0.47	0.66	0.12	2.95
Disks with hub, thins (d)	Pearlitic	0.36	1.19	0.58	0.23	2.59
Disks with hub, mediums (d)	Pearlitic-ferritic	0.36	1.19	0.58	0.23	2.59
Disks with hub, thicks (d)	Ferritic-pearlitic	0.36	1.19	0.58	0.23	2.59

(*) (a) Tubes (b) Plate cams (c) Rectangular bars (d) Disks with hub.
 Always 3[% C]3.5; 0.033[% Mg]0.048; % P[0.03; S[0.02

Fig. 2. Basic shapes of industrial parts: a) tubes (internal gears), b) plate cams, c) rectangular bars (mill blades), d) disks with hub.

Table 5. Industrial parts: Thermal cycles.

PART	Austenitizing	Austempering	ADI Grade
Internal gears I	910°C – 90'	300°C – 120'	2
Internal gears II to IV	910°C – 90'	310°C – 90'	2
Plate cams	920°C – 120'	280°C – 120'	3
Mill blades I	920°C – 120'	260°C – 120'	4
Mill blades II	920°C – 120'	220°C – 120'	5
Mill blades III	920°C – 180'	270°C – 90'	4
Disks with hub (all of them)	900°C – 60'	360°C – 90'	1

amount of $n=10$ industrial parts, or test specimens, was adopted for each variable studied (chemical composition, microstructure, shape, size and austempering temperature).

The percent Dimensional Change, ($DCi\%$), of each specimen or part dimension (X), was calculated using the measured actual values before (Xo), and after (Xf) heat treatment, following the expression:

$$DCi\% = 100[(Xf - Xo)/Xo] \quad (3)$$

The average Dimensional Change, $DC\%$, of any dimension of a batch of n pieces, was calculated as:

$$DC\% = \sum_{i=1}^n (DCi\%) / n \quad (4)$$

and the standard deviation $\Delta DC\%$, as:

$$\Delta DC = \sqrt{\sum_{i=1}^n [(DCi\% - DC\%)^2] / n} \quad (5)$$

The values of ΔDC , used to calculate the machining toler-

ances Tm , are expressed in units of length, [mm] or [μm], as follows:

$$\Delta DC [mm] = Xo \Delta DC\% / 100 \quad (6)$$

3. Results and Discussion

3.1. DC and ΔDC in Industrial ADI Parts

Table 6 lists the results of $DC\%$ and $\Delta DC\%$ for the different industrial ADI parts, previously described in Fig. 2 and Tables 4 and 5.

The DC values, as a consequence of the different chemical composition, heat treatment cycles, shape, microstructure, etc., show important differences, ranging from 0.04 to 0.53%, for the different parts. Nevertheless the values of ΔDC were consistently small, and they fluctuate within a narrow range. The exception are those values corresponding to the smaller measured dimensions, where the higher fluctuation can be attributed to a larger influence of the measuring error (for example in the case of thickness of internal gears II, III and IV reported in Table 4).

Table 6 lists the values of ΔDC [μm] calculated by using Eq. (6).

The machining tolerance (Tm), which could be obtained when using CNC lathes (accuracy: $\pm 5 \mu m$) or CNC Machining Centers (accuracy: $\pm 15 \mu m$) compatible with the machining equipment, must be added to the ΔDC value in order to calculate the minimum size tolerance ($Tmin$).

Table 6 also lists the equivalent IT ISO standard tolerance grades,⁷⁾ in correspondence with the mentioned $Tmin$ values.

3.2. DC and ΔDC for Experimental Specimens of ADI and SAE 4140 Steel

Table 7 shows the results of $DC\%$ and $\Delta DC\%$ for the length and diameter of the ADI and SAE 4140 steel specimens, previously indicated in Tables 1 and 2.

Figure 3 shows the values of $DC\%$ and $\Delta DC\%$ for the length of ADI and steel specimens. Figure 3(a) corresponds to ADI grade 2 and SAE 4140 steel with heat treatment identified as T1 (Table 2). Figure 3(b) compares the values for ADI grade 5 and the steel with treatment T2.

The results show that the dimensional changes are higher for ADI than for steel. This only implies that the nominal machining size Xm (Fig. 1-a) must be different for each material, but it does not influence the machining tolerance (Tm) (Fig. 1-d), because Tm is independent from DC , and is

Table 6. Average results of DC and ΔDC of industrial parts. IT-ISO tolerance grades obtainable by CNC machining processes.

Part	Dimension		DC [%]	ΔDC [%]	ΔDC [μm]	Minimum size tolerance (T_{min}) [μm]		Equivalent IT ISO standard tolerance grade		ADI Grade
	Type	[mm]				CNC-L	CNC-MC	CNC-L	CNC-MC	
Internal Gears I	Length (L)	53	0.087	0.012	6	11	-	7	-	2
	Ext. Dia. (D)	105	0.056	0.014	15	20	-	8	-	
Internal Gears II	Thickness (e)	9.5	0.371	0.041	4	9	-	8	-	2
	Length (L)	58	0.187	0.042	24	29	-	9	-	
	Ext. Dia. (D)	105	0.230	0.049	51	56	-	10	-	
Internal Gears III	Thickness (e)	9.5	0.302	0.050	5	10	-	8	-	2
	Length (L)	82	0.237	0.034	28	33	-	9	-	
	Ext. Dia. (D)	105	0.221	0.026	27	32	-	9	-	
Internal Gears IV	Thickness (e)	9.5	0.405	0.070	7	12	-	9	-	2
	Length (L)	38	0.193	0.034	13	18	-	8	-	
	Ext. Dia. (D)	105	0.222	0.041	43	48	-	10	-	
Plate Cams	Thickness (e)	22	0.425	0.030	7	12	-	8	-	3
	Hole Dia. (d)	44	0.344	0.025	11	16	-	8	-	
	Hub Dia. (D ₂)	80	0.370	0.010	8	13	-	7	-	
	Ext. Dia. (D ₁)	263	0.367	0.013	34	-	49	-	9	
Disks With hub Thins	Thickness disk (e ₂)	10	0.373	0.018	2	7	-	7	-	1
	Thickness hub (e ₁)	25	0.432	0.017	4	9	-	7	-	
	Hub Dia. (D ₂)	53	0.236	0.020	10	15	-	7	-	
	Ext. Dia. (D ₁)	147	0.275	0.010	15	20	-	7	-	
Disks With hub Mediums	Thickness disk (e ₂)	21	0.163	0.027	6	11	-	8	-	1
	Thickness hub (e ₁)	47	0.191	0.027	13	18	-	8	-	
	Hub Dia. (D ₂)	54	0.102	0.017	9	14	-	7	-	
	Ext. Dia. (D ₁)	148	0.085	0.013	19	24	-	8	-	
Disks With hub Thicks	Thickness disk (e ₂)	40	0.042	0.017	7	12	-	7	-	1
	Thickness hub (e ₁)	82	0.100	0.010	8	13	-	7	-	
	Hub Dia. (D ₂)	53	0.077	0.021	11	16	-	8	-	
	Ext. Dia. (D ₁)	147	0.038	0.014	21	26	-	8	-	
Mill Blades I	Thickness (b)	18	0.532	0.030	5	-	20	-	9	4
	Width (a)	62	0.432	0.010	6	-	21	-	8	
	Length (L)	360	0.475	0.032	115	-	130	-	11	
Mill Blades II	Thickness (b)	18	0.440	0.030	5	-	20	-	9	5
	Width (a)	62	0.412	0.017	11	-	26	-	9	
	Length (L)	360	0.416	0.021	76	-	91	-	10	
Mill Blades III	Thickness (b)	19	0.490	0.025	5	-	20	-	9	4
	Width (a)	64	0.460	0.030	19	-	34	-	9	
	Length (L)	395	0.410	0.032	126	-	141	-	11	

CNC-L: Numerical control lathes. CNC-MC: Numerical control machining centers

Table 7. Results of DC and ΔDC for experimental specimens.

Material	DC %		ΔDC %	
	Diameter (D)	Length (L)	Diameter (D)	Length (L)
ADI grade 2	0,186	0,158	0,036	0,026
ADI grade 5	0,347	0,300	0,027	0,028
SAE 4140 T1	0,051	0,029	0,060	0,041
SAE 4140 T2	0,062	0,039	0,043	0,031

only influenced by ΔDC . Then, the higher values of DC for ADI do not imply a disadvantage for ADI, nor the smaller amounts of DC imply an advantage for steel.

ΔDC values were consistently lower for ADI than for steel, and, as it was shown in Fig. 1-d), ΔDC is an important factor that directly affects T_m . This indicates that the use of ADI allows to have a higher T_m than those obtainable when SAE 4140 steel is employed (Fig. 4). This, in fact, could lead to economic benefits in a serial production process, since ADI parts have better possibilities to satisfy T_m , in the previous machining before the heat treatment, than steel parts. Nevertheless it is important to point out that this advantage could not be real if any variable of the process modifies the DC average for ADI. For this reason, it is necessary to have under control the variables affecting DC .

The low value of ΔDC seems to be characteristic of ADI, since this observation has been consistently valid along the great number of measurements carried out for each type of piece, and even after significant changes in the operating variables were considered (chemical compositions, as-cast microstructures, ADI grades, and shape and size of the

parts used in the present study).

3.3. ΔDC as a Decisive Factor to Determine the Fabrication Steps

Taking into account the following factors: size tolerance (T), machining tolerance (T_m) and dimensional accuracy of the machining process (DA), the value of ΔDC allows to decide whether the final machining operation of a part can be carried out before, or must be done after heat treatment.

When ΔDC is greater than the size tolerance T , the machining tolerance T_m disappear, and it is necessary a final machining step after heat treatment, working under worse machinability conditions.

When ΔDC is lower than the size tolerance T , there can be three different situations:

- T_m is greater or equal than DA : In this case the final machining can be made before heat treatment, making use of the best machinability conditions.
- T_m is lower than DA : In this case a higher precision machining procedure can be used, if available, which involves higher cost.

Fig. 3. DC and ΔDC for the length (L) of ADI and SAE 4140 steel specimens.

Fig. 4. Comparative values of ΔDC and T_m for ADI and SAE 4140 steel.

c) T_m is much lower than DA : In this case it is impossible to reach the required tolerance, and it will be necessary to carry out the final machining step after heat treatment, working under the worse machinability conditions, and the use of grinding may be necessary.

In summary, it is desirable that ΔDC remains as lower as it is possible.

3.4. Influence of the Previous Microstructure, Heat Treatment Variables and Anisotropy, on the DC of ADI

Table 6 shows that the internal gears, identified as I in Table 4, have lower DC than the other gears. Also the disks with hub show lower DC than the medium and thin disks. This implies that, for the same grade of ADI, the parts having a ferritic matrix before heat treatment show lower DC than those having pearlitic matrix. Figures 5(a) and 5(b) show DC of one dimension of the mentioned parts. This results are in coincidence with previous reports.⁷⁾

For the same previous microstructure the DC for specimens of ADI grade 2 was lower than that of ADI grade 5 ones. The same behavior was observed for the DC of the industrial parts reported on Table 6. Note, for example, that

Fig. 5. Effect of previous microstructure on DC: 5-a, dimension (D) of internal gears; 5-b, dimension (D_1) of disks with hub.

Fig. 6. Influence of ADI grade on DC (qualitative scheme).

Fig. 7. Anisotropic behavior of DC.

the medium disks with hubs made in ADI grade 1 show lower DC than the plate cams of ADI grade 3. A similar comparison can be done for the mill blades I and II of ADI grades 4 and 5 respectively. This results are also in coincidence with other studies, as it is shown in Fig. 6.^{7,9)}

Comparing the DC values of all the industrial parts indicated in Table 6 and Fig. 7, it is clear that the smaller the measured dimension, the higher the value of DC . This results also confirm a similar tendency observed by the authors in a previous work, where this anisotropy was found to be maximum for very different dimensions located in or-

thogonal directions.^{7,9)}

4. Conclusions

(1) Typically, ADI parts suffer larger DC than SAE 4140 steel parts of similar mechanical properties. On the other hand, the standard deviation values of the dimensional change (ΔDC) were always lower for ADI than for steel.

(2) The low value of ΔDC seems to be characteristic of ADI, since this observation has been consistently valid along the great number of measurements carried out for each type of piece, and even after significant changes in the operating variables were considered.

(3) Being ΔDC an important factor that directly affects T_m , the use of ADI allows to have a higher T_m than those necessary when SAE 4140 steel is employed. This, in fact, could lead to economic benefits in a serial production process, since ADI parts have better possibilities to satisfy T_m , in the previous machining before heat treatment.

(4) The results of this study confirm previous reports referred to the influence that the prior microstructure, the austempering temperature and the piece anisotropy, exert on the DC of ADI.

Acknowledgements

Financial support received from FONCYT (grant 1252)

and from the National University of Mar del Plata and CONICET, are gratefully acknowledged.

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