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Some Aspects of Hot Forging Characteristics Of Sintered Ultra – High Strength Ring Preforms

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Abstract: - Present investigation pertains to assess the hot upset mode of forging characteristics of sintered P/M ring preforms of iron and AISI 4340 P/M steels containing 0.80, 1.20 and 1.60 percent chromium. P/M rings of iron and AISI 4340 grade of blended powders were prepared using suitable die set assembly on a 1.0 MN capacity hydraulic press. The ring geometries were maintained to outer Diameter: Inner Diameter: Height:: 8:4:2 and density in the range of 86 ±1 per cent of theoretical by employing controlled pressure in the range of 480 ±10 MPa and taking pre-weighed powders. These ring preforms were coated with indigenously developed ceramic coating to protect them against oxidation during sintering. These preforms were sintered in an electric muffle furnace at $1150^0 \pm 10^0$C for a period of 100 minutes and subsequently hot upset forged to different height strain levels and quenched in linseed oil. Residual ceramic coating was gently machined off followed by dimensional and density measurements. Analysis of the experimental data has revealed that the rate of densification followed the second order polynomial of the form: $Y = a_0 + a_1X + a_2X^2$; Where, Y = fractional theoretical density achieved, i.e., (ρ_f/ρ_{th}), X = the fractional height deformation. The values of 'a_0', 'a_1' and 'a_2' were dependent upon the composition. Further, the effect of chromium content in AISI 4340 steel was negligibly small on the relationship between per cent decrease in I.D. and the per cent height reduction.

Keywords: - *AISI 4340, Coated, Deformation, Geometries, Hot, Muffle Furnace, Preforms, Sintered, Ring, Upset,*

I. INTRODUCTION

Ring compression test was technically developed to characterize the lubricants during metal forming operations. This test involves in the measurement of the change in inner diameter of a ring of specific O.D.: I.D.: Ht. geometry during axial deformation and the same is employed to assess the friction factor and the effectiveness of lubrication [1]. Therefore, a complex mode of measuring forces is not necessarily required instead inward or outward flow of ring material during compression is of a great significance. Inward or outward flow of the ring material with respect to the inner diameter would depend upon the lubricating conditions prevalent between the die and the ring preforms contact surfaces. However, Male and Pierre [2] extended the ring test for the determination of flow stresses of cent per cent dense materials. But, Dulton et.al [3] have attempted the ring test on porous materials while considering the complexities in densification of rings during compression due to intricate nature of the shrinkages of pores their closure mechanisms and their movement kinetics. Few research publications [4-6] on P/M ring deformation with emphasis on densification mechanisms are available Rao and Pandey [7] have developed a relationship between density and the geometric parameters of a ring preforms initial and final parameters inclusive of their initial and final densities. Further, Han et.al [8] had also studied the deformation behaviour of rings under compression and developed the following relationships for plastic Poisson's ration (γ_p) and density change as given underneath:

$$\gamma_p = -[(d_0\text{-}dr_i) / (r_0 - r_i)]/(dh/h) \text{ ----- ----- -------- (1), and,}$$
$$(d\rho/\rho) = - [\{2(r_0dr_0\text{-}r_idr_i) / (r_0^2\text{-}r_i^2)\} + (dh/h)] \text{ ------ ------ ------ (2)}$$

It has been reported elsewhere [9-12] that initial geometric ratio of the ring preforms and lubrication affected densification during cold compression of sintered Al – Cu rings. Rao and Pandey [5] have reported that the application of graphite as lubricant during cold axial compression of Al – Cu sintered ring preforms led to decrease in inner diameter (flow reversal) which is an indication of pore flattening and their collapse. However, the ring preforms under compressive forces would experience frictional shear forces along the lateral direction –directed radially inward which help the pores to flatten out. Rao and Pandey [5, 6] have reported that the rings of higher geometric ratios have shown enhancement in densification rate and crushing strengths. Deformation behaviour of P/M rings dealing with the prediction of friction and its evaluation, a mathematical and finite elemental analysis, influence the flow stresses and friction upon characteristic behaviour of metal flow are described elsewhere [13-25] in detail.

The present investigation is an attempt to evaluate the upset mode of ho forging characteristics of iron and AISI 4340 P/M steels containing 0.80, 1.20 and 1.60 per cent chromium. Attempt is also made to evaluate the densification mechanism and its dependence upon the chromium addition in AISI 4340 steel.

II. EXPERIMENTAL DETAILS

II.1 Materials Required

Atomized iron powder of -180µm was obtained from m/s Hoeganaes India Limited Hyderabad, Andhra Pradesh, India and the graphite powder of 3-5µm was supplied by m/s Ashbury Graphite Mills Inc., Ashbury Warren County, New Jersey, USA. Chromium powder (-37µm), molybdenum powder (-37µm), nickel powder (-37µm) were obtained from m/s Ghrishma Specialty powder Materials, Mumbai, India and silicon powder (-37µm) was procured from the m/s The Metal Powder Company, Thirumangalam, Madurai, Tamil Nadu, India. The chemical analysis of chromium, molybdenum, manganese, and nickel including silicon powder yielded 99.59, 99.57, 99.85, and 99.33 percent respectively. Remaining 0.41, 0.43, 0.62, 0.15 and 0.67 per cent respectively were the insoluble impurities in them individually. The basic characteristic of iron powder and AISI 4340 steels with 0.80, 1.20 and 1.60 per cent chromium contents independently prepared as blends are given in Table 1 along with the sieve size analysis of the base iron powder.

Table 1 Characteristics of Iron Powder, AISI 4340 **with 0.8, 1.20 and 1.60 Percent Chromium Separately.

Sl. No.	Property	Systems			
		Iron	AISI4340-0.80Cr	AISI4340-1.20Cr	AISI4340-1.60Cr
1.	Apparent Density, g/cc	2.93	2.91	2.87	2.87
2.	Flow rate by Hall Flowmeter, Sec/50g	25.00	26.30	27.25	28.00
3.	Compressibility, g/cc at a pressure of 480±10Mpa	6.652	6.665	6.672	6.678

4. Sieve Size Analysis of Iron Powder

Sieve Size in µm	-180 +150	-150 +125	-125 +106	-106 +90	-90 +75	-75 +63	-63 +53	-53 +45	-45 +38	-38
Wt % Ret.	1.43	13.40	8.08	1.22	22.28	13.59	13.22	6.75	1.63	19.35
Cum, Wt. % Ret.	1.43	14.83	22.91	23.13	45.41	59.00	72.22	78.97	80.60	99.95

AISI 4340 standard composition: Fe- 0.4%C – 0.25%Si – 0.75%Mn – 0.25%Mo – 1.90%Ni – 0.80%Cr.**

II.2 Powder Blending

Three powder mixes corresponding to final compositions as given below were prepared on a potmill by taking pre-weighed elemental powders for each compositions corresponding to P, Q and R respectively:

P=Fe-0.4%C–0.25%Si–0.75%Mn–0.25%Mo–1.90%Ni–0.80%Cr,

Q=Fe-0.4%C-0.25%Si–0.75%Mn–0.25%Mo–1.90%Ni–1.20%Cr,

R= Fe-0.4%C–0.25%Si–0.75%Mn–0.25%Mo–1.90%Ni–1.60%Cr.

Three different compositions of steels as stated above were taken separately in stainless steel pots with the powder mix weights to porcelain balls (10-15mm diameters) weights ratio of 1.2:1.0 and the same was fixed on the pot mill after securely tightening their lids. The blending operation was carried out for a period of 30 hours.

The homogeneity of the powder blends were established by conducting hourly tests for flow rates and apparent densities by taking out separately approximately 100±10g of powder mixes from each pot and returning the same back to respective pots after carrying out the aforementioned tests and re-tightening the lids, the pots were fixed on the potmill and the blending operation was continued. Once the flow rates and apparent densities for respective blends were found to be consistent in the last three tests, the blending operation was discontinued. Thus, the blending time turned out to be 36 hours which was good enough to attain homogeneity in the respective powder blends.

II.3 Green Compacts Preparation and Application of Ceramic Coating

Green compacts of ring geometry, i.e. O.D.: I.D.: Height as 8:4:2 were prepared from iron powder and powder blends P, Q and R respectively on a 1.00MN capacity Universal Testing Machine using suitable die, hollow punch, core rod and bottom inserts. The powder compaction assembly is shown in figure-1. The initial ring preform

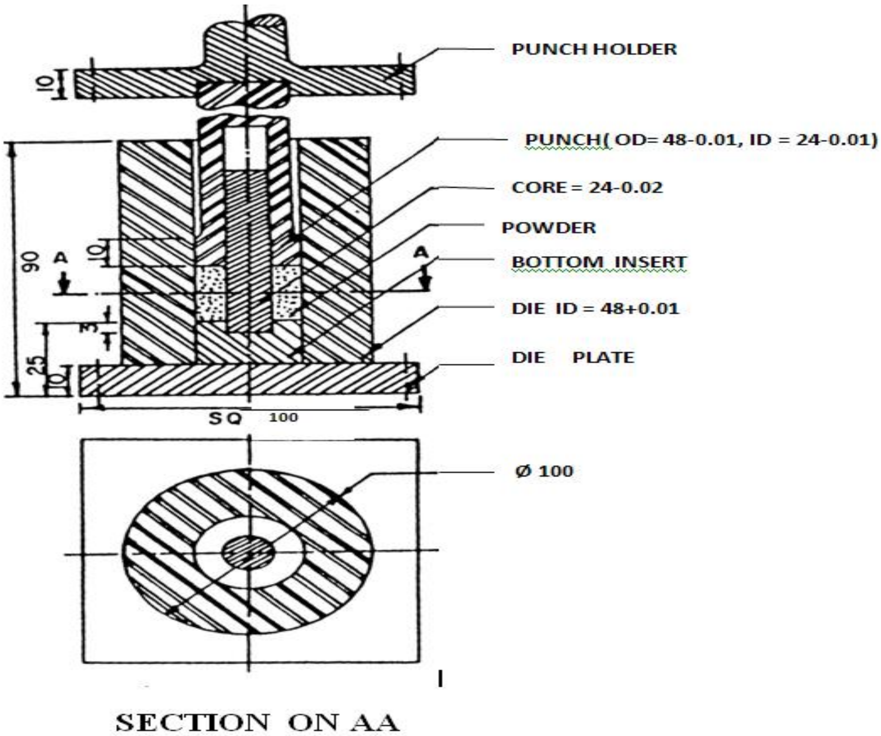

Figure 1 Die Assembly for Compaction of Powder Preforms

densities were maintained in the range of 86±1 per cent of theoretical by employing a pressure in the range of 480±10M Pa. The inner,, outer, the top and bottom ring surfaces were coated by indigenously developed ceramic coating [26] in order to protect the ring preforms during sintering against oxidation. However, the applied ceramic coating was dried under the ambient conditions for a period of sixteen hours followed by recoating the ring preform 90^0 to the previous coating. The second coating was dried for a further period of sixteen hours under the ambient conditions. During compaction specially prepared graphite paste with acetone was used as lubricant to avoid powder sticking but for easy ejection so as to obtain damage free ring compacts.

II. 4 Sintering of the Ceramic Coated Ring Compacts and Hot Upset Forging

Ceramic coated ring compacts of each system were separately sintered in an electric muffle furnace for a period of 100 minutes in the temperature range of 1150 ± 10^0 C. The sintering schedule included pre-heating of the compacts 1n the temperature range of 750 ± 10^0 C and holding them at this pre-heat temperature for a period of nearly 60 minutes in order to avoid any accidental bursting of ring compacts during actual sintering operation in accordance with the reported results elsewhere [27]. Immediately after the completion of pre-heating operation, the furnace temperature was raised to 1150 ± 10^0 C and was retained at this temperature for a period of 100 minutes. A minimum of eleven (11) ring preforms were sintered for each system. Ten out of eleven sintered P/M ring preforms were hot upset forged to different height strains and the same were quenched in linseed oil. One sintered ring of each composition was cooled to room temperature inside the furnace itself by switching off the furnace. All forged and oil quenched rings were cleaned off oil, and, subsequently the residual ceramic coatings were removed by mild rubbing with emery papers are fine files so as to use them for dimensional and density measurements. Three main measurements were required and they were namely, deformed inner diameters, outer diameters and the forged heights. In some rings negative barreling was observed. Density measurements of sintered rings were carried out by finding out the mass in air and the volume by geometrical calculations where as the density of forged rings were found out by employing Archimedian principle by adopting the technique described elsewhere [28]. Using the initial and the dimensions of the forged rings, various parameters were calculated and used to plot different plots.

III. RESULTS AND DISCUSSION

III. 1 Axial Hot Upset Forging and Densification

Figure-2 has been drawn in order to evaluate the relationship between fractional theoretical density (ρ_f/ρ_{th}) and fractional height reduction. While observing this figure-2 it is found that curve corresponding to iron

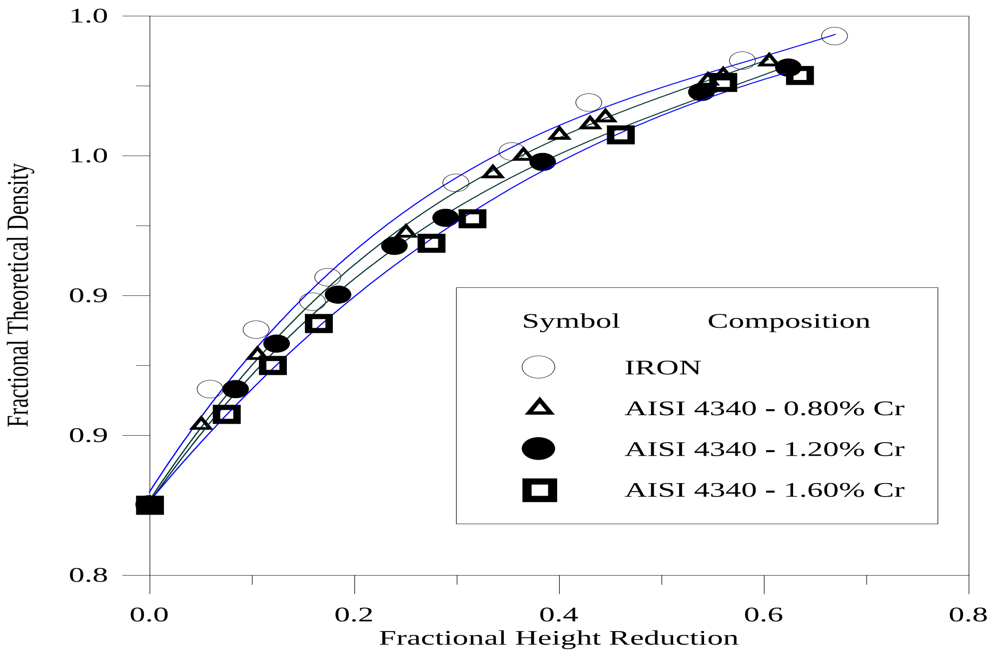

Figure 2 Relationship Between Fractional Density and the Fractional Height Reduction During Hot Forging of Sintered P/M Steel Ring Preforms of Initial Preform Geometry.

has densified at the much faster rate compared to all other compositions of AISI4340, namely, AISI 4340 with 0.80%CrAISI 4340 with 1.20%Cr and AISI 4340 with 1.60%Cr steels respectively. Further, it is found that the curve corresponding to AISI 4340 with 1.60%Cr densified at the least rate compared to other chromium additions, namely, 0.80% and 1.20% respectively. The characteristic natures of these curves are found to be similar,and, they mathematically conformed to a second order polynomial of the form:

$$(\rho_f/\rho_{th}) = a_0 + a_1 (\Delta H/H_0) + a_2 (\Delta H/H_0)^2,$$

Where, ‘a_0’, ‘a_1’ and ‘a_2’ are found to be empirically determined constants. These constants are tabulated in Table 2.

Table 2 Coefficient of the second order polynomial of the form:
$(\rho_f/\rho_{th}) = a_0 + a_1 (\Delta H_f/H_0) + a_2 (\Delta H_f/H_0)^2$

Sl. No	System	Coefficients			Regression Coefficient R^2
		a_0	a_1	a_2	
1	Iron	0.86360	0.45610	-0.62653	0.99498
2	AISI 4340-0.8%Cr	0.86120	0.44250	-0.59682	0.999451
3	AISI 4340-1.2%Cr	0.86070	0.41571	-0.54453	0.999422
4	AISI 4340-1.6%Cr	0.86095	0.35201	-0.31813	0.99861

The values of ‘a_0’ are found to be in very much close proximity to the initial preform densities, and, hence, they do not contribute to densification, whereas, the constant ‘a_1’ is positive and linearly multiplied to the fractional height reduction and, therefore, contributes linearly to densification. However, the constant 'a_2' is always negative and of very low magnitude and the same is multiplied by the square of the fractional height reduction, i.e., $(\Delta H/H_0)^2$ and thus, the term $a_2(\Delta H/H_0)^2$ becomes a value of very low magnitude and plays a role in plateaueing the curves in their final stages of densification. Since in all cases, the value of the regression coefficient 'R^2' is in extremely close proximity to unity, and, hence, the second order polynomial's correspondences to the actual data points are justified. Further, it can be safely said that the constants 'a_0', 'a_1' and 'a_2' depend upon the initial preform geometry and their composition, i.e., the composition of each system independently. However, the values of the regression coefficient (R^2) in each case are found to be much beyond 0.99, i.e., in close proximity to unity. Therefore, the relationship exhibiting a second order polynomial stands justified.

III.2 Relationship Between (ΔDi/Di) and ($\Delta H/H_0$)

Figure-3 is a plot drawn between the fractional decrease in inner diameter (ΔDi/Di) and fractional height reduction during hot upset forging of sintered iron, and AISI 4340 steel ring preforms with 0.80%Cr, 1.2%Cr and1.6%Cr addition independently. The fig.3 further shows that the characteristic nature of each curve is similar to each other, and, therefore, they can be represented by a similar type of mathematical expressions.

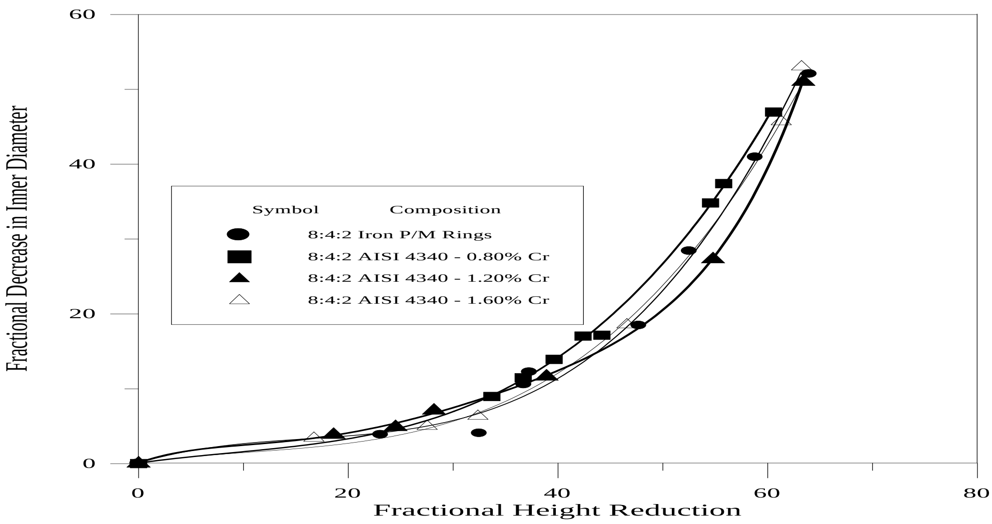

Figure 3 Relationship between Fractional Inner Diameter Decrease and Fractional Height Reduction of 8:4:2 Ring geometry Preforms of Sintered P/M Steels during Hot Upset Forging

Hence, an attempt has been made to evaluate each of these curves, and, it has been found out that the best fitting expression is a third order polynomial of the form:

$$(\Delta Di/Di) = b_0 + b_1(\Delta H/H_0) + b_2(\Delta H/H_0)^2 + b_3(\Delta H/H_0)^3 \text{ ---- ------ ------ } (3)$$

Where, 'b_0', 'b_1', 'b_2' and 'b_3' are found to be empirically determined constants and they also were observed to depend upon the steel compositions. The addition of chromium in different proportions, i.e., 0.80%, 1.2%, and 1.6% separately in AISI4340 steel revealed the mixed response as far as the relationship between fractional decrease in inner diameter and the fractional height reduction is concerned. These constants 'b_0', 'b_1', 'b_2' and 'b_3'are tabulated in Table-3. Since the values of regression coefficient in each case was found to be beyond 0.99, and, therefore, the curve fitting has been done accurately and reliably.

Table 3 Coefficient of the Third order polynomial of the form:
$(\Delta Di/Di) = b_0 + b_1(\Delta H/H_0) + b_2(\Delta H/H_0)^2 + b_3(\Delta H/H_0)^3$

Sl. No.	System	Coefficient of the polynomial				Regression Coefficient, R^2
		b_0	b_1	b_2	b_3	
1.	Iron	0.2452	0.20537	-0.009725	0.00030105	0.9921
2.	AISI 4340-0.8%Cr	0.0077	0.19923	-0.000751	0.000283	0.9985
3.	AISI 4340-1.2%Cr	0.0024	0.52108	-0.047373	0.00235	0.9948
4.	AISI4340-1.6%Cr	0.00730605	0.42307	-0.020566	0.0004258	0.9993

IV. CONCLUSIONS

Based on the experimental data and calculated parameters and various plots constructed and their critical analysis has led to the following main conclusions:

1. Visual observation has established that up to sixty per cent (60%) of height reduction of the rings, there was no appearance of any surface cracks irrespective of the compositions investigated.
2. Fractional theoretical density and fractional height reduction were related with each other by a second order polynomial of the form: $(\rho_f/\rho_{th}) = a_0 + a_1 (\Delta H/H_0) + a_2 (\Delta H/H_0)^2$, where, ‘$a_0$’, ‘$a_1$’ and ‘$a_2$’ are found to be empirically determined constants. These constants were found to depend upon the compositions of the systems. ‘a_0’ did not contribute to densification as the same was found to be almost the initial density of ring preforms, whereas, the constant ‘a_1’ contributed to densification linearly, and, the low negative values of ‘a_2’assisted in flattening the densification curves in their final stages. Nearly unity was the regression coefficient (R^2) which has clearly established the perfect curve fittings.
3. Addition of chromium exhibited the mixed response on the relationship between fractional I.D. decrease and the fractional height reduction. However, these curves were found to conform to a third order polynomial exhibiting best curve fit.

Thus, the finding of the present investigation can be successfully utilized for forging of sintered rings for ball-bearing races and spur gears with appropriate tool design economically.

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