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Mechanical Failures and Design of High Pressure Die Casting Tools

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ABSTRACT

The horizontal cold chamber pressure die casting produces a variety of net shape, complicate-geometry castings with desired mechanical properties, dimensional tolerance, and surface finish. However, top quality castings can be achieved only when optimal performance of the cold chamber (shot sleeve) and plunger is maintained during the molten metal injection phase of the process. Unfortunately, in reality, shot sleeves deteriorate fast and sometimes fail catastrophically due to incorrect design. These early and unexpected failures of shot sleeves cost die casters money and productivity. To prevent premature failures of shot sleeves major failure mechanisms were investigated. With the aid of analytical solutions robust design criteria for shot sleeves have been developed. The data directly obtained from failed shot sleeves in the die casting industry for automotive parts, support a strong correlation between design and failures. By applying these design criteria we expect premature failures of shot sleeves can be avoided in die casting industry.

Key Words
horizontal cold chamber pressure die casting, stress intensity factor, low cycle fatigue, yielding

1. Introduction

In horizontal pressure die casting, molten metal is ladled from a furnace into an injection chamber or shot sleeve which is exposed to atmosphere. After lading is finished, the molten metal is injected into a die cavity by the linear movement of a plunger in the shot sleeve. The shot sleeve is the center of the molten metal injection system in the cold chamber die casting process. Also, this injection process is the most critical phase with respect to the quality of die castings.[1] High quality die castings result from uninterrupted and smooth molten metal injection coinciding with pre-determined injection profile, i.e., optimal acceleration and velocity of injection or plunger movement. This optimal metal injection is contingent upon optimal performance of a shot sleeve and plunger. A shot sleeve accepts and retains molten metal until it is injected into a die cavity. It is an open-ended, thick-walled cylindrical tube with a pour hole on top to accept molten metal from a ladle. One end (die end) is attached to a machine fixture and a cover die, and the other end (pour end) is connected to a hydraulic cylinder, which activates a plunger.

The most popular material for shot sleeves is AISI H13 hot work tool steel (Cr 4.75-5.50, Mo 1.10-1.75, V 0.80-1.20, Si 0.80-1.20, C 0.32-0.45, Mn 0.20-0.50, Fe balance in weight percent). Annealed H13 steel is machined to meet the requirement of die casting machine and die size, and it is heat treated (quenching and multiple temperings) to final hardness of 46 to 48 Rockwell C scale (Rc).[2]

1.1 Review of the Mechanisms of Mechanical Failures

Due to harsh casting conditions, high temperature up to 700 °C and high pressure, shot sleeves deteriorate fast and even fail catastrophically. In the final stage of molten metal injection die casters apply an extremely high intensification pressure to reduce porosity in solidified castings. This pressure can induce a high hoop tension stress in the shot sleeve wall, which assists lengthwise cracking of a shot sleeve. This longitudinal cracking initiates from the die end portion of a shot sleeve and propagates in the opposite direction to the pour hole. Also this high metal pressure in a shot sleeve, being cyclic as die casting cycle repeats, can initiate fatigue cracks on the inside surface of the shot sleeve. These cracks propagate to the outer surface as die casting cycle continues until final cracking, accumulated cracking, occurs.

Lastly, yielding and plastic deformation of shot sleeves are also observed. Deformation of a shot sleeve I.D. can cause not only wear from friction with a plunger tip but also is detrimental to the

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quality of die castings because it impedes the smooth movement of a plunger. Thus, the desired injection profile of the molten metal is not accomplished. It results in inconsistent injection pressure, cavity filling, machine operation, and a high scrap rate. Based on these observations, the following analyses are presented to support failure mechanisms. Subsequently design criteria to prevent these shot sleeve failures are developed. Finally, collected data from failed shot sleeves in the die casting industry are presented to show a strong correlation between shot sleeve design and failures.

2. Longitudinal Cracking of Shot Sleeves

The die-end portion of a shot sleeve is subject to higher stresses than other areas because a shot pressure can sometimes reach 160 [MPa] in the intensification stage. To reduce voids and porosity due to shrinkage and entrapped gases, and to improve mechanical properties subsequently, a plunger applies a high pressure to molten metal. For example, it was observed that doubling the pressure transmitted to molten metal during solidification in an experiment by Kaye reduced 40% of porosity in die castings. 3) This hydrostatic pressure induces a high circumferential stress in the shot sleeve wall.

2.1 Analysis of Stresses

Since a shot sleeve is a long, open-ended, thick-walled cylindrical tube (mean diameter / thickness < 20), the hoop (or tangential) stress in the shot sleeve wall under pressure 'p' is:

$$\sigma_\theta = \frac{pa^2}{r^2}\left(\frac{b^2+r^2}{b^2-a^2}\right) \quad \text{(Eq. 1)}$$

where 'a' is the inner radius, 'b' is the outer radius of a shot sleeve, and 'r' is any arbitrary radial position of the point at which the stress is given in the shot sleeve wall. This is Lame's solution for a thick-walled cylinder. The hoop stress has a maximum value at the inside surface of a shot sleeve, $\sigma_{\theta,\max} = p(b^2+a^2)/(b^2-a^2)$. The magnitude of a maximum hoop stress is determined by the ratio of 'a' and 'b'. As 'b' increases it approaches the hydrostatic pressure. A radial stress is also induced in the wall:

$$\sigma_r = -\frac{pa^2}{r^2}\left(\frac{b^2-r^2}{b^2-a^2}\right) \quad \text{(Eq. 2)}$$

At the inner surface (r = a), it has a maximum compressive value of an internal pressure, $\sigma_r = -p$. Most of longitudinal crackings initiate at the inside surface of the die-end portion of shot sleeves, which is subject to a high tensile stress. And it was observed that a small crack was imbedded and oriented along the longitudinal direction on the inside surface of a shot sleeve wall. Thus the hoop tension stress is applied normal to the crack plane, i.e., 'Mode I crack displacement'. The hoop stress is acting into and out-of-paper direction (Fig. 1). Also, a crack is assumed to be a part-through ellipsoidal (or thumbnail) surface crack and its geometry is semi-elliptical with minor axis 'a' (crack depth) and major axis 'c' (crack length), $x^2/a^2+z^2/c^2=1$. In fact, a part-through thumbnail is a typical starting-crack shape customarily found in the examination of fracture failures. 4)

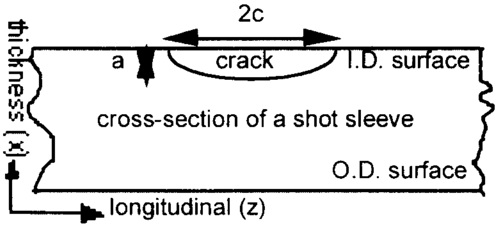

Fig. 1 Geometry of a surface crack imbedded in a shot sleeve wall

To obtain the critical size of a crack, i.e., depth (a_{cr}), the following criterion is used: Fracture is predicted to occur if a stress intensity factor (K_I) exceeds plane strain fracture toughness (K_{IC}) of H13 steel. K_{IC} of H13 steel is a material property, which is dependent on tempering temperature of a shot sleeve. Since displacement in the longitudinal (z) direction of a long shot sleeve is assumed virtually zero the plane strain condition is satisfied. A stress intensity factor for a semi-elliptical surface crack in an infinite medium is

$$K_I = (1.12/\sqrt{Q})\sigma\sqrt{\pi a}$$

$$Q = \Phi_0^2 = \left(\int_0^{\pi/2}\sqrt{1-\frac{c^2-a^2}{c^2}\sin^2\phi}\,d\phi\right)^2 \quad \text{(Eq. 3)}$$

'Q' is a surface flaw shape parameter and 1.12 is a free-surface correction factor. In this example, the ratio of crack depth to length (a/2c) is assumed 0.25. Then 'Q' is approximately 1.47. However, due to the effect of plastic deformation in the vicinity of the crack tip on the stress intensity factor value, 'Q' is redefined:

$$Q = \Phi_0^2 - 0.212\left(\frac{\sigma}{\sigma_{\text{yield}}}\right)^2 \quad \text{(Eq. 4)}$$

where, σ is a nominal tensile stress applied and σ_{yield} is yield strength of H13 steel. To obtain the typical hardness of 46 - 48 Rc for shot sleeves, tempering is performed at 575 - 593°C according to a tempering curve of H13 steel. For simplicity, a H13 steel shot sleeve is assumed to have been tempered at 600°C with a resultant K_{IC} of 33.2 [MPa(m)$^{0.5}$]. Based on these information a critical depth and length of a crack to cause catastrophic fracture are obtained by substituting K_I with K_{IC} in Eq. 3,

$$a_{cr} = \frac{Q}{\pi}\left(\frac{K_{IC}}{1.12\sigma}\right)^2 \quad \text{(Eq. 5)}$$

A failed shot sleeve in a die casting plant has 89 mm O.D. and. 64 mm I.D. (O.D. to I.D. = 1.390 : 1). If this shot sleeve is subject to an internal pressure of 150 MPa (hoop tension stress of 471 MPa from Eq. 1) the critical crack depth (a_{cr}) is 1.765 [mm]. Table 1 shows critical crack sizes at various shot sleeve operating temperatures.

Table 1 Dimension of critical crack size in a failed shot sleeve (O.D. = 89 and I.D. = 64 mm)

Shot sleeve temperature [°C]	Q (Flaw shape parameter)	a (Crack depth [mm])	2c (Crack length [mm])
100	1.40	1.765	7.060
400	1.39	1.753	7.012
500	1.36	1.715	6.860
600	1.28	1.614	6.456

A crack of 1.765 mm-deep on the surface could cause catastrophic longitudinal cracking of this shot sleeve. Using another cracked shot sleeve (O.D. = 85 and I.D. = 65 mm), we find 1.150 [mm] is the critical crack depth under 150 MPa. (hoop tension stress of 573 MPa from Eq. 1). However, we obtained the results in Table 1 assuming 600 °C tempering of H13 steel, instead of 575 - 593°C to achieve the target hardness of 48 - 46 Rc in the cases of most shot sleeves in die casting industry. In fact, the actual hardness of these two failed shot sleeves was measured to be 50 - 52 Rc, which is a result of tempering at 530 – 560 °C. Consequently it greatly lowers K_{IC} to 23.1 - 24.3 [MPa(m)$^{0.5}$]. Therefore, K_{IC} of these cracked shot sleeves must be below 33.2 [MPa(m)$^{0.5}$] even though exact data is not available. Evidently a critical crack size must be smaller than the value in Table 1. With this low K_{IC} critical crack sizes decrease to only 48% of the previous critical sizes, i.e., 0.850 instead of 1.765 [mm], and 0.552 instead of 1.150 [mm]. Accordingly, the two shot sleeves fractured due to both poor tool steel quality by inappropriate tempering and wrong design as will be discussed next.

2.2 Design Criterion for Longitudinal Cracking

To avoid cracking we need a larger K_{IC} and/or minimal crack size in a shot sleeve. However die casters usually have no control over these factors. Meanwhile we can design a shot sleeve with lower probability of cracking using the same, ordinary H13 steel. The critical size of a crack depends on the magnitude of hoop tension stress ('a_{cr}' is a function of σ^{-2} in Eq. 5). 'a_{cr}' diminishes rapidly as a hoop tension stress increases. Therefore, the maximum allowable size of a crack a die caster will tolerate should be determined by the hoop stress. Given an internal pressure of 150 [MPa], 'a_{cr}' causing catastrophic cracking in the following shot sleeve with K_{IC} = 33.2 [MPa(m)$^{0.5}$] is calculated (Table 2). For example, at 100°C the critical crack depth is 3.21 [mm] assuming the shot sleeve has ratio of O.D. : I.D. = 1.574 : 1. (This ratio to prevent yielding of a shot sleeve will be derived from Eq. 15 later.) This newly designed thicker-wall shot sleeve is robust against fracture because 'a_{cr}' is larger than those of cracks in the previous two failed shot sleeves; 1.765 [mm] and 1.150 [mm] respectively at 100°C.

Table 2 Dimension of critical crack size in a newly designed shot sleeve with a ratio of O.D./I.D.=1.574:1

Shot sleeve temperature [°C]	Q (Flaw shape parameter)	a (Crack depth [mm])	2c (Crack length [mm])
100	1.43	3.21	12.84
400	1.42	3.19	12.76
500	1.41	3.16	12.64
600	1.37	3.07	12.28

Given a maximum tolerable crack size, to satisfy the criterion to prevent longitudinal cracking of a shot sleeve containing a crack, a minimum wall thickness (t) of a shot sleeve is:

$$t > r_i\left\{\left(\frac{1+\sqrt{\Pi}}{1-\sqrt{\Pi}}\right)^{1/2} - 1\right\} \quad \text{(Eq. 6)} \quad \text{where,}$$

$$\Pi = \left(\frac{p}{\sigma_{yield}\Phi_0}\right)^2 \left\{\pi\left(\frac{1.12\sigma_{yield}}{K_{IC}}\right)^2 a_{cr} + 0.212\right\}$$

Thus, thickness (t) or O.D. = $2(r_i + t)$ of a shot sleeve (design parameter) can be determined based on a desired inner radius (r_i) when operating parameter (intensification pressure, p), material parameters (K_{IC} and σ_{yield}) and a maximum crack size a die caster allows (a_{cr}) are specified. Suppose a die caster wishes to build a shot sleeve safe up to 3.21 mm crack and 150 MPa is the intensification pressure used. He knows he uses H13 steel with K_{IC} of only 23.1 [MPa(m)$^{0.5}$] due to a low tempering temperature or high hardness requirement. Then wall thickness should be at least 1.02 times r_i from Eq. 6 instead of 0.574 using H13 steel with K_{IC} of 33.2 [MPa(m)$^{0.5}$]. In other words, shot sleeve design is very sensitive to K_{IC} of H13 steel.

3. Accumulated Cracking of Shot Sleeves

In die casting plants, shot sleeves also crack in 30,000 - 40,000 shots after installation, and small initial cracks in steel are suspected to be the cause. A repeated hoop tension stress can cause these fatigue crack nuclei to grow and propagate to the final failure of shot sleeves. 'a_{cr}' to ultimately cause cracking of a shot sleeve was obtained in Eq. 5. Here we calculate the number of cycles to initiate a fatigue crack and to grow it to 'a_{cr}'. Currently most shot sleeves are withdrawn from service before 50,000 shots for numerous other reasons anyway. Thus only the low cycle fatigue behavior of shot sleeves is our concern, i.e., the situation of a pre-existing crack growing to a critical dimension within the mean life of shot sleeves. Typically, low cycle fatigue refers to the condition that plastic strain dominates and a short life (10,000 - 50,000 cycles) is expected. In general, any surface imperfections, such as a scratch, dent, burr, cut, and manufacturing flaws can be sites for fatigue crack initiation. 5)

3.1 Crack Propagation

In low cycle fatigue, crack growth constitutes the major portion of a fatigue life. Therefore, an empirical growth equation that governs the rate of crack propagation can be employed to predict a fatigue life once pre-existing crack size is known. In general, the most critical parameter to decide the propagation rate is the stress intensity factor range. Other mechanical and metallurgical factors of steels have relatively small effects. 6) For example, crack growth was shown to be governed by the matrix hardness and rather insensitive to coarse microstructure. 7) Martensitic steels with a yield strength greater than 552 MPa show a stable crack growth rate. 6)

$$da/dN = 0.66 \times 10^{-8} (\Delta K_I)^{2.25} \quad \text{(Eq. 7)}$$

where 'a' is a crack size, 'N' is number of cycles, and stress intensity factor range, DK_I is:

$$\Delta K_I = \frac{1.12}{\sqrt{Q}} \Delta\sigma\sqrt{\pi a} \quad \text{(Eq. 8)}$$

First, let us check whether a crack opens up, i.e., propagates, or closes as fatigue cycle continues. For example, a crack may not grow under a very small ΔK_I. This limit is called threshold stress intensity factor range ($\Delta K_{threshold}$), which is roughly between 5.5 - 16.5 [MPa(m)$^{0.5}$]) for steels. 8) Below this value fatigue crack growth is immeasurably slow. Given internal pressure of 150 MPa and an 1 mm crack existing on the inner surface of a shot sleeve (with O.D.: I.D. = 1.574 : 1), ΔK_I is about 19 [MPa (m)$^{0.5}$]. This is not greater than 33.2 [MPa(m)$^{0.5}$] (K_{IC} of H13 steel tempered at 600 °C), but is greater than ΔK_{th}. Therefore, even if a shot sleeve is designed by a rule to prevent yielding (as will be shown in Eq. 15), it still can fracture by fatigue once a flaw of a considerable size exists. Certainly an under-designed shot sleeve will suffer even faster crack growth and final fracture. In Fig. 2 a crack size approximately below 0.5 mm will not create possibility of low cycle fatigue because of its small ΔK_I value. This small size requires a larger number of die casting cycles to grow to the final fracture than a typical shot sleeve life (50,000 shots). This is consistent to the observation that 0.5 - 1.3 [mm] is the typical size of an initial crack in many fatigue-caused fractures in real world engineering. 8) Meanwhile 0.8 mm crack has ΔK_I exceeding the upper limit of ΔK_{th}. Thus it will grow to a final size eventually to cause catastrophic fracture.

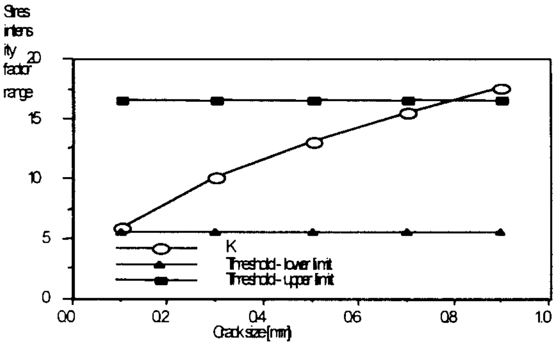

Fig. 2 Stress intensity factor range vs. initial crack sizes

3.2 Fatigue Life of Shot Sleeves

If we assume an initial size of a pre-existing crack of 1 mm and a cyclic hoop stress of 353 MPa (which is induced by internal pressure of 150 MPa in a shot sleeve with O.D.:I.D.= 1.574 :1), the number of cycles for a crack to grow to the critical size (3.21 mm in Table 2) can be obtained. By substituting Eq. 8 into 7 and using a definite integral from 1 to 3.21 mm, N is calculated to be 11,300 in (Eq. 9),

$$N = \left(\int_{a_0}^{a_f} a^{-1.125} da \right) / 0.66 \times 10^{-8} \left(\frac{1.12}{\sqrt{Q}} \Delta\sigma \sqrt{\pi} \right)^{2.25}$$

(Eq. 9)

Approximately 11,300 cycles of die casting leads a shot sleeve to the final fracture after a 1 mm-deep crack is detected. In die casting industry it is generally known that nitrided H13 steel surface is more resistant to thermal fatigue. This observation seems also true in mechanical fatigue. The crack growth rate of nitrided martensitic steel is:

$$da/dN = 0.50 \times 10^{-8} (\Delta K_I)^2 \quad \text{(Eq. 10)}$$

Again, using closed-form integration from 1 to 3.21 [mm] N is 32,400 cycles. The average crack growth rate in martensitic steel from 0.5 to 3.21 [mm] is 1.45 x 10^{-4} [mm/cycle]. Nitriding decreases this rate to 5.26 x 10^{-5} [mm/cycle]. A fatigue crack in nitrided martensitic steel grows at a rate 36% of a counterpart in martensitic steel. A typical nitrided depth is 0.1 - 0.7 [mm] in shot sleeves for increased hardness. Fig. 3 shows crack growth as a function of number of die casting cycles. Obviously the crack propagation rate accelerates with crack size because ΔK_I increases with crack size.

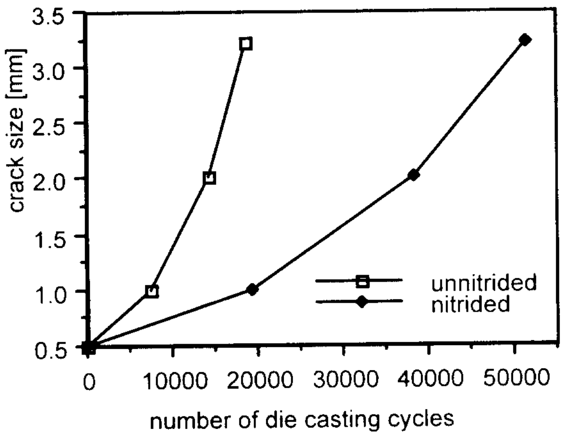

Fig. 3 Fatigue crack growth vs. die casting cycles

3.3 Design Criterion for Accumulated Cracking

To prevent fatigue cracking, we can design a shot sleeve to suppress ΔK_I below a threshold value. It is accomplished by decreasing the hoop tension stress amplitude ($\Delta\sigma$). A criterion to prevent an initial crack of size 'a' from growing is to keep ΔK_I lower than ΔK_{th} (5.5 - 16.5 [MPa $(m)^{0.5}$]).

$$\Delta K_I = \frac{1.12}{\sqrt{Q}} \Delta\sigma \sqrt{\pi a} < \Delta K_{threshold}$$

$$\Delta\sigma < \frac{\Delta K_{threshold} \Phi_0}{\sqrt{1.2544 \pi a + 0.212 \left(\frac{\Delta K_{threshold}}{\sigma_{yield}} \right)^2}} \quad \text{(Eq. 11)}$$

For example, to prevent an initial crack of 1 mm with 'a/2c' = 0.25 from growing and assuming ΔK_{th} = 16.5 [MPa$(m)^{0.5}$] (upper limit), a maximum hoop stress should be less than 315 MPa from Eq. 11. Given the internal pressure of 150 MPa, in order to limit a hoop stress to 315 [MPa] on I.D. a wall thickness should be at least 0.679 times r_i of a shot sleeve (or O.D.: I.D.= 1.679 :) in $\sigma/p = (r_o^2+r_i^2)/(r_o^2 - r_i^2) = 2.1$ (Eq. 1), where r_o and r_i are outer and inner radius of the shot sleeve. From the criterion for fatigue-induced cracking, a minimum wall thickness (t) should be:

$$t > r_i \left(\sqrt{\frac{\Delta\sigma + p}{\Delta\sigma - p}} - 1 \right)$$

$$\Delta\sigma = \frac{\Delta K_{threshold} \Phi_0}{\sqrt{1.2544 \pi a + 0.212 \left(\frac{\Delta K_{threshold}}{\sigma_{yield}} \right)^2}} \quad \text{(Eq. 12)}$$

Design parameter (t) is again obtained as a function of material parameters (ΔK_{th} and σ_{yield}), initial crack size (a), and service pressure (p). Meanwhile, if martensitic H13 steel has a lower limit of K_{th} equal to 5.5 [MPa$(m)^{0.5}$] (lower limit) a maximum allowable hoop stress should be unrealistically small. Hence, it is impossible to prevent a 1 mm initial crack from growing by wall thickness design alone. In other words, prevention of fatigue failure either can or cannot be achieved depending on ΔK_{th} of H13 steel. Unfortunately, the exact value of fatigue threshold of H13 steel under the realistic operating condition is not known currently.

4. Deformation and Wear of Shot Sleeves

4.1 Mechanism of Deformation

The hoop and radial stresses from hydrostatic pressure in Eq. 1 and 2 can cause elastic or even plastic deformation of a shot sleeve. If we assume only a hoop stress (σ_θ) and radial stress (σ_r) exist in a shot sleeve wall (no stress in the longitudinal direction), the stress state on the inside surface is biaxial and both σ_θ and σ_r are principal stresses. Since these stresses can induce strain of a shot sleeve (especially on the inner surface), it is necessary to check whether the strain is only elastic or plastic. Temporarily assuming the linear elastic stress-strain relationship is validly applied to the strain calculation, the strains in a shot sleeve with the inner radius of 'a' and outer radius 'b' is:

$$\varepsilon_\theta = \frac{pa^2}{Er^2}\left[\left(\frac{b^2+r^2}{b^2-a^2}\right)+\nu\left(\frac{b^2-r^2}{b^2-a^2}\right)\right]$$

$$\varepsilon_r = -\frac{pa^2}{Er^2}\left[\left(\frac{b^2-r^2}{b^2-a^2}\right)+\nu\left(\frac{b^2+r^2}{b^2-a^2}\right)\right] \quad \text{(Eq. 13)}$$

where ε_θ and ε_r are the strain in the circumferential and radial direction. 'E' is elastic modulus of H13 steel (200 - 140 [GPa] at 100 - 600°C) and 'ν' is Poisson's ratio (0.3). At the inner surface (r = a) circumferential and radial strain have maximum values:

$$\varepsilon_{\theta,a} = \varepsilon_{\theta,\max} = \frac{p}{E}\left(\frac{b^2+a^2}{b^2-a^2}+\nu\right)$$

$$\varepsilon_{r,a} = \varepsilon_{r,\max} = -\frac{p}{E}\left[1+\nu\left(\frac{b^2+a^2}{b^2-a^2}\right)\right] \quad \text{(Eq. 14)}$$

If the same cracked shot sleeve (O.D. = 89 and I.D. = 64 [mm]) were subject to a pressure of 150 [MPa], strain would be $\varepsilon_\theta = 0.00369$ (or 0.369 %) and $\varepsilon_r = -0.00208$ (or -0.208%) at 600°C. Following the convention of 0.2% offset plastic strain, the strain of 0.369% in the circumferential direction is obviously in the plastic region. Thus, the circumference or I.D. can increase permanently. Also, since the strain in radial direction is negative the wall-thickness of the shot sleeve could decrease. The magnitude of actual displacement on the inner radius is 0.118 mm ('$a\varepsilon_\theta$' = 32 x 0.00369), i.e., the inner radius changed from 32 mm to 32.118 mm. The enlargement of I.D. implies change of clearance between a plunger tip and shot sleeve inner surface. In industry, die casters set the clearance between a shot sleeve and plunger tip to be 0.0254 mm per 25.4 mm shot sleeve I.D. 9) 10) Since I.D. of the failed shot sleeve is 64 [mm] the clearance in each side was about 0.032 mm (half of 0.064 mm). In the injection and intensification stage, when the molten metal was not solidified 100 %, the clearance changed instantly from 0.032 to 0.150 mm (=0.032 + 0.118). Theoretically 4.7 times increase in clearance was possible in this failed shot sleeve.

An appropriate clearance is critical to the quality of solidified castings. Too tight a clearance causes a shot sleeve to pinch a plunger tip and thus results in an irregular or insufficient injection pressure. In the extreme case a plunger tip sticks and cannot apply enough injection and intensification pressure. Meanwhile, too liberal a clearance allows liquid metal to penetrate backwards between O.D. of a plunger tip and shot sleeve I.D. Then excessive solidified "flash" is present on the shot sleeve wall. As a result extreme friction occurs in every reciprocation, and a plunger tip and shot sleeve wear fast to be replaced too frequently. Evidently it also yields a high scrap rate. Since the above calculation of strain was based on a theory of linear elasticity, a portion of strain beyond the elastic range was not calculated accurately. Obviously the total strain is a sum of an elastic and plastic portion. In any case, the goal is to prevent any plastic strain in a shot sleeve. Design rules to achieve this objective are presented as follows.

4.2 Design Criteria for Plastic Deformation and Wear

To prevent yielding by Tresca theory, $\sigma_\theta - \sigma_r < \sigma_{yield}$, a design rule for minimum shot sleeve wall thickness is $p\left(\frac{b^2+a^2}{b^2-a^2}\right)+p<\sigma_{yield}$

$$t > a\left(\sqrt{\frac{\sigma_{yield}}{\sigma_{yield}-2p}}-1\right) \quad \text{(Eq. 15)}$$

where, 't' is wall thickness of a shot sleeve and 'b' = 'a' + 't'. For instance, if 'p' is 150 [MPa] and 'σ_{yield}' is 503 [MPa] at 600°C, a wall thickness should be greater than 0.574 times of inner radius (O.D. vs. I.D. = 1.574 : 1). A design rule using Von-Mises theory, $(\sigma_\theta - \sigma_l)^2 + (\sigma_l - \sigma_r)^2 + (\sigma_r - \sigma_\theta)^2 < 2(\sigma_{yield})^2$, wall thickness should be:

$$t > a\left[\left(\frac{\sqrt{\left(\frac{\sigma_{yield}}{p}\right)^2-\frac{3}{4}}+\frac{1}{2}}{\sqrt{\left(\frac{\sigma_{yield}}{p}\right)^2-\frac{3}{4}}-\frac{3}{2}}\right)^{1/2}-1\right] \quad \text{(Eq. 16)}$$

The criterion based on Von-Mises theory tolerates a thinner wall thickness. A wall thickness should be greater than 0.468 times of inner radius (O.D. vs. I.D. = 1.468 : 1) under 'p' of 150 and 'σ_{yield}' of 503 MPa at 600°C. According to Tresca criterion, a shot sleeve should be designed more conservatively (O.D. vs. I.D. = 1.574 : 1). One failed shot sleeve (A) from the industry has a ratio of O.D. to I.D. equal to 1.390 : 1 (89 vs. 64 and wall thickness of 12.5 mm). Therefore, it violates both the Von-Mises and Tresca criteria. Another failed shot sleeve (B) has a ratio of O.D. to. I.D. equal to 1.310 : 1 (85 vs. 65 and wall thickness of 10 mm). Under a pressure of 150 MPa, a hoop stress is 573 MPa, which alone exceeds 503 MPa (σ_{yield} at 600°C). Both Von-Mises and Tresca theories predict yielding of this shot sleeve even at 500°C where σ_{yield} is 641 MPa. In aluminum alloy die casting, the temperature of molten metal sometimes reaches 700°C. Therefore, we conclude both shot sleeves were not designed properly.

5. Conclusions: Correlation of Mechanical Deterioration and Failures, and Design

To find out any correlation of wall thickness design and mechanical failures in general, wall thicknesses of 14 shot sleeves collected from the die casting industry manufacturing automotive parts, have been measured. Frequency distribution of ratio of O.D. to I.D. of them is presented (Table 3).

Table 3 Frequency distribution of ratio of O.D./I.D. of shot sleeves withdrawn from service in the die casting industry for automotive parts

	Ratio of O.D. to. I.D. (O.D./ I.D.)						
	<1.3	<1.4	<1.5	<1.6	<1.7	<1.8	<1.9
Freq.	**1**	**5**	3	*2*	*1*	*1*	*1*

6 sleeves have O.D./I.D. ratio of less than 1.4. (Compare with Tresca rule of 1.574 or Von-Mises rule of 1.468 under 600^{o}C and pressure of 150 [MPa].) Five sleeves out of these 6 failed by cracking. Two of them also suffered wear. The one suffered fatigue failure has a mere ratio of 1.3. The remaining shot sleeve with a ratio of 1.330 failed by severe wear without cracking.

None of the 5 shot sleeves which have O.D./I.D. ratio of larger than 1.5, failed by cracking. Three of them were simply replaced by a regular replacement schedule, and two were failed by washout (a phenomenon by the chemical interaction between shot sleeve steel and corrosive molten aluminum with no mechanical characteristics).

The two shot sleeves out of the remaining 3 intermediate wall-thickness shot sleeves (O.D./I.D. ratio of between 1.4 and 1.5) did not fail actually. And the other failed by longitudinal cracking. The above observation is summarized in Table 4.

Table 4 Failure modes of 14 shot sleeves

Ratio of O.D. to I.D.	Mechanical failures	Wear	Non-mechanical failures
O.D./I.D. < **1.4**	5	3	0
1.4 < O.D./I.D. < **1.5**	1	0	2
O.D./I.D. > **1.5**	0	0	5
Total	6	3	7

This data is an evidence supporting that mechanical failures (cracking) and mechanical deterioration (wear) are strongly correlated with wall thickness design of shot sleeves. Unfortunately, the data are not obtained from designed experiments but are "anecdotal evidence". Nevertheless, based on the data of failed shot sleeves in real die casting plants, we can conclude the design modification rules proposed in this study are very promising. They will prevent future mechanical failures of shot sleeves to a great extent and improve quality of automotive parts produced in die casting plants.

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