THE EFFECT OF SHOT PEENING ON FATIGUE PROPERTIES OF A DIE-CAST ALUMINIUM ALLOY

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ABSTRACT

Shot peening involves modifications of the surface and subsurface condition of a material that can be described by the change of the residual stresses, the hardness, and the surface roughness. Moreover there is the possibility of introducing additional surface defects. The influence of these modifications on the fatigue behaviour of the aluminium die casting alloy GD-AlSi8Cu3 is investigated. S-N curves are determined for four surface conditions produced by milling, shot peening, and a combined treatment. The improvement of fatigue limit by shot peening is confirmed. The additional effect of mean stresses is determined. Pores and pipes as well as surface defects induced by shot peening act as fatigue crack initiation sites.

KEYWORDS

Aluminium die casting alloy, shot peening, fatigue properties, S-N curves, fatigue limit, mean stress effect, residual stress, roughness, surface defects, bulk defects.

INTRODUCTION

Despite high solidification rates and the resulting fine microstructure, the fatigue properties of conventionally die-cast aluminium parts are often worse in comparison with parts produced by permanent mould casting of the same alloy (1). A higher density of bulk defects like pores, pipes and oxides as well as surface defects like oxide skins, laps and microcracks is made responsible for this observation. Another disadvantage of the conventional die casting process is the deficient possibility of heat treating the castings to improve their mechanical properties. This is due to their tendency to blister during solution treatment, so many of the general-purpose die casting alloys are used only in the as-cast temper.

The improvement of the fatigue, fretting fatigue, and stress corrosion performance by shot peening engineering components has long been known, particularly for steels. Various investigations of shot peened wrought aluminium and titanium alloys showed that shot peening has a beneficial effect on fatigue behaviour also in the case of light alloys (2)(3)(4). This effect is caused by the induced residual compressive stresses and the work-hardening of the surface. The amount of change of e. g. the fatigue limit depends on the kind of alloy and its heat treatment. Another modification introduced by shot peening is an increase in surface roughness with the possibility of introducing surface defects (5), which both can have a negative effect on fatigue properties.

In this investigation shot peening was applied to the polyphase aluminium die casting alloy GD-AlSi8Cu3 (similar to AA No. 380). This is a widely used, general-purpose die casting alloy, which is temperature resistant and appropriate also for complicated and thin-walled castings. To assess the effects on fatigue properties caused by modifications of the different surface properties, bending fatigue tests were carried out with specimens in four different surface conditions: as-cast, shot peened, surface milled off, and milled and shot peened. The fatigue limits were determined for fully reversed bending (R = -1) and for zero-maximum bending (R = 0), so that the sensitivity to mean stress can be evaluated. Fracture surfaces were investigated in a scanning electron microscope (SEM) to determine the position and the size of fatigue crack initiation sites.

EXPERIMENTAL PROCEDURE

Material and Heat Treatment

Flat bending specimens with a test cross section of 5 x 10 mm^2 as shown in Fig. 1 were die-cast with a gate area of 18 x 1.5 mm^2. The gate velocity of the melt was 40 m/s, the melt temperature was 700°C. It took 13 ms to fill the mould. During solidification of the melt a pressure of about 500 bar was maintained. Thereupon the specimens were quenched in water of about 30°C. The whole test material was aged for 5 hours at a temperature of 165°C in an air circulation furnace. Tensile tests resulted in the values for mechanical properties listed in Table 1.

Table 1: Mechanical properties of Al-alloy GD-AlSi8Cu3 in a die-cast condition

	Mean Value and Standard Deviation
0.2% Proof Stress $\sigma_{0.2}$	146.3 ± 1.5 MPa
Tensile Strength σ_{ts}	286.7 ± 1.2 MPa
Elongation after Fracture	3.7 ± 0.3 %
Hardness	117.8 ± 1.8 HB 2.5/62.5

The chemical composition of the alloy used in this investigation was determined on the surface and in the core of a cast specimen. The results are shown in Table 2. A segregation of the alloying elements is established over the cross-section of the specimen.

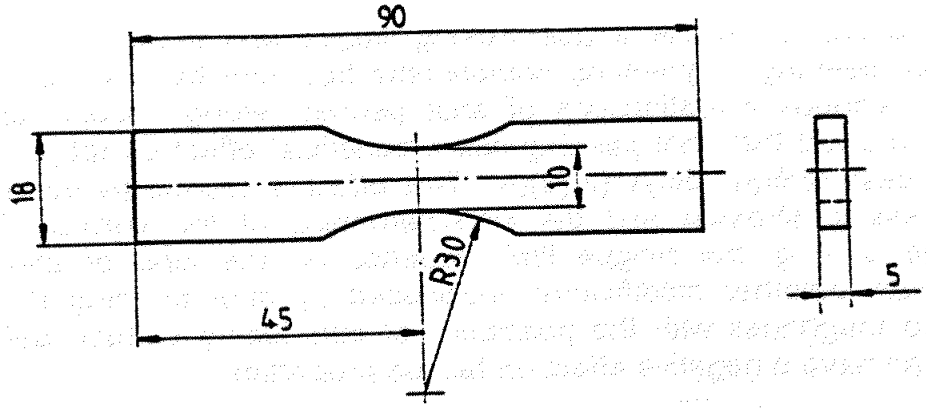


Fig. 1: Specimen shape for the fatigue experiments

Table 2: Chemical composition of Al-alloy GD-AlSi8Cu3 (weight%)

	Si%	Mn%	Cu%	Fe%	Zn%	Mg%	Ni%	Pb%	Al%
Surface	8,76	0,20	2,96	1,30	1,16	0,17	0,10	0,28	balance
Core	6,60	0,18	2,12	1,06	1,03	0,14	0,07	0,14	balance

Surface Treatments and Means of Characterization

The surfaces of half of the specimens were milled off in a thickness of 0.5 mm on every side of the specimens. So the test cross section was reduced to 4 x 9 mm^2. A number of the unchanged as well as of the milled specimens was shot peened on both sides to an Almen intensity of I = 0.385 A. This intensity corresponds to a coverage of 150%. Shot peening was performed with glass beads (d = 0.42 - 0.84 mm) to prevent any corrosion problems. All together four different surface conditions were produced which are abbreviated from now on as defined in Table 3.

Table 3: Definition of the different surface conditions

Abbreviation	Surface Treatments
Condition 'C'	all surfaces as-cast
Condition 'M'	all surfaces milled off
Condition 'CP'	condition 'C' shot peened
Condition 'MP'	condition 'M' shot peened

The surface roughness was measured by a profilometer. The characteristic value R_z is defined as the arithmetic mean value of peak-to-valley heights determined for 5 consecutive gauge length of the same length. The surface hardness was surveyed at the very edge of a metallographic section using a Vickers indenter under a load of 200 g. Residual stresses σ^{ES} were obtained from X-ray measurements with a Ψ-diffractometer. Interference line profiles of the {222}-planes of aluminium were mapped using Cr-K_α-radiation (λ = 0.229 nm) under different tilt angles ψ. After determinating the line peaks $2\Theta_{\varphi,\psi}$ the macroscopic residual stress was calculated by the $\sin^2\psi$-method (6). The broadening of the interference line profiles induced by a surface treatment can be seen as a measure for the dislocation density or similar to the hardness as a measure for the work-hardening condition. So also the full width at half maximum height (FWHM) of each line profile was surveyed.

Fatigue Tests

Flat bending fatigue tests were carried out in air at room temperature. The cyclic loading was sinusoidal with a frequency of 24 Hz. The stress ratio R defined as minimum stress devided by maximum stress was fixed to R = -1 (fully reversed bending) and to R = 0 (zero-maximum bending). For every S-N diagram about 20 specimens were loaded in the transition region to obtain statistically ensured values for the fatigue limit. Specimens reaching the limit of 10^7 cycles were valued as unfractured.

RESULTS

Characterization of Surface Conditions

Averaged measured values describing the different surface conditions are summerized in Table 4.

Table 4: Properties of the surface conditions

Condition	R_z	Hardness	σ^{ES}	FWHM
'C'	3.1 μm	132 HV 0.2	0 MPa	1.8°
'M'	2.4 μm	119 HV 0.2	0 MPa	2.2°
'CP'	36 μm	148 HV 0.2	-84 MPa	2.7°
'MP'	43 μm	141 HV 0.2	-66 MPa	2.4°

Milling off the surfaces of the specimens results in no major change in surface roughness nor in the effective macroscopic residual stresses on the surface. But there has been a change in the state of residual stresses by this machining process, which becomes obvious in a ψ-splitting and a broadening of the interference line profile (7). Nevertheless the hardness is reduced due to the removal of the fine-grained casting skin.

Considerable increases in surface roughness of one order of magnitude were induced by shot peening. Moreover, metallographic sections showed that surface defects like laps and small cavities were produced. The rise in hardness is due to the work-hardening during this process. It is remarkable that despite equal peening parameters the harder surface condition 'C' reaches a higher hardness than condition 'M'. Also the compressive residual stress and the line broadening are higher in condition 'CP' than in condition 'MP'.

The residual stresses in the processed specimens as a function of the distance from the surface are shown in Fig. 2. Minimum residual stresses of -160 MPa in a depth of 0.15 mm and of -145 MPa in a depth of 0.25 mm are obtained in condition 'CP' and 'MP', respectively. The residual stress values in condition 'M' remain about zero. Fig. 3 shows the interference line width as a function of the depth below the surface. For the shot peened conditions there is a monotonous decrease of the maximum values at the surface to the core value of about 1.6°. For condition 'M' this value is already reached immediately beneath the surface in a depth of 0.02 mm. In every case the surface layer has experienced the strongest work-hardening.

X-ray measurements at unfractured specimens after fatigue tests with low stress amplitudes resulted in nearly the same values for residual stresses as measured before loading. So there has been no relaxation of residual stresses during cyclic loading.

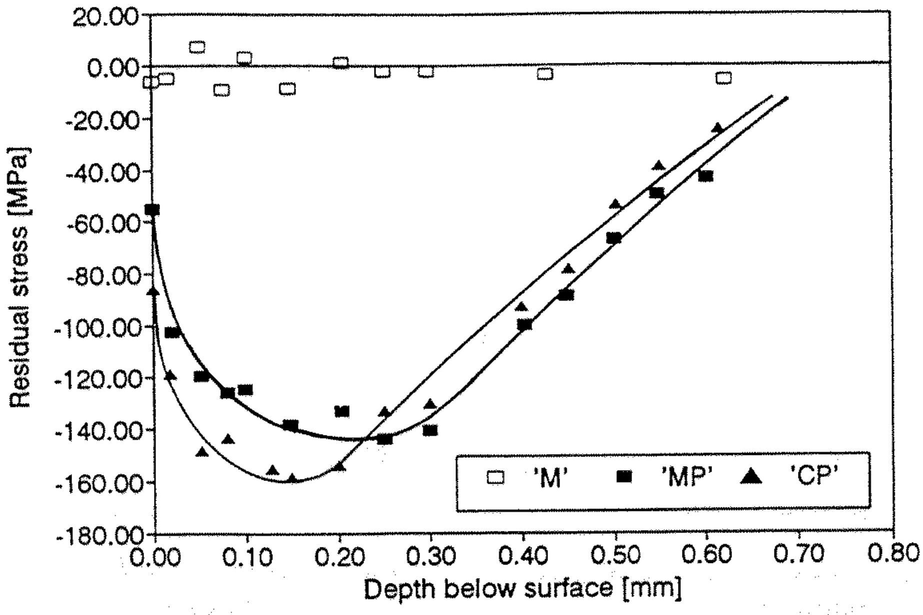


Fig. 2: Residual stresses as a function of the depth below surface

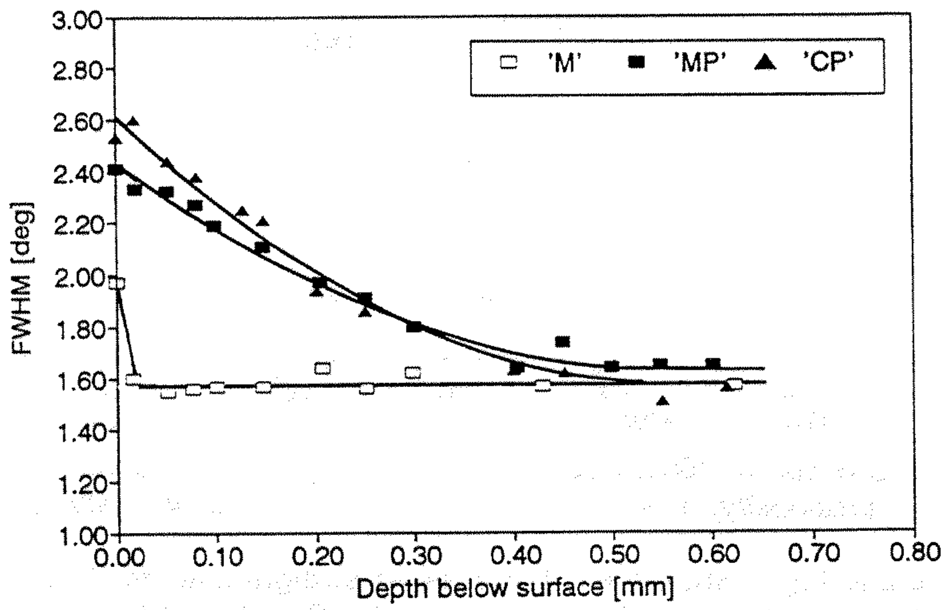


Fig. 3: Width of interference line profiles as a function of the depth below surface

Fatigue Tests

The results of the bending fatigue tests are presented exemplarily for the as-cast condition 'C' in Fig. 4 for the stress ratio $R = -1$ and in Fig. 5 for $R = 0$. The numbers of unfractured specimens are indicated within the diagrams behind the arrows on the right hand side. The diagrams also show the straight line for 50% fracture probability in the limited life region computed by the $\arcsin\sqrt{P}$-method (8). The horizontal lines plotted in the transition region indicate the fatigue limits, i. e. the corresponding stress amplitudes, for 5%, 50% and 95% fracture probability assuming a limit of 10^7 cycles.

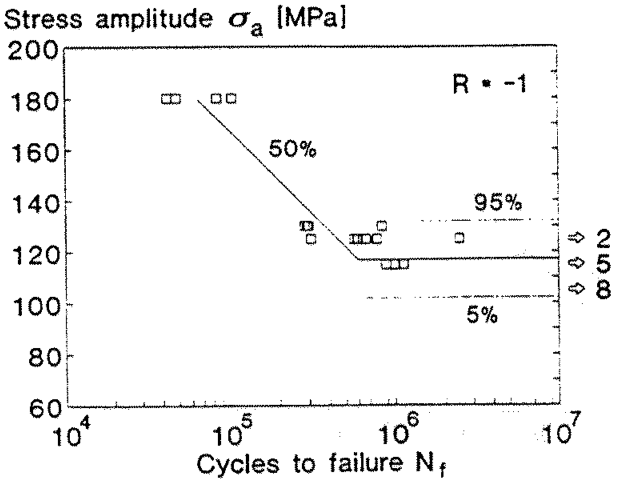


Fig. 4: S-N curve for GD-AlSi8Cu3 Condition 'C', R = -1

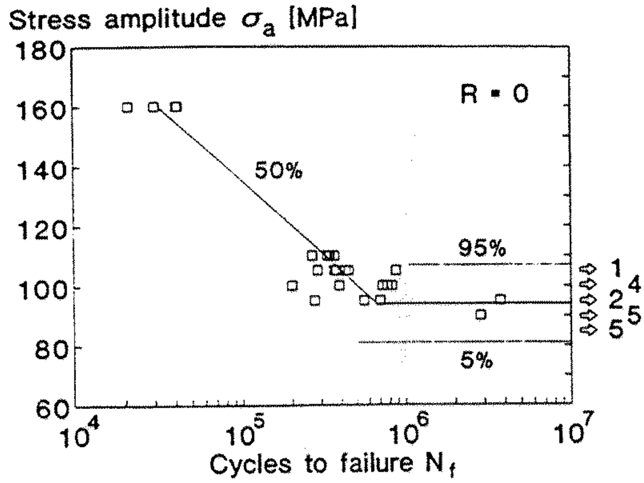


Fig. 5: S-N curve for GD-AlSi8Cu3 Condition 'C', R = 0

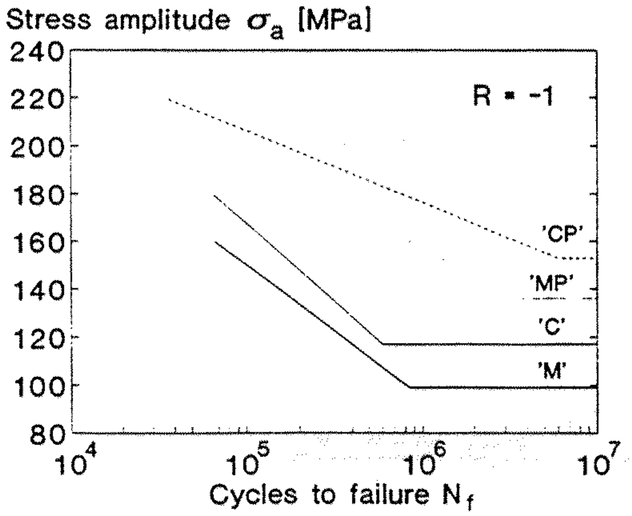


Fig. 6: S-N curves (50% fracture probability), R = -1

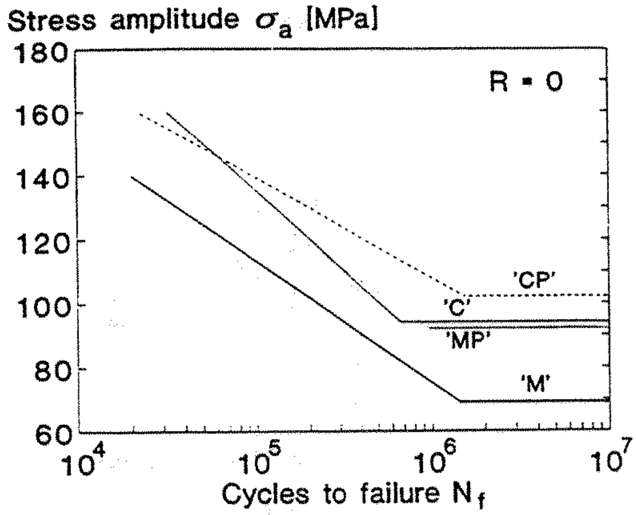


Fig. 7: S-N curves (50% fracture probability), R = 0

Fig. 6 and Fig. 7 show the S-N curves as straight lines for 50% fracture probability for all four surface conditions obtained for R = -1 and for R = 0, respectively. For both stress ratios shot peening has produced an improvement in fatigue properties. As a measure for the improvement in the limited life region the stress amplitude $\sigma_a(N_f=10^5)$ corresponding to a lifetime of 10^5 cycles and the number of cycles N_D at the kneepoint of the S-N curve were computed. A compilation of all theses values and of the fatigue limits σ_D is given in Table 5. The bending fatigue limit σ_D is defined here as the nominal stress amplitude in the test cross-section for 50% fracture probability.

Table 5: Characteristic fatigue values for 50% fracture probality

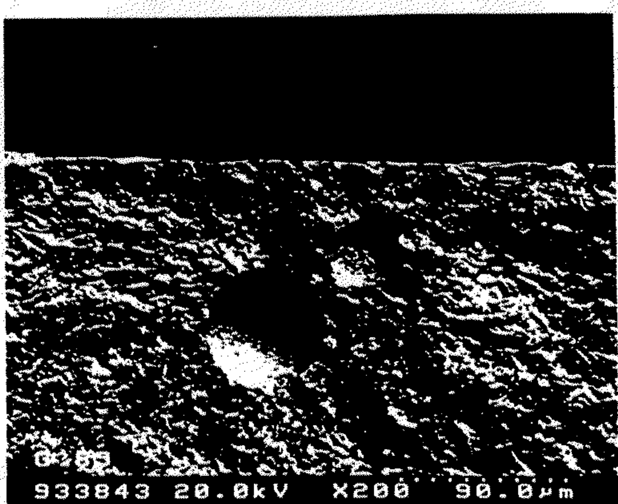
Condition	R = -1			R = 0		
	$\sigma_a(N_f=10^5)$	N_D (x10³)	σ_D	$\sigma_a(N_f=10^5)$	N_D (x10³)	σ_D
'C'	168 MPa	679	117 MPa	135 MPa	721	94 MPa
'M'	150 MPa	885	99 MPa	113 MPa	1570	69 MPa
'CP'	206 MPa	6636	153 MPa	139 MPa	2134	102 MPa
'MP'	196 MPa	3523	136 MPa	130 MPa	1012	92 MPa

The increase in the fatigue limit for fully reversed bending (R = -1) by shot peening is 31% in case of surface condition 'C' and even 37% in case of condition 'M'. The values for σ_D are raised from less than 10^6 cycles to some 10^6 cycles. Milling off the surfaces of the cast specimens produces a large decrease in fatigue limit for the stress ratio R = 0. The fatigue limit is raised by shot peening nearly to the value of the as-cast condition again. Shot peening of the as-cast condition raises the fatigue limit only by 8.5%.

Fractography

In case of the as-cast specimens fatigue cracks initiate preferentially at pores or pipes beneath the surface. A typical example is shown in Fig. 8. Pores filled with gases during solidification have an ellipsoidic shape and a nearly smooth inner surface. They are often surrounded by interdendritic micropipes with a corresponding surface (Fig. 9). Rarely surface defects like steps formed by ridges in the casting mould act as crack initiation sites.

Pores are also the most frequent reason for fatigue crack initiation in specimens of condition 'M'. As a speciality pores were found that were cut up by milling (Fig. 10) and so having a high notch effect.



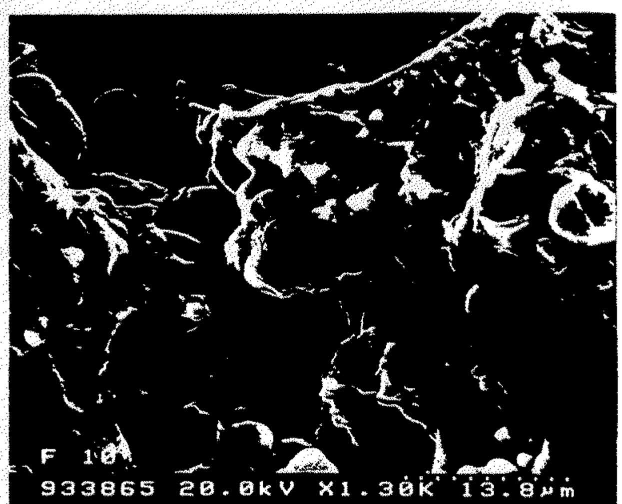


Fig. 8: Fatigue fracture surface (Cond. 'C') showing crack growth from a pore *Fig. 9: Micropipes nearby a pore*

Similar to shot peened steels two different locations of crack initiation were found on the fracture surface of shot peened specimens of the aluminum alloy. Mainly, fatigue cracks started at surface defects like laps or cavities produced by shot peening or at particularly deep impressions of glass beads (Fig. 11). In a few cases pores, which were situated in a large distance (up to 1 mm) from the surface were causal for failure (Fig. 12).

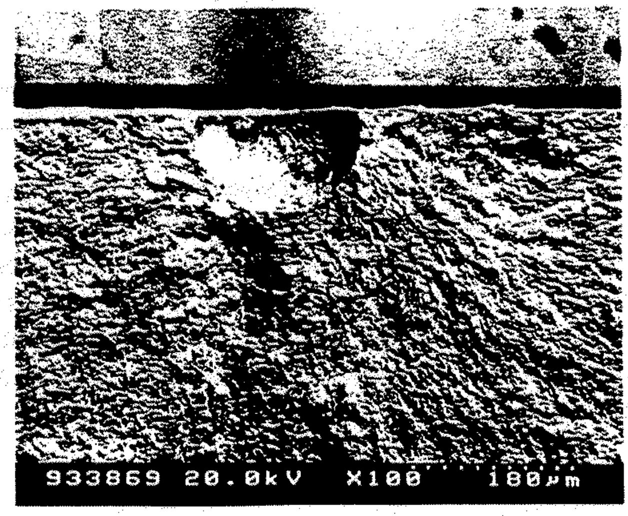


Fig. 10: Fatigue fracture surface (Cond.'M') showing crack growth from a cut up pore

Fig. 11: Crack growth from the surface (Condition 'CP')

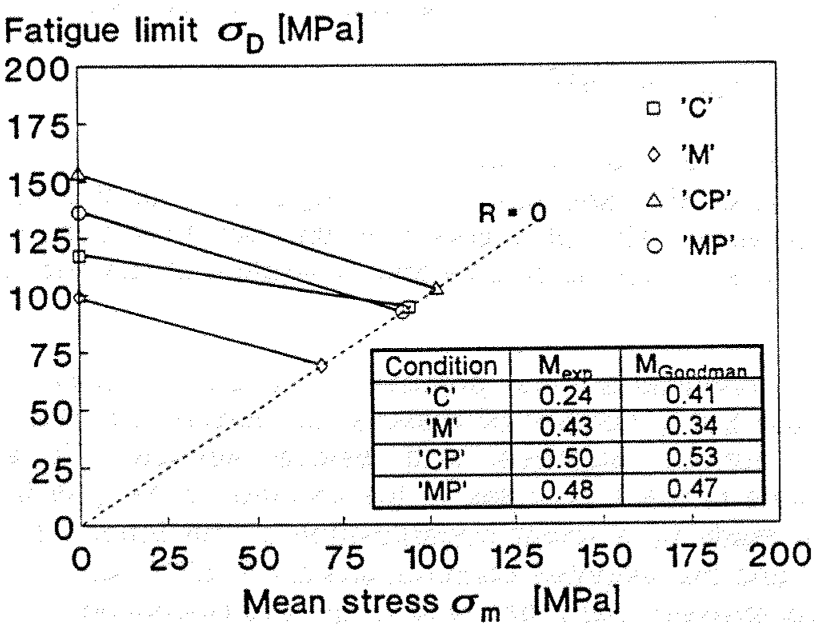
Fig. 12: Crack growth from a pore at a large distance from the surface

DISCUSSION

Fracture surface investigation showed that the fatigue behaviour of the investigated die-cast aluminium alloy is mainly controlled by fatigue cracks emanating from inner casting defects (pores and pipes), seldom from surface defects. Classical crack initiation from persistent slip bands was not observed. By milling off the surfaces the fine-grained casting skin is removed. Moreover a higher density of pores is found beneath the surface and even cut up pores are observed. This leads to a distinct reduction in fatigue limit.

Nevertheless the present work proved the beneficial effect of shot peening on the fatigue properties of the die-cast specimens. This can be explained by several mechanisms:

- Increase in fatigue strength of a surface layer by work-hardening. A higher stress amplitude is needed to initiate fatigue cracks beneath this layer due to the stress gradient under bending loading (9).
- Increase in fatigue lifetimes by an induced compressive residual stress field. Fatigue crack propagation starting from surface defects is slowed down and microcracks can even be arrested (10).
- Pores and pipes beneath the surface can be closed by shot peening. This causes a gain in fatigue strength by a 'removal' or a reduction of inner flaws, which may act as crack initiation sites. This surface treatment can also diminish the notch effect of surface flaws like cut up pores. This explains the extraordinary effect in case of shot peening surface condition 'M'.



Condition	M_{exp}	$M_{Goodman}$
'C'	0.24	0.41
'M'	0.43	0.34
'CP'	0.50	0.53
'MP'	0.48	0.47

Fig. 13: Haigh-diagram for GD-AlSi8Cu3

The influence of mean stress on the fatigue behaviour of the investigated aluminium die-casting alloy is presented as a Haigh-diagram in Fig. 13. Several proposals have been made for a functional equation between the fatigue limit σ_D and the mean stress σ_m. Well-known is the statement of Goodman (11):

$$\sigma_D = \sigma_W \cdot \left(1 - \frac{\sigma_m}{\sigma_{ts}}\right) \quad (1)$$

Using the sensitivity to mean stress M defined by Schütz (11)

$$M = \frac{\sigma_D(R=-1) - \sigma_D(R=0)}{\sigma_m(R=0)} = \frac{\sigma_W}{\sigma_D(R=0)} - 1 \quad (2)$$

eq.(1) can be rewritten as follow:

$$\sigma_D = \sigma_W - M \cdot \sigma_m \quad (3)$$

with

$$M = \sigma_W / \sigma_{ts} \quad (4)$$

Values M_{exp} obtained from the results of the fatigue tests using eq.(2) and the computed values $M_{Goodman}$ using eq.(4) are listed in the Haigh-diagram. There is a good agreement for the shot peened conditions, but a rather large difference for conditions 'C' and 'M'. This can be attributed to the different failure mechanisms in peened and unpeened specimens. Especially the as-cast condition exhibits a very low sensitivity to mean stress which is in contrast to the general observation that M increases with hardness.

Similar to M a sensitivity to residual stress m can be defined by the equation

$$\sigma_D^{ES} = \sigma_W^0 - m \cdot \sigma^{ES} \quad (5)$$

where σ_D^{ES} is the fatigue limit of a certain material condition affected with a residual stress σ^{ES}, and σ_W^0 is the fatigue limit of the same condition without residual stresses (12). Of coarse m is different from zero only for such material conditions that exhibit no or only little relaxation of residual stresses during cyclic loading.

In most mechanical surface processes like shot peening not only the residual stress state but a number of material properties are changed, namely surface hardness, surface roughness and residual stresses. To assess the individual contributions of these changes to the variation of fatigue limit a simplified setup has been made by a linear superposition of the fatigue limit σ_W of a reference condition and the weighted contributions $\Delta\sigma^{ES}$, ΔHV, and Δr belonging to changes in residual stresses, hardness, and roughness respectively:

$$\sigma_D = \sigma_W - m \cdot \Delta\sigma^{ES} + \alpha \cdot \Delta HV - \beta \cdot \Delta r \quad (6)$$

r is defined as $r = \log(R_z/R_z^*)$ (13). R_z^* is a lower limit for the efficiency of roughness; so $r = 0$ for $R_z < R_z^*$. Assuming $R_z^* = 10$ µm the results for the fatigue limits obtained for $R = -1$ and the measured values shown in Table 2 give a set of equations for the unknown σ_W and the weighting factors m, α and β. Solving this set of equations results in:
$\sigma_W = \sigma_W$(condition 'M') = 99 MPa, m = 0.31, α = 1.38 MPa/HV and β = 22 MPa.

Similar calculations for comparable aluminium alloys are not known from the literature. From results obtained on the wrought aluminium alloy AlCu5Mg2 (14) a value of m = 0.32 can be calculated. Moreover the m value determined in this investigation satisfies the relation m < M known for steels. Utilizing data for wrought aluminium from the literature (15) a relation $\sigma_W = 0.5 \cdot \sigma_{ts}$ can be stated for not aged aluminium alloys. Furthermore yield strength increases with increasing hardness with a slope of about 3.3 MPa/HV (data from (16)). So this rough estimation yields $\alpha = 1.65$ MPa/HV. The proportion β/σ_W corresponds in order of magnitude to the values determined for steels (13).

It has to be mentioned that the influence on fatigue limit induced by changes in the size or position of bulk and surface defects is not considered explicitly in eq.(6). It is implicitly included especially in the values for σ_W and for the weighting factor α.

CONCLUSIONS

The fatigue properties of the aluminium die casting alloy GD-AlSi8Cu3 in different surface conditions were investigated under bending loading. The following conclusions may be drawn from this work:

1. The fatigue behaviour of the as-cast condition is mainly controlled by fatigue crack initiation from casting defects, particularly from inner porosity.

2. Milling off the surfaces of the cast specimens decreases the fatigue limit because the fine-grained, hard casting skin is removed and a higher number of pores is now situated beneath the surfaces or pores are even cut up.

3. Shot peening increases the fatigue limits for both starting conditions and for both stress ratios investigated ($R = -1$, $R = 0$). Best results are obtained for the shot peened as-cast surface. This beneficial effect of the peening treatment results from work-hardening of the surface, inducement of compressive residual stresses and closure or moderation of near surface pores.

4. The sensitivity to mean stress is dependent on the surface condition. The lowest sensitivity was observed for the as-cast condition ($M = 0.24$), for the shot peened conditions M is about 0.5.

5. The sensitivity to residual stress was assessed to be in the range of $m = 0.3$ in accordance with values determined for wrought aluminium alloys.

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REFERENCES

(1) Bomas H, Grauerholz T, Mayr P, *Verhalten von Flachproben aus GD-AlSi8Cu3 unter Zug- und Zugschwellbeanspruchung*, Aluminium 64, 524 - 528, 1988

(2) Hirsch T, Vöhringer O, Macherauch E, *Der Einfluß des Kugelstrahlens auf die Biegeschwingfestigkeit von AlCu5Mg2 in verschiedenen Wärmebehandlungs-zuständen*, Härterei-Technische Mitteilungen 41, 166 - 172, 1986

(3) Hirsch T, Vöhringer O, Macherauch E, *Optimizing of the Bending Fatigue Behaviour of TiAl6V4 by Shot Peening*, in: Proceedings 5. Int. Conf. on Titanium, Lütjering G, Zwicker U, Bunk W, Editors, DGM 1985

(4) Wagner L, Müller C, *Effect of Shot Peening on Fatigue Behavior in Al-Alloys*, Materials & Manufacturing Processes 7, 423 - 440, 1992

(5) Luo W, Noble W, Waterhouse R B, *The Effect of Shot-Peening Intensity on the Fatigue and Fretting Fatigue Behaviour of an Aluminium Alloy*, Advances in Surface Treatments Vol. 5, Paris 1986

(6) Macherauch E, Müller P, *Das* $sin^2\psi$*-Verfahren in der röntgenographischen Spannungsmessung*, Z. angew. Phys. 13, 305 - 312, 1961

(7) Hauk V, *Non-destructive Methods of Measurement of Residual Stresses*, in: Advances in Surface Treatments Vol. 4, Niku-Lari A, Editor, Pergamon Press 1987

(8) Dengel D, *Empfehlungen für die statistische Abschätzung des Zeit- und Dauerfestigkeitsverhaltens von Stahl*, Mat.-wiss. u. Werkstofftech. 20, 73 - 81, 1989

(9) Macherauch E, Wohlfahrt H, *Eigenspannungen und Ermüdung*, in: Ermüdungsverhalten metallischer Werkstoffe, Munz D, Editor, DGM 1984

(10) Mutoh Y, Fair G H, Noble B, Waterhouse R B, *The Effect of Residual Stresses Induced by Shot-Peening on Fatigue Crack Propagation in Two High Strength Alloys*, Fatigue Fract. Engng. Mater. Struct. 10, 261 - 272, 1987

(11) Haibach E, *Betriebsfestigkeit*, VDI-Verlag, Düsseldorf 1989

(12) Scholtes B, *Eigenspannungen in mechanisch randschichtverformten Werkstoffzuständen*, DGM 1990

(13) Siebel E, Gaier M, *Untersuchungen über den Einfluß der Oberflächenbeschaffenheit auf die Dauerfestigkeit met. Bauteile*, VDI-Z. 98, 1751 - 1774, 1956

(14) Hirsch T, *Zum Einfluß des Kugelstrahlens auf die Biegeschwingfestigkeit von Titan- und Aluminiumbasislegierungen*, Ph.D. thesis, Universität Karlsruhe 1983

(15) Altenpohl D, *Aluminium und Aluminiumlegierungen*, Springer-Verlag 1965

(16) DIN 1745 Teil 1, Beuth-Verlag 1983