FATIGUE of MATERIALS III
ADVANCES and EMERGENCES in UNDERSTANDING

Proceedings of the third biennial symposium

Cover Photograph: Scanning electron micrographs of the longitudinal test sample of 300 M alloy steel cyclically deformed under stress control at a maximum stress of 369 MPa and a fatigue life of 166,549 cycles, showing coplanar array of fine microscopic cracks in the region prior to onset of unstable crack growth.

(from K. Manigandan, T.S. Srivatsan, G. Doll, and T. Quick)
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This volume contains the papers presented in the third international symposium titled *Fatigue of Materials III: Advances and Emergences in Understanding* held during the Materials Science and Technology 2014 meeting at Pittsburgh, Pennsylvania, USA in October 2014. The six-session symposium was sponsored by the Mechanical Behavior of Materials Committee of The Minerals, Metals & Materials Society (TMS) and ASM International. It is essentially the seventh in a series of symposia on the topic of fatigue of materials. The first three symposia focused on deformation and fracture of ordered intermetallic materials: the first symposium was held in Pittsburgh in 1993; the second symposium was held in Rosemont (Illinois, USA) in 1994, and the third symposium was held in Cincinnati (Ohio, USA) in 1996. The fourth symposium was in honor of Professor Paul C. Paris and focused on high cycle fatigue of structural materials and held in Indianapolis (Indiana, USA) in 1997. The fifth symposium related to advances and emergences in understanding was held in Houston (Texas, USA) in October 2010. The sixth symposium also related to advances and emergences in understanding was held in Pittsburgh in October 2012.

This symposium was well represented with abstracts from engineers, technologists, and scientists from academia, research laboratories, and industries, located both within the United States and few countries overseas. The 30-plus abstracts that were approved for presentation at the symposium were divided into five sessions:

- **Session 1:** Aluminum Alloys
- **Session 2:** Ferrous Materials I
- **Session 3:** Ferrous Materials II
- **Session 4:** Composite Materials
- **Session 5:** Advanced Materials
- **Session 6:** Modeling

The abstracts chosen for presentation at the symposium cover a broad spectrum of topics that represent the truly diverse nature of the subject of fatigue as it relates to the world of materials. The domain and importance of materials has grown appreciably in strength and significantly in stature to become a key area of scientific and applied research. We, the co-organizers, have made every attempt to bring together individuals who could in a positive way put forth the advances while concurrently striving to enhance our prevailing understanding of the topic of fatigue of materials. We extend our warmest thanks and appreciation to both the authors and session chairmen for their enthusiastic commitment and participation.

We also extend our most sincere thanks and appreciation to elected representatives that serve on the Mechanical Behavior of Materials Committee of ASM International and TMS for their understanding and acknowledgment of our interest and approval of
our request to organize this intellectually stimulating event. An overdose of special
thanks, gratitude, and appreciation are reserved and extended to Ms. Trudi Dunlap
(Programming Manager at TMS) for her sustained attention, assistance, interest,
involvement, and participation stemming from understanding and enthusiastic
willingness to help. This ensured a timely execution of the numerous intricacies related
to smooth orchestration and layout of this symposium from the moment immediately
following its approval and up until compilation and publication of this publication.
At moments of need, we the symposium organizers have found her presence in TMS
and participation to be a pillar of support, courteous, understanding, professional,
and almost always enthusiastically helpful and receptive. Timely thanks and assured
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TMS) for his efforts and enthusiasm in ensuring organization and compilation of the
material included in this bound volume in a cohesive, convincing, and compelling
manner. Special thanks and appreciation is also extended to Mr. K. Manigandan
(University of Akron) for his time and efforts in formatting few of the submitted
manuscripts very much in conformance with instructions for manuscript preparation
for inclusion in this volume. The timely compilation and publication of this volume
would not have been possible without the cooperation of the authors and the publishing
staff at TMS (Warrendale, PA, USA).

We truly hope that this volume will provide engineers, scientists, and technologists
with new perspectives and directions in their research endeavors toward evaluating,
understanding, and improving the fatigue behavior of materials, spanning the entire
spectrum to include both engineering materials and engineered materials.

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Dr. Srivatsan has authored/edited/co-edited fifty-three (53) books in areas cross-pollinating mechanical design; processing and fabrication of advanced materials; deformation, fatigue, and fracture of ordered intermetallic materials; machining of composites; failure analysis; and technology of rapid solidification processing of materials. He serves as co-editor of International Journal on Materials and Manufacturing Processes and is on the editorial advisory board of journals in the domain of Materials Science and Engineering. His research has enabled him to deliver over two-hundred plus (200+) technical presentations in national and international meetings and symposia; technical/professional societies; and research and educational institutions. He has authored and co-authored over six-hundred and fifty plus (650+) archival publications in international journals, chapters in books, proceedings of national and international conferences, reviews of books, and technical reports. In recognition of his efforts and contributions and his impact on furthering science, technology, and education he has been elected Fellow of American Society for Materials, International (ASM Int.); Fellow of American Society of Mechanical Engineers (ASME); and Fellow of American Association

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FATIGUE of MATERIALS III
ADVANCES and EMERGENCES
in UNDERSTANDING

Aluminum
IMPROVEMENT OF FATIGUE PROPERTIES OF CAST ALUMINUM ALLOY A356 BY WARM DEFORMATION

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Abstract

Aluminum foundry alloys such as A356 are used extensively in applications where high cycle fatigue (HCF) resilience is a key design consideration. Fully reversed, multiaxial HCF studies on this alloy in the T6 condition have shown that endurance limits are governed by maximum principal stress and driven by crack propagation as opposed to initiation. In light of these fatigue characteristics, it has been found that warm deformation imparted via flow forming prior to heat treatment improves the fatigue resilience by upwards of 30% depending on the degree of deformation. The fatigue performance improvement has been attributed to eutectic particle size and morphology changes and potential recrystallisation of the primary phases. This hypothesis is supported by extensive particle characterisation and preliminary EBSD results.

Keywords: A356, Fatigue, Flow forming
1. Introduction

Aluminum castings are employed by many different industries to provide lightweight, near net-shape components. However, these components may be defective due to inherent porosity and microstructure inhomogeneity. Standard forging operations can mitigate some of these issues, but are expensive in terms of tooling and operation costs. A lower cost and more flexible alternative for hollow axisymmetric components is rotary forming. This process consists of fixing the workpiece on a rotating mandrel followed by local deformation with a roller or other shaping tool which moved axially along the component. This introduces a highly localized plastic zone which reduces the wall thickness and elongates the component. Rotary forming is often commercially referred to as spinning, shear forming or flow forming depending on the degree of deformation imparted to the workpiece [1].

A356 (Al-7Si-0.3Mg) is a common aluminum casting alloy consisting of a dendritic structure comprised of α-Al surrounded by Si-rich eutectic (Fig. 1) which typically undergoes a T6 heat treatment after casting. High cycle fatigue (HCF) lives within this material are typically decided by porosity and large eutectic particles or other inclusions remaining post-heat treatment [2]. Previous work [3, 4] which investigated the multiaxial fatigue properties of this alloy have indicated that fatigue life limiting defects are quite large, upwards of 400 µm as crack propagation dominates HCF behaviour. Outside of pure torsion, the maximum principal stress is the primary driver of crack propagation which indicates that S-N data tabulated from uniaxial fatigue testing may be employed to gauge multiaxial performance.

2. Experiment details

Two sources of flow formed A356 were used to characterize the effects on fatigue resilience due to processing. Material that was commercially formed and heat treated to the T6 condition was received as unmachined, low pressure die cast wheel blanks from a North American automotive wheel manufacturer, referred to further as 'commercial'. The second source of material was modified as-cast (AC) wheel blanks from the same supplier. A portion of these blanks were T6 treated immediately and the remainder processed with a purpose-built experimental rotary forming apparatus, referred to further as 'experimental'. The second source of material was modified as-cast (AC) wheel blanks from the same supplier. A portion of these blanks were T6 treated immediately and the remainder processed with a purpose-built experimental rotary forming apparatus, referred to further as 'experimental'. In both cases, the material was deformed at a target temperature of 350°C, with the commercial material experiencing heavy deformation (upwards of 50% wall thickness reduction) and the experimental material undergoing light deformation (approximately 10% wall thickness reduction). All material in this study was subjected to a standard T6 heat treatment consisting of solutionizing at 540°C for 3 hours, followed by a 60°C water quench and concluded with an artificial aging period at 150°C for 3 hours immediately after quenching. The effect of deformation on the microstructure showed either a light deformation of the dendrite cells in the direction of forming or a complete loss of dendritic structure. The former microstructure was predominant in the experimental material, while the commercial material exhibited a range of microstructure between the two conditions.
Figure 1. As-cast A356 microstructure (left), as-cast eutectic (top right) and eutectic post T6-treatment (bottom right).

Table 1. Source, condition and quantity employed in fatigue study.

<table>
<thead>
<tr>
<th>Source</th>
<th>Condition</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Comm.</td>
<td>4 (A)</td>
<td>24 (AD)</td>
</tr>
<tr>
<td></td>
<td>4 (H)</td>
<td>4 (HD)</td>
</tr>
<tr>
<td>Exp.</td>
<td>AC 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Formed 12</td>
<td></td>
</tr>
</tbody>
</table>

Post heat-treatment, hour-glass uniaxial fatigue specimens were extracted with geometry conforming to ASTM E606. The commercially-formed material had specimens extracted from different locations within the blank, corresponding to heavy and light deformation in the axial (A and AD, respectively) and hoop direction (H and HD, respectively). Samples from the experimentally-formed material were drawn solely in the axial direction from the most heavily deformed region of the component. As cast, undeformed material (AC) corresponding to both blank configurations had specimens extracted from equivalent locations. See Table 1 for specimen counts, and Fig. 2 for specimen extraction points.

All specimens were run-out tested to failure under fully reversed conditions (R = -1) with a Sonntag eccentric fatigue machine at 33 Hz, with load amplitudes targeting the mid to high cycle ($10^5$-$10^6$) fatigue regime. The microstructure was analyzed to ascertain effects of forming using microindentation, optical and scanning electron microscopy (OM and SEM) techniques.
3. Fatigue Results

Fig. 3 demonstrates S-N data for undeformed (I commercial and II experimental) versus flowformed (III commercial and IV experimental) material. The improvement in endurance has been quantified by fitting Basquin relationships ($b = 0.17$) through results from each sample type and source via non-linear least-squares (Table 2). As a general assessment of how the endurance limit improved, the commercial and experimental S-N data was combined and fitted. The endurance limit($sf$) evaluated at 106 cycles using this relationship showed an improvement of 75 MPa for undeformed material versus 107 MPa for flow-formed or an improvement of 30%.

Separate analysis on each of the flow-formed specimen streams (experimental vs. commercial) was also conducted. There was little difference in fatigue limit noted for each of the commercial specimen orientations (AD vs. HD) or degree of deformation (A vs. AD and H vs. HD). At least four of the A specimens had fatigue lives that meet or exceed the AD specimens at the same load amplitude. One HD specimen failed prior to an H specimen at a load amplitude of $\sigma^a = 110$ MPa with the opposite occurring at $\sigma^a = 125$ MPa. Therefore, little conclusions can be drawn regarding the effect of orientation and deformation within the scatter of S-N data. Overall, the commercial material showed a 33% increase in fatigue limit over undeformed material. The experimental material showed approximately the same fatigue lives as the specimens taken from the commercial material for loading amplitudes between 110 and 120 MPa, and other specimens had lives falling within two orders of magnitude of the commercial specimens with identical $\sigma^a$. The undeformed experimental material demonstrated significantly higher fatigue limits than the undeformed commercial material (72 vs. 84 MPa, respectively), which accounts for the reason why experimental material only showed a 19% increase in fatigue limit due to forming. This is likely due to a specimen size effect; larger specimens have an increased number of defects which could affect fatigue limits.

Overall, flow-forming has been shown to significantly improve the fatigue properties of A356. Departure from fitted Basquin relationships, quantified by both $R^2$ and RMSE was diminished for both sources of material. As the improvement in fatigue limits for commercial material was appreciably higher than the experimental material, increased deformation and resulting porosity mitigation is the principal reason.
Figure 2. Pre and post deformed geometry of commercial specimens. Micrographs correspond to locations in the diagram above.

Figure 3. Pre and post deformed geometry of experimental specimens. Micrographs correspond to locations in the diagram above.
Figure 4. AC-T6 versus formed-T6 fatigue results.

Table 2. AC-T6 versus formed-T6 Basquin relationships

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Series</th>
<th>Conditions</th>
<th>( \sigma'_f ) (MPa)</th>
<th>( R^2 )</th>
<th>RMSE</th>
<th>( \sigma_f \times 10^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>AC-T6</td>
<td>851.14</td>
<td>0.7441</td>
<td>21.69</td>
<td>72.25</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Commercially formed-T6</td>
<td>1270.02</td>
<td>0.8629</td>
<td>166.7</td>
<td>107.80</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>AC-T6</td>
<td>985.49</td>
<td>0.8322</td>
<td>15.90</td>
<td>83.64</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Exp. formed-T6</td>
<td>1215.16</td>
<td>0.8850</td>
<td>17.32</td>
<td>103.15</td>
<td></td>
</tr>
<tr>
<td>I &amp; II</td>
<td>AC-T6</td>
<td>880.56</td>
<td>0.7454</td>
<td>21.49</td>
<td>74.75</td>
<td></td>
</tr>
<tr>
<td>III &amp; IV</td>
<td>formed-T6</td>
<td>1256.7</td>
<td>0.8703</td>
<td>17.04</td>
<td>106.67</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5. Undeformed A356-T6 eutectic particles (top) versus deformed (bottom)

Figure 6. Phase-specific microhardness measurements of untempered (AC), undeformed-T6 (T6) and deformed-T6 (F-T6)
5. **Summary**

In the case of rotary formed material, a comparison of runout S-N data showed the overall HCF endurance limit was improved by 30% over undeformed material. The commercially processed material showed a 33% increase in endurance limit, and the experimentally flow formed material showed a 19% improvement. As the commercially processed material was deformed to a much higher extent than the experimentally processed material, this implies that increased levels of rotary forming improves the fatigue properties of the material accordingly. The cause for this increase is primarily attributed to the mitigation of porosity. Secondary causes may be attributed to the refinement of eutectic particles induced by processing, which in turn slows crack propagation and potential recrystallization.

6. **References**


ROLE OF DISPERSOIDS ON THE FATIGUE BEHAVIOR OF ALUMINUM ALLOYS: A REVIEW

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ABSTRACT

Aluminum alloys contain dispersoids, namely thermodynamically stable second phase particles ranging in size from 0.1 to 1.0 μm, which are used, for example, to control grain size. The presence of second phase particles could have a beneficial or detrimental effect on fatigue behavior depending on their properties and distribution within the aluminum matrix. Hard non-shearable particles promote cross-slip and deformation homogenization that delays fatigue crack initiation, while shearable particles result in planar slip, which promote strain reversal and crack closure and slows crack propagation. Cracking and fragmentation of the particles, or strain incompatibility at the interface of the dispersoids with the matrix, can lead to the nucleation of cracks ahead of the main advancing crack. This paper presents a review of the effect of dispersoids on the fatigue behavior of aluminum alloys.
1. Introduction

Fatigue failure or failure of an engineering component that occurs after repetitive or fluctuating loads has been attributed to over 90% of service related failure of metallic components. Based on the stress level, fatigue behavior has been broadly classified into high cycle fatigue (HCF), when the stress is below the macroscopic yield strength of the metal, and low cycle fatigue (LCF), when the stress level exceeds the yield stress over a part of the loading cycle. LCF failures are broadly grouped into failures that occur after less than about $10^4$ cycles whereas HCF failures occur after $10^6$ or more cycles. There is, however, no definite boundary that separates LCF from HCF behavior, because, irrespective of the type of failure, fatigue failure typically progresses through three stages, the initiation of a crack, the growth of the crack, and finally fast fracture when the remaining cross section of the component is no longer able to support the applied load, as shown in Figure 1. The initiation and growth stages of fatigue failure involve the movement of dislocations, while the final fracture is related to the fracture toughness of the material.

Models for fatigue crack growth (FCG) that are based on linear elastic fracture mechanics relate FCG rate to the range of stress intensity factor $\Delta K$ resulting from the variation in stress. If there is a pre-existing crack of length $a$ in a sample, and the stress varies between $\sigma_{\text{min}}$ and $\sigma_{\text{max}}$, then the stress intensity factor range is $\Delta K = K_{\text{max}} - K_{\text{min}} = \sigma_{\text{max}} \sqrt{\pi a} - \sigma_{\text{min}} \sqrt{\pi a}$. In Figure 1, the FCG rate is essentially zero when $\Delta K$ is below a threshold $\Delta K_{\text{th}}$. Under these conditions, though cracks may be present in the material, they do not grow. In Region II, cracks grow as a function of $\Delta K$. The Paris model for the growth of cracks is given by: $da/dN = A(\Delta K)^n$; where the LHS is the rate at which the crack length $a$ increases for each cycle of fatigue loading. $A$ and $n$ are empirical material constants. During fatigue loading, the crack length increases continuously, as a result $\Delta K$, also increases. Once the crack length reaches a critical value, there is a rapid and unstable crack growth because $K_{\text{max}}$ has reached a value equal to the fracture toughness of the material $K_{\text{IC}}$.

Improvements in fatigue behavior can be achieved by addressing the factors that influence the initiation and growth stages of cracks. At the macroscopic level, this involves elimination mechanical stress concentrators such as notches, localized changes

![Figure 1. Fatigue crack growth (FCG) as a function of $\Delta K$ [1]](image-url)