IMPROVEMENT OF FATIGUE STRENGTH OF AA 7050 T7451

A. Heinz and W. Schelb
Hoogovens Aluminium Walzprodukte GmbH, Postfach 920, D-56009 Koblenz, Germany

Abstract

Efforts were undertaken to considerably improve fatigue strength of 7050 T7451 plate. Under constant amplitude axial fatigue loading premature failure was found to be due to early crack initiation at casting related inclusions and micropores in the thin and thick gauge range, respectively. Critical processing parameters were identified and four different processing approaches designed. Results were evaluated by assessment of fatigue life as well as microstructure using quantitative optical, acoustic and X-ray microscopy.

Introduction

Due to its excellent combination of strength, damage tolerance and corrosive properties alloy 7050 is widely used in thick sections for aerospace applications. One drawback in this context is the fact that fatigue properties normally decrease with increasing product thickness. Therefore fatigue performance of heavy gauge 7050 material may be a limiting factor and improving the fatigue strength may translate directly into an expanded applicability. Thus there is an increasing interest of the aerospace industry in fatigue resistant thick 7050 material in recent years.

As a supplier of thin and heavy gauge plate for aerospace applications Hoogovens Aluminium is comitted to a steady improvement of critical material properties. Therefore a project was defined in order to improve the fatigue performance of thick 7050 plates without sacrificing any other relevant property such as strength, toughness, ductility or corrosion resistance. The project comprised of three major activities. As a first step the reason for premature fatigue failure was analyzed in thin and thick plate material, respectively. Then several methods for the characterization of the relevant microstructural features were developed. Parallel to this a number of different approaches were designed in order to determine the influence of various processing parameters on both the microstructure and the fatigue performance of the finished plates. This part of the program involved both laboratory work and production trials. Finally a new process for the fabrication of fatigue resistant thick plate was defined, which is Hoogovens proprietary and leads to a drastically improved fatigue strength of thick plates in the gauge range above 100mm (4inches).

Step 1: Failure Analysis

An investigation on several lots fabricated according to Hoogovens' standard practice was performed in the beginning of the project. About 60 specimens from 14 different lots in the gauge range from 30 to 152mm (1.2-6.0inches) were fatigue tested and subsequently inspected in a scanning electron microscope (SEM). This investigation revealed that fatigue cracks initiated exclusively at micropores in the case of heavy gauge plates while in thinner material non-metallic inclusions were usually found as nucleation sites. Fig. 1 shows a SEM micrograph of a fractured smooth axial fatigue specimen. The lower part of the micrograph represents the original surface of the specimen while the upper part shows the fracture surface. In the middle of the micrograph the crack nucleation site can be identified by the radial fatigue marks emanating from a microdefect in the middle. The higher magnification of Fig. 2 reveals that this defect is a micropore of about 270μm length which was caused by shrinkage during solidification.

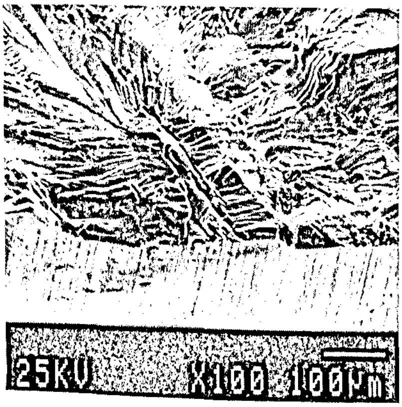


Fig. 1

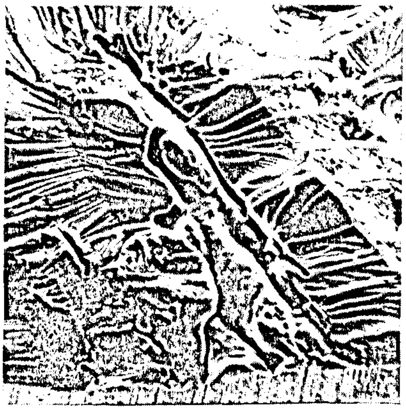
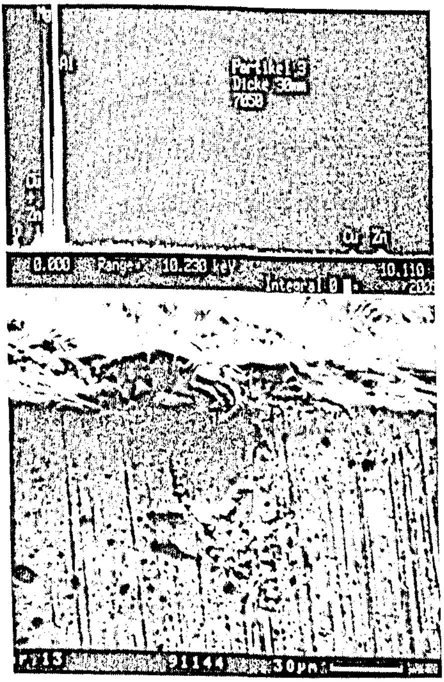


Fig. 2

Fig. 1: Fatigue failure in thick (152mm) 7050 T7451 plate material
Fig. 2: Higher magnification of Fig. 1 (x2.5); crack initiation by a micropore

An example of crack initiation in thin material is given in Fig. 3. The lower part shows the fractured fatigue specimen with a non-conductive particle as the crack nucleation centre in the middle. The energy dispersive X-ray (EDX) analysis of this particle shown in the upper part of Fig. 3 reveals that failure was due to an oxide inclusion in this case.

Log-average fatigue life versus plate thickness in the gauge range from 50 to 152mm (2-6 inches) is shown in Fig. 4. The arrows indicate that fatigue tests were terminated at a maximum of 1,000,000 cycles if failure did not occur. Fatigue life decreases with increasing plate thickness. Obviously the crack initation phase was accelerated dramatically by the micropores that were present in thick plate material. As the relevant gauge is above 100mm (4inches) it was decided to concentrate on the improvement of fatigue strength by suppressing microporosity in these thick sections.



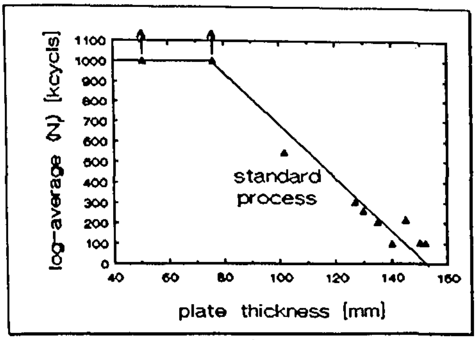


Fig. 4

Fig. 4: Influence of plate thickness on average fatigue life, standard production practice at the beginning of the project

Fig. 3: Crack initiation by an oxide inclusion in thin (30mm) 7050 T7451 plate material

Step 2: Material Characterization

Microporosity

Metallography, Penetrant Inspection and Optical Microscopy (OM): Both plate and ingot samples were used for analysis of failure inducing microdefects in the as-cast and finished plate structure, respectively. Metallographic samples with dimensions of approximate 50x80mm were prepared from 12.7mm (0.5inch) thick ingot and plate slices which were excised perpendicular to the casting and hot rolling direction, respectively. The smeared out material covering the surface of the micropores after grinding and polishing was removed by pickling using a standard solution described in [1]. The samples were penetrant inspected with an ultraviolet (UV) fluorescent penetrant. The UV reflections were marked and the samples were transfered to an optical microscope in order to check whether each individual reflection was due to a pore or an artefact. After that pore size distributions were measured using an optical microscope and an image analyzer system. Penetrant inspection tests were also performed on full thickness samples excised from ingot or plate material.

Acoustic Microscopy (AM): Metallographic samples similar to those used for optical microscopy were inspected with a high frequency scanning acoustic microscope. This technique uses an ultrasonic (US) probe that focuses US waves on a certain plane in the specimen via a sapphire lense. The US probe scans the specimen in a rectangular pattern. The US signals returning to the probe are gated so that only signals returning from a layer at a specific depth of the specimen are used for evaluation. Defects in this layer cause a change of the intensity of the returned US signals. This variations in intensity are used to produce a map of defect sites of the scanned area. The lateral resolution of the method increases and the penetration depth decreases with increasing frequency of the US waves. The parameters for the inspection tests were adjusted in order to reveal defects in a 75μm thick layer approximate 300μm below the surface. For further details of this technique see [2-4]. The acoustic images were transfered to an image analyzer system to evaluate the defect size distributions of the inspected specimens.

Plate Properties

Fatigue Testing: Blanks for smooth axial fatigue specimens were sawn from the center thickness at the one third width position at each end of the fabricated plates. Sample preparation and fatigue testing was performed by a certified test house (Westmoreland Mechanical Testing and Research Inc., Youngstown, PA, U.S.A.). Testing conditions were specified as per ASTM E466 and [5] (constant amplitude smooth axial fatigue, axis parallel to long transvers direction, length and diameter of test section: l=50.8mm (2inch), d=12.7mm (0.5inch), air, room temperature, frequency f=10/s, stress ratio R=0.1). Usually a maximum stress of 241MPa (35ksi) was applied which is required by the aerospace industry [5-6].

Mechanical and Corrosive Testing: In order to check if there is an influence of modified processing variables on final plate properties mechanical and corrosive testing was performed in accordance with ASM 4050 [7] on full thickness samples which were sawn at the midwidth position at each end of the finished plates.

Step 3: Production Trials

Based on the above mentioned methods a number of critical processing steps and parameters were identified. As laboratory equipment appeared to be non-adequate a statistically designed program of production trials was defined to determine the influence of these critical processing parameters on final plate properties. A number of ingots were DC cast at Hoogovens' plant in Koblenz, Germany, hot rolled to 152mm (6inch) thick plates and artifically aged to the T7451 temper. The finished plates were tested as described above in order to verify the anticipated influence of processing variables on microstructure and fatigue performance.

Results

Microporosity

An optical micrograph of a typical pore cluster as it is found in the as-cast structure is shown in Fig. 5. The individual pores of the cluster are presumably connected below the surface via interdendritic channels which are due to shrinkage during solidification. Fig. 6 shows the pore density as a function of pore diameter for three different locations within the cross-section of the ingot. The material was cast according to Hoogovens' standard casting process and the pore density was measured using optical microscopy. The detrimental influence of porosity on fatigue strength was expected to increase with increasing pore size. Therefore an arbitrarily chosen limit to assess the influence of location and processing variables on microporosity was defined which is represented by the vertical line at 80μm.

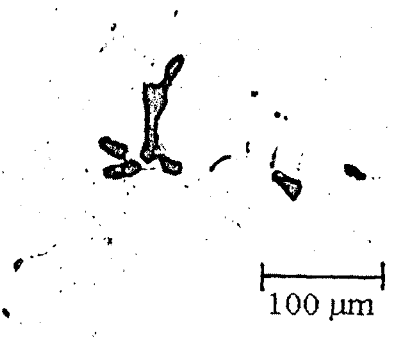


Fig. 5

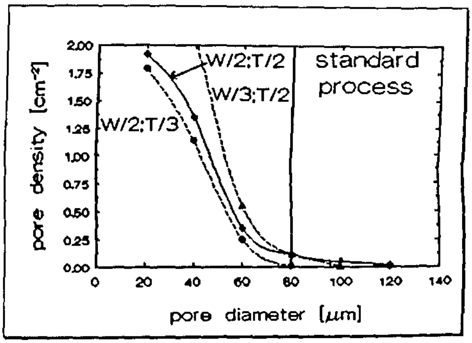


Fig. 6

Fig. 5: Cluster of micropores in the as-cast structure of a 7050 ingot, standard casting process
Fig. 6: Influence of position within the ingot cross-section on pore size distribution;
W=width, T=thickness of ingot, standard casting process

It is obvious from Fig. 6 that the critical position within the ingot cross-section is the midplane (W/2-T/2/W/3-T/2) as remarkable porosity is found above 80μm. Outside the center plane porosity was less pronounced and no pores were measured above the assessment limit.

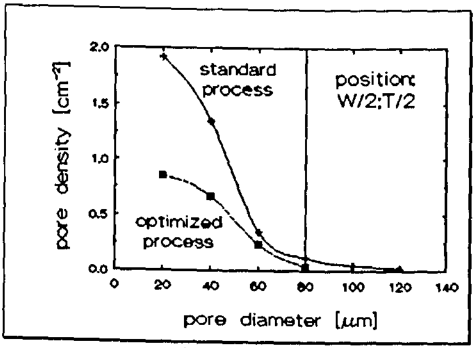


Fig. 7a

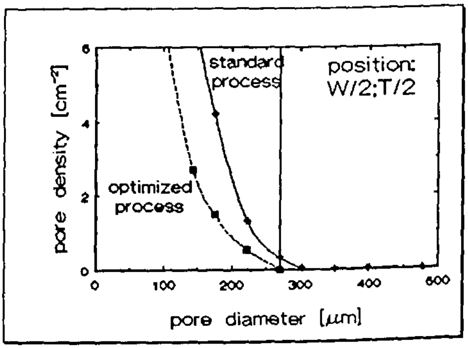


Fig. 7b

Fig. 7a: Microporosity is reduced by a modified casting process, optical microscopy
Fig. 7b: Same specimens as in Fig. 7a, but pore densities measured by acoustic microscopy

Fig. 7a shows that microporosity at the critical position could be reduced considerably by optimizing the process. Pore density could be decreased by a factor of two and - more important - no remaining porosity was detectable above 80μm. Fig. 7b shows a similar result which was obtained by acoustic microscopy on the same specimens as in Fig. 7a. Compared to optical microscopy the pore sizes are shifted to larger diameters. This is mainly due to the subsurface extension of the micropores which is not revealed of course by optical but by acoustic microscopy. Accordingly the assessment limit had to be shifted to a larger value for the acoustic microscopy. A further fact is that the densities of small pores are much larger when determined by acoustic microscopy. This is shown in Fig. 8, where the pore density measured by acoustic microscopy is plotted versus the pore density measured by optical microscopy. Large values of pore density refer to small pore diameters and vice versa. If the pore density exceeds a value of approximate 0.05 pores per square centimeter acoustic microscopy detects considerably more pores than optical. This is due to the fact that the acoustic microscope probes a 75µm thick subsurface layer and therefore measures a much larger number of pores provided that the diameters of these pores are below the thickness of the probed layer. If the diameter of the pores under consideration is larger than that thickness however both methods will give the same results. This can be seen in Fig. 8 for small pore densities which correlate to large pore diameters. As large pores are considered to be detrimental to fatigue strength both methods are essentially of the same relevance.

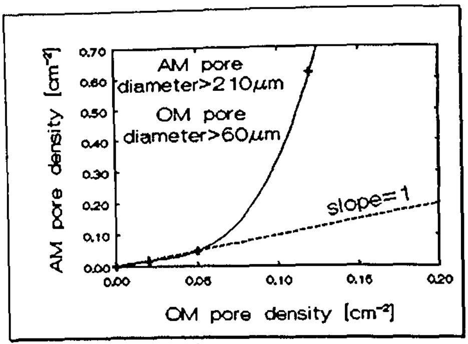


Fig. 8

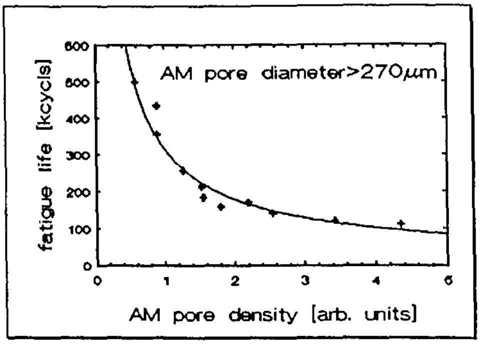


Fig. 9

Fig. 8: Pore densities measured by optical and acoustic microscopy

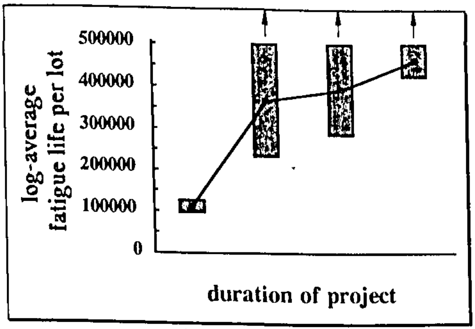
Fig. 9: Fatigue life of finished plate as a function of pore density in the as-cast structure, pore densities measured by acoustic microscopy

In order to calibrate fatigue performance of the finished plate against pore density in the as-cast structure a number of ingots were cast with varying defect densities and fabricated to 152 mm (6inch) thick plates. An exponential dependence of average fatigue life on pore density resulted (cf. Fig. 9). Fig. 9 allows also to deduce maximum values for microporosity in the as-cast structure for obtaining satisfying fatigue strength of the finished plate.

Fatigue Testing

The scatter of log-average fatigue life of 152mm (6inch) thick plates is plotted versus the duration of the project in Fig. 10. The arrows indicate that fatigue testing was terminated at a maximum of 500,000 cycles if failure did not occur. The left column represents the situation at the beginning of the project where average fatigue life was between 95,000 and 127,000 cycles. Step by step fatigue strength could be improved by taking into consideration further critical processing variables. The right column represents the optimized processing route. Its lower limit is 422,300 cycles, which is an improvement of +340% compared to 95,000 cycles from the beginning of the project.

The achieved improvement is also demonstrated very impressively by Fig. 11 which shows the cumulative failure as a function of the logarithmic fatigue life for 152mm (6inch) thick plates. The plates were fabricated by either the standard (4 lots) or the optimized (6 lots) processing route. A value of 5.7 on the x-axis represents a fatigue life of 500,000 cycles which was the value to terminate the tests. The plates manufactured according to the standard procedure exhibit a scatter of fatigue life between 80,000 and 150,000 cycles. The plates of the optimized process on the other hand show fatigue lifes between 142,000 and at least 500,000 cycles. In fact only four of the tested specimens failed before half a million cycles and all others were runouts. These results were confirmed so far by a total of 18 production lots.



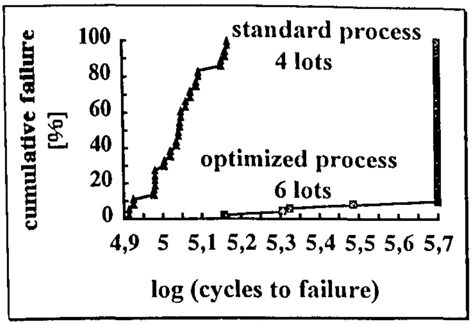


Fig. 10 Fig. 11

Fig. 10: Improvement of average fatigue life per lot during the project

Fig. 11: Cumulative failure versus logarithmic fatigue life, standard and optimized process, almost all specimens of the optimized process were runouts at 500,000 cycles

Finally, Fig. 12 shows the S-N-curves of both the standard and the optimized plate material (gauge: 152mm=6inch). The applied stress amplitudes range from 138 to 345MPa (20 to 50 ksi). At the required stress level of 241MPa (35ksi) the fatigue life could be improved from about 100,000 to at least 3 million cycles. For a given fatigue life of 100,000 cycles on the other hand the applied stress was considerably raised.

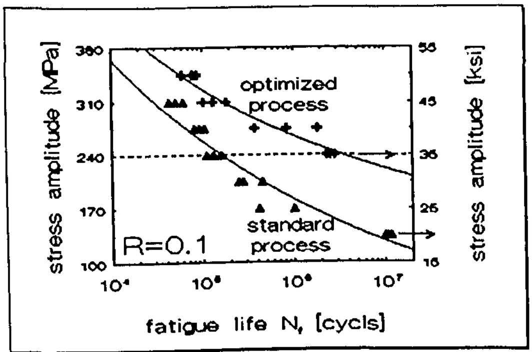


Fig. 12: S-N-Curves of 6in thick plates fabricated by the standard and the optimized process

Mechanical Properties

The mechanical properties of thick plates (152mm=6inch) that were fabricated according to the new process were evaluated and compared to the results obtained for standard processing. No significant difference could be found for the two processing routes except for short transvers (ST) elongation and T-L fracture toughness which could be slightly improved.

Conclusions

1. When fabricated according to the standard processing route fatigue failure was exclusively due to micropores in the thick and to inclusions in the thin gauge 7050 T7451 plates.
2. Both optical microscopy in connection with penetrant inspection and acoustic microscopy both followed by automated image analysis are suitable methods to characterize microporosity in 7050 ingots and plates.
3. Microporosity has been characterized throughout the cross-section of commercial ingots.
4. Microporosity at the critical position within the ingot has been related to fatigue performance of the finished plate.
5. By optimized processing fatigue strength of thick 7050 T7451 plate material was improved drastically without sacrificing any other relevant property such as strength, ductility, toughness or corrosion resistance.

Closing Remark

Apart from the development work described above Hoogovens Aluminium Koblenz is presently working on the implementation of a new inspection technique that allows for an assessment of fatigue strength via ultrasonic nondestructive inspection of the whole finished plate. The method was developed recently by another group and will also provide an ideal tool for quality assurance purposes. In principle it uses the attenuation of ultrasonic waves by microporosity as a measure for the pore density in the plate. As microporosity in turn is related to fatigue life it is possible to calibrate ultrasonic attenuation versus fatigue life for a given material and a given plate thickness. For further details of the new technique see **[8]**. A number of thick 7050 plates that were fabricated in accordance with the new process were inspected using this facility which also confirmed their excellent properties compared to standard plate material.

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