Influence of the production process on the deformation and fatigue performance of friction drilled internal threads in the aluminum alloy 6060*

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Aluminum alloys are used for enhancement of dynamic range, resource optimization and emission reduction in many fields of traffic engineering, whereby aluminum components are manufactured by means of welded, adhesive and screw joints. Friction drilling, as forming process with subsequent manufacturing of threads, offers the opportunity to produce an internal thread in lightweight profiles with a usable thread depth larger than the profile thickness, making use of local material expansion. Moreover, the direct manufacturing offers a huge potential for time and cost saving in comparison to conventional thread machining. Microstructural characterization of mechanical properties of EN AW-6060 internal threads, both in profile and bulk material specimens, was carried out using tensile tests and fatigue tests in the tensile loading range. A comparison was made between the manufacturing techniques tapping, thread forming and thread milling. The maximum tolerable loads of the profile specimens are about 50 % lower in the quasi-static range and about 25 % lower in the cyclic range in comparison to bulk material specimens. Formed threads show the best and cut threads the worst mechanical properties which were correlated with the production-related profile qualities and changes in microstructure. Multiple step tests prove that the fatigue limit of aluminum internal threads, validated in single step tests until 10^7 cycles, can be reliably estimated by means of plastic strain.

Article Information

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Aluminum alloys have been established for saving material, energy and costs as well as for weight reduction of components and are used in many fields of technical engineering, especially in automotive industry [1]. The various advantages that accrued are, for example, carriages of relative high cargo loads with low vehicle weights and high maximum velocities with reduced fuel consumption. By reducing the weight of specific components, the functionality must be obtained. Therefore, newly developed aluminum alloys are often used, that ensure high stiffness at minimal weight. Aluminum alloys provide various application possibilities due to their low density and good machining behavior.

Friction drilling processes are used to generate high strength threads in lightweight profiles [2, 3]. In the conventional process, a fast rotating tool penetrates perpendicular into the profile wall, whereby bushings are formed chipless in feed direction without additional material input [4]. Subsequently, heavy duty threads with increased usable thread depths can be generated so that more flanks of the internal thread are usable [5]. Furthermore, a newly developed applicability of the friction drill-

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ing process to generate sustainable internal threads is the machining of the cross-sectional area of thin-walled profiles.

This contribution deals with the qualitative comparison of the mechanical properties of internal threads manufactured by means of the new method of friction drilling. The research focus is the characterization of the quasi-static and cyclic deformation behavior of internal threads from aluminum wrought alloy EN AW-6060 and the behavior correlation with the profile qualities and process induced microstructural changes.

Testing strategy

The mechanical properties of internal threads in rolled flat profile specimens were investigated to characterize the influence of the common manufacturing techniques tapping (thread cutting, TC), thread forming (TF) and thread milling (TM) on the quasi-static and cyclic deformation behavior, whereby extruded bulk material specimens with equivalent threads were used as a reference. Since the microstructures of flat profile and bulk material specimens vary, due to different heat treatments, this study focuses on the influence of different production chains on the mechanical behavior. Tensile and fatigue tests in form of continuous load increase tests in tensile load range were performed and microstructurally evaluated. The fatigue strength of internal threads was estimated in continuous load increase tests [6, 7] by the determination of the transition from nearly steady to significantly increasing materials response values (see Figures 6 and 7), and validated in single step tests until 10^7 cycles [8-10]. The maximum loads and fracture strains determined in quasi-static and cyclic investigations, respectively, were compared to quantify the production chain-related influences on the mechanical properties of the manufactured specimens. After the mechanical investigations, the results were correlated with the profile qualities and microstructural changes of the internal threads at initial condition, i. e., after manufacturing and before mechanical testing. For that purpose, longitudinal sections were prepared for metallographic investigations and microhardness tests at thread crests and roots.

Specimen preparation and experimental setup

The core holes and M10 internal threads were drilled on a machining center (Grob, BZ 600) with three synchronic axes, a CNC path control system (Siemens, Sinumerik 840D) and a horizontally arranged main spindle with a speed range of n = 45...12 500 min^{-1} including a tool holder system (HSK 80). The core holes in bulk material specimens were drilled by means of conventional drilling with a cutting speed of v_c = 222 m/min and a feed of f = 0.4 mm. A peripheral speed of v_u = 330 m/min and a feed of f = 0.025 mm were used for the friction drilling process in flat profile specimens, whereby the nominal diameter of the subsequent manufactured threads corresponded to the wall thickness of the specimens (d = 10 mm). Tapping and thread forming were conducted with a cutting speed and peripheral speed, respectively, of v_c = 40 m/min, whereby the feed was determined by the control. Thread milling was conducted with a cutting speed of v_c = 300 m/min and a feed of f = 0.08 mm. The used geometry for bulk material and flat profile specimens including the position of the M10 internal threads are schematically shown in Figure 1.

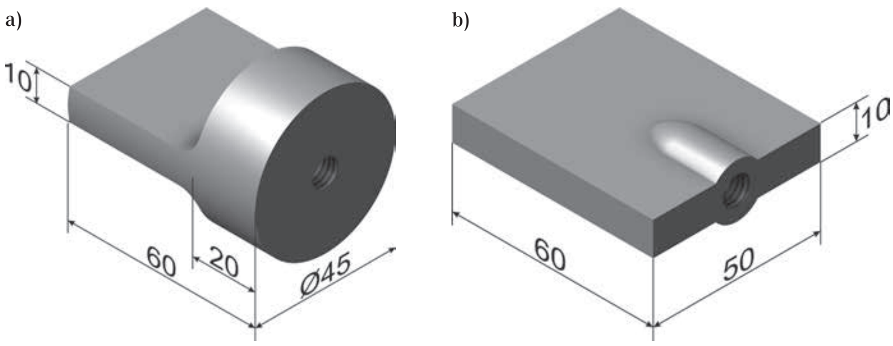

Figure 1: Geometry of specimens, a) bulk material, b) flat profile

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
DIN EN 573-3	0.3-0.6	0.1-0.3	0.1	0.1	0.35-0.6	0.05	0.15	0.1	balance
Bulk material	0.43	0.16	0.01	< 0.05	1.55	0.01	< 0.05	< 0.05	97.44
Flat profile	0.48	0.16	< 0.05	< 0.05	1.46	0.02	0.01	0.01	97.53

Table 1: Chemical compositions of both alloys of EN AW-6060 type (wt.-%)

The chemical compositions of both aluminum wrought alloys of EN AW-6060 type used for specimen preparation are given in Table 1 in wt.-%. The values were determined by an energy dispersive X-ray fluorescence spectrometer (Shimadzu, EDX-720-P). The limiting values for alloying elements and impurities, respectively, are also given as reference according to DIN EN 573-3. All elements are in the range according to the standard except magnesium whose values for bulk material and flat profile specimens are above the given maximum value.

Figure 2 illustrates the microstructures of bulk material (a) and flat profile (b) specimens before manufacturing as light micrographs taken with polarized light after electrolytic Barker's etching. The bulk material specimens were heated up and extruded at T = 430 °C. The heat treatment of flat profile specimens lead to T6 condition, i. e. solution heat treatment and artificial aging. The grain sizes were determined by means of linear intercept method (see Table 2). Three different orthogonal planes were measured in two different directions to take account of possible anisotropy. The grain sizes in bulk material specimens are 229 µm parallel to extrusion direction a_3 and 139-147 µm perpendicular to extrusion direction (grain deformation about 60 %). Flat profile specimens are characterized by grain sizes of 50-60 µm; thus more homogenous and independent from rolling direction a_1 and about 60-75 % smaller than that in bulk material specimens.

Quasi-static tensile tests were performed at room temperature on a universal testing system (Shimadzu, AG-X plus) with a maximum load of 100 kN with an integrated high accuracy video extensometer (Shimadzu, TRViewX) for strain measurements. The experimental setup is illustrated in Figure 3a. A threaded steel rod M10 in strength class 12.9 was used as counter thread. The aluminum specimen was connected with a steel counter holder to the threaded rod. The geometry of the counter holder was equivalent to the geometry of bulk material specimens. The

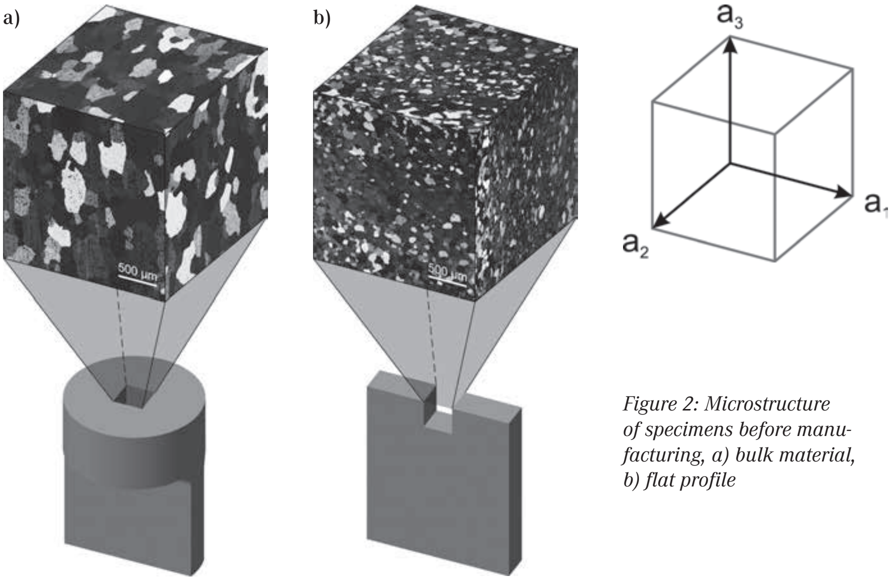

Figure 2: Microstructure of specimens before manufacturing, a) bulk material, b) flat profile

Specimen	Direction	Grain size (µm)
Bulk material	a_1	147 ± 13
	a_2	139 ± 15
	a_3	229 ± 21
Flat profile	a_1	60 ± 9
	a_2	56 ± 4
	a_3	50 ± 4

Table 2: Grain sizes before manufacturing

threaded rod was screwed five turns into the test specimen, whereby a defined screw-in depth of t = 7.5 mm was realized. Gauge marks in form of horizontally arranged white hashes on black background were used to measure the elongation by video extensometer in the area of the internal threads. The tensile tests were carried out with a deformation rate of $\dot{\varepsilon} = 2 \times 10^{-3}\ s^{-1}$ (traverse speed v = 5 mm/min) until the abort criterion $F_{ac} = 5\,\%\ F_{max}$, i. e. 95 % loss of maximum force F_{max}, was reached.

Continuous load increase tests (LIT) were carried out at room temperature on a servohydraulic fatigue testing system (Schenck PC63M with Instron 8800 control unit) with a maximum load of 63 kN. The specimens were loaded with sinusoidal load time functions at a load ratio of R = 0.1 and a frequency of f = 10 Hz. The tests were started at the quasi-damage-free load level $F_{max,start}$ = 1 kN and the load was continuously increased by $dF_{max}/dN = 1\ kN/10^4$ until failure. Deformation-induced changes in strain and electrical resistance were determined load- and cycle-dependent as material responses [7-9]. The experimental setup for the fatigue tests is illustrated in Figure 3b. The specimen was assembled analogous to the tensile test and applied with a high precision direct current (DC) to measure the change in electrical resistance.

Results and discussion

The maximum forces F_{max} were determined in quasi-static tensile tests. The force-total strain diagrams for thread cutting (TC), thread forming (TF) and thread milling (TM) are illustrated in Figure 4 for bulk material (a) and flat profile (b) specimens. The slopes of the curves are quite similar for the different manufacturing techniques in their respective group. A linear force-total strain slope is followed by reaching maximum force with increasing total strain, then a force decrease and a secondary force maximum follows, before a declining trend leads to fracture.

For a better overview, the maximum forces of the tensile tests are illustrated in form of bar diagrams in Figure 5a. The values for flat profile specimens are about 56-62 % less than those in bulk material specimens. In this context, cut threads (TC) show worst and formed threads (TF) best mechanical properties. In Figure 5b the failure force amplitudes $F_{a,f}$ from continuous load increase tests are given in form of bar diagrams. The values for flat profile specimens are about 24-30 % less than those in bulk material specimens. Cut threads (TC) show worst and formed threads (TF) best mechanical properties, analogous to the tensile test results. In contrast to maximum loads, the fracture strains of flat profile specimens exceed the characteristic values of bulk material spec-

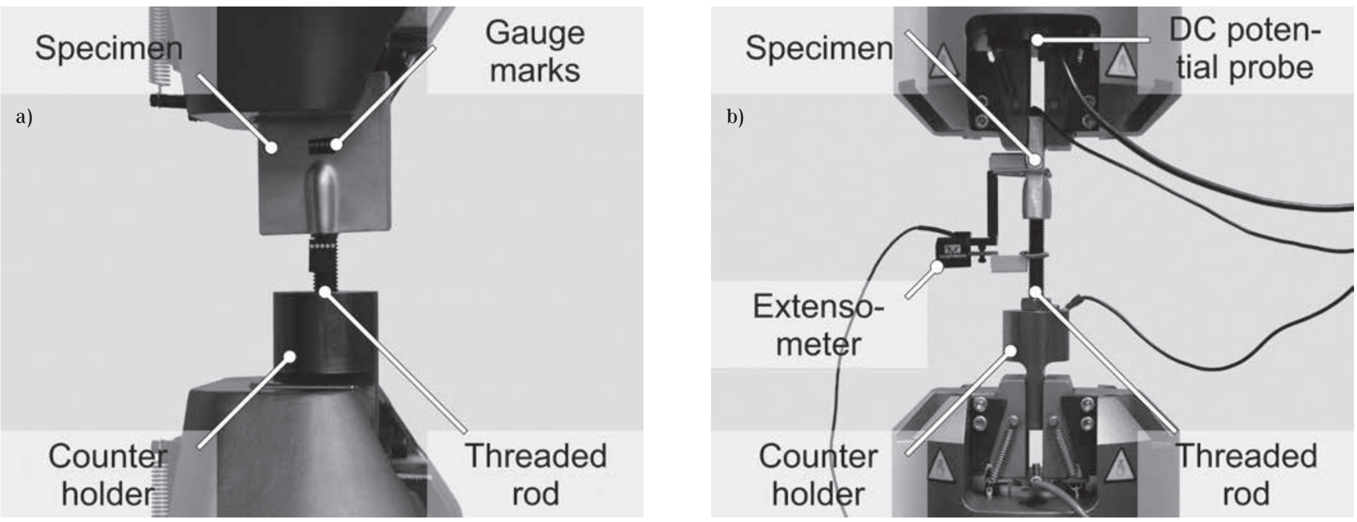

Figure 3: Experimental setups with integrated flat profile specimen, a) tensile test, b) fatigue test

imens in tensile and load increase tests. No special grading is identifiable concerning the different manufacturing techniques.

Figure 6a shows an example of a continuous load increase test (LIT) from a cut internal thread (TC) of a flat profile specimen. The force amplitude F_a and the maximum force F_{max}, respectively, the plastic strain amplitude $\varepsilon_{a,p}$ determined from

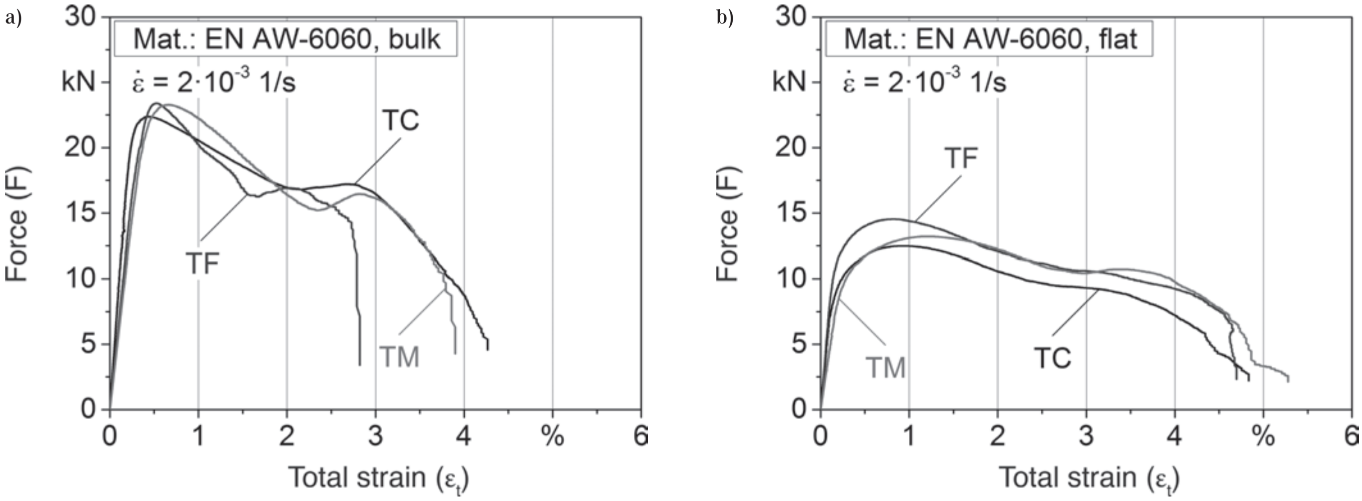

Figure 4: Force-total strain diagrams, a) bulk material, b) flat profile

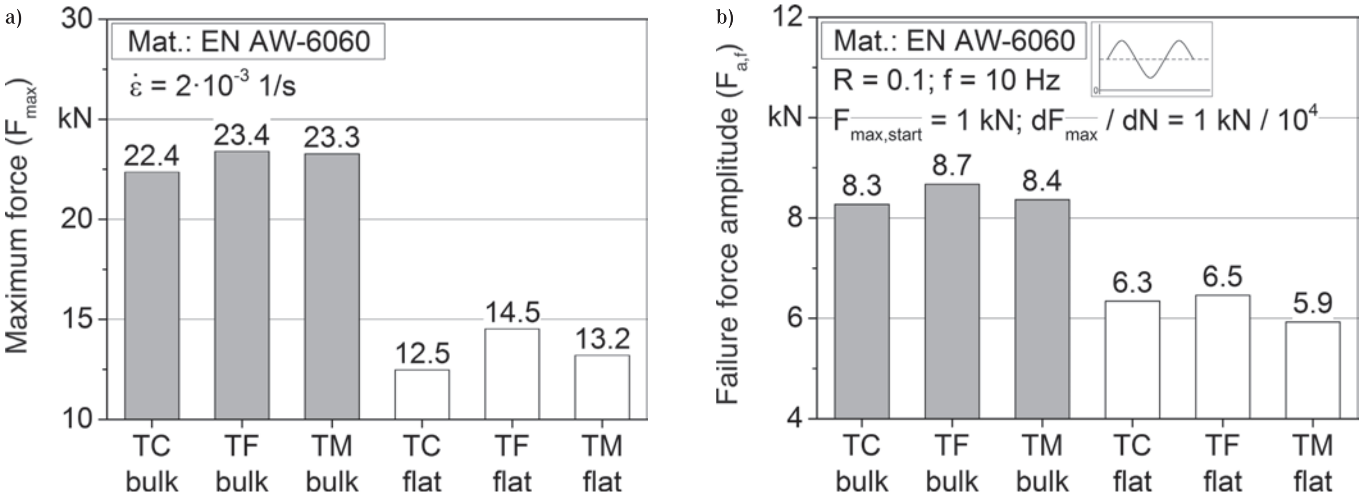

Figure 5: a) Maximum forces in tensile tests, b) failure force amplitudes in load increase tests

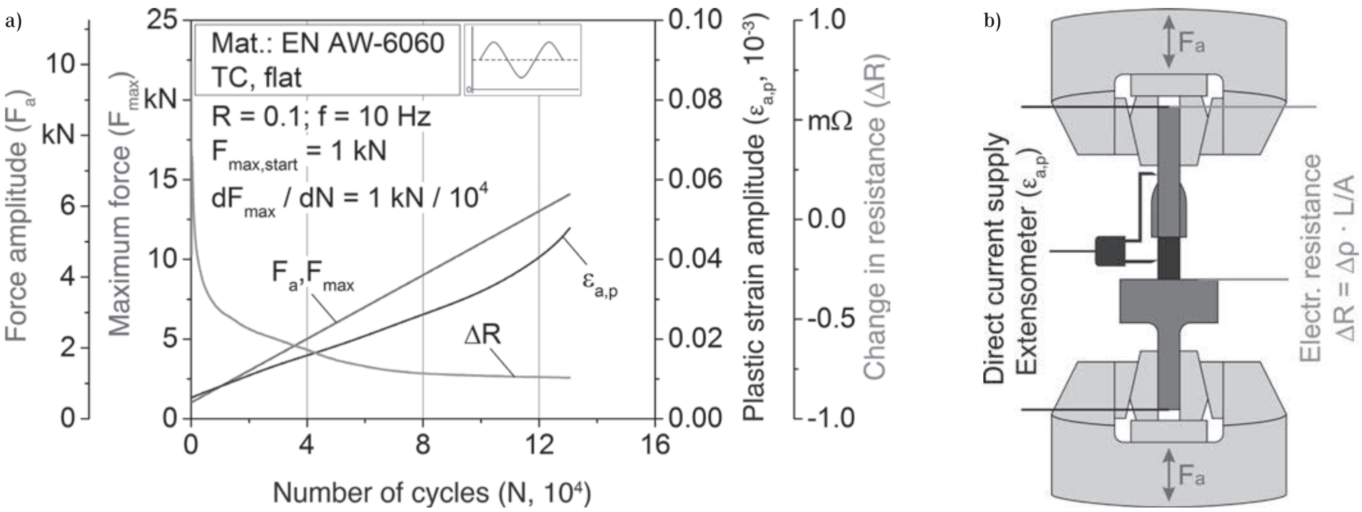

Figure 6: a) Plastic strain amplitude and change in electrical resistance in continuous load increase test for a cut internal thread (TC) in flat profile specimen, b) schematic illustration of clamped flat profile specimen with applied sensors

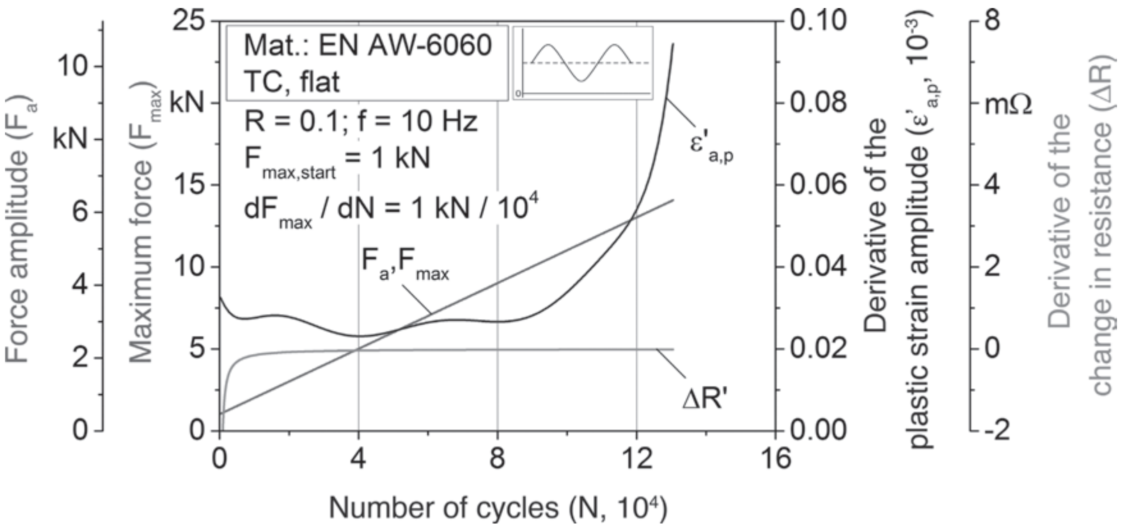

Figure 7: Evaluation of the material reactions for a cut internal thread (TC) in flat profile specimen by means of derivatives

stress strain hysteresis loops and the deformation induced change in electrical resistance ΔR based on microstructural changes are plotted as functions of the load cycles N. The position of the applied sensors for a flat profile specimen is schematically shown in Figure 6b.

Starting at the quasi-damage-free load $F_{max,start}$ = 1 kN, the force was continuously increased by the rate dF_{max}/dN = 1 kN/10^4 until failure. The change in electrical resistance ΔR shows a continuous decrease after a short increase during the initial load cycles. The contact area between the threaded rod and the internal thread increases during the test time. The measurement of the electrical resistance in DC mode seems to record only the macroscopic changes of the threads, so that microstructural changes cannot be distinguished. The plastic strain amplitude increases linearly with load cycles until about N = 8 × 10^4 which corresponds to force amplitude F_a = 4.0 kN, followed by an exponential course until failure at $F_{a,f}$ = 6.3 kN after N_f = 1.3 × 10^5.

For the estimation of the fatigue limit at N = 10^7 cycles, the development of the plastic strain amplitude was mathematically expressed as a differentiated polynomial. The slope of the derivative $\varepsilon'_{a,p}$ is given in Figure 7. The fatigue limit $F_{a,e\,(LIT)}$ was estimated as the force amplitude that leads to a significant change of the materials reaction [7, 9], which is given after the last minimum of the curve. The estimated fatigue limit for a cut internal thread (TC) in flat profile specimen was $F_{a,e\,(LIT)}$ = 3.9 kN at R = 0.1. The derivative ΔR' approximates to nearly zero after about N = 2 × 10^4.

Subsequent to continuous load increase tests, single step tests (SST) were performed to validate the estimated fatigue limits. Figure 8b shows an example of cyclic deformation curves for formed internal threads of flat profile specimens at load amplitudes of F_a = 3.5 kN and 4.0 kN, respectively. The plastic strain amplitude is nearly constant in the tests, whereby higher load amplitude leads to higher $\varepsilon_{a,p}$ values and lower lifetimes N_f. The fatigue limit for a formed internal thread (TF) in

a)

b)

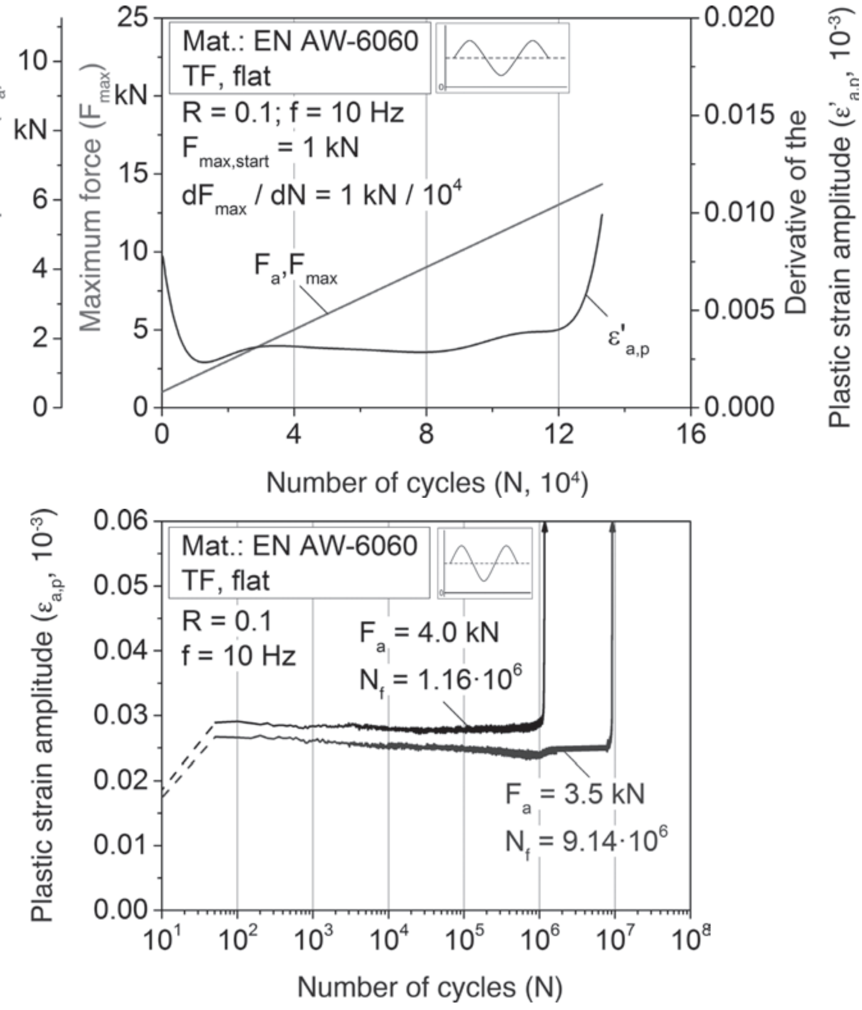

Figure 8: a) Derivative of plastic strain amplitude in continuous load increase test, b) cyclic deformation curves for single step tests; formed internal threads (TF) in flat profile specimens

flat profile specimen was estimated to be $F_{a,e\,(LIT)} = 3.8$ kN and R = 0.1 in load increase test (see Figure 8a). In single step test at loading amplitude $F_a = 4.0$ kN, the number of cycles to failure is $N_f = 1.16 \times 10^6$, whereas with $N_f = 9.14 \times 10^6$ cycles, loading amplitude $F_a = 3.5$ kN nearly exceeds ultimate number of cycles $N = 10^7$. The accordance coefficient of the estimated and determined fatigue limit is about 108 %, i. e. that the fatigue limit estimated in load increase test is 8 % overestimated compared to validation under single step loading until $N = 10^7$ cycles. In other words, the fatigue limit estimated in load increase tests on the basis of the described mathematical basis will not reach $N = 10^7$ cycles but something in between $N = 10^6$ and 10^7 cycles.

The profile qualities of internal threads in initial condition, i. e. after manufacturing and before testing, were microstructurally investigated for correlation approaches with the determined mechanical properties of the different manufacturing techniques. Flat profile specimens showed lower tolerable loads compared with bulk material specimens, due to oval forms of the core holes caused by the friction drilling process. Figure 9 shows a longitudinal section of a cut internal thread in flat profile specimen. The widths of the thread crests at the first three turns were measured lengthwisely and crosswisely. The lengthwise crests were not completely formed which was detected by higher values of the crest widths (about 470 µm in average) in contrast to the crosswise crest widths (about 270 µm in average). The third turn could not be measured lengthwisely because the threads were cut unevenly. Milled threads in flat profile specimens showed a similar picture and formed threads in flat profile specimens had pronounced characteristic claw shapes lengthwise.

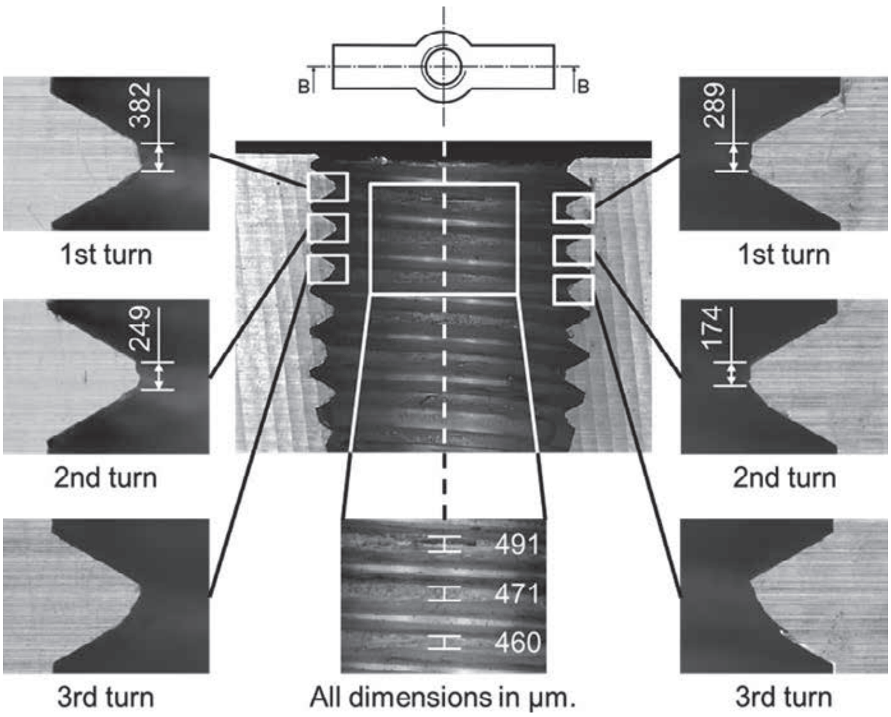

Figure 9: Measuring of thread crests to determine the profile quality of a cut internal thread (TC) in flat profile specimen

The influence of the manufacturing technique on the microstructures of the specimens is illustrated in Figure 10 in form of micrographs. The different grain sizes for bulk material and flat profile specimens are due to the different heat treatments as discussed based on Figure 2. Cut threads, especially those from flat profile specimens, had thread profiles of low quality because the threads were cut unevenly. Formed threads showed characteristic claw shapes, whereby the claws from the flat profile specimens were closed. In addition, work-hardened microstructures were formed at the edge area of the thread crests and roots, respectively. The thread profiles from milled specimens are well constructed and do not show any conspicuous features.

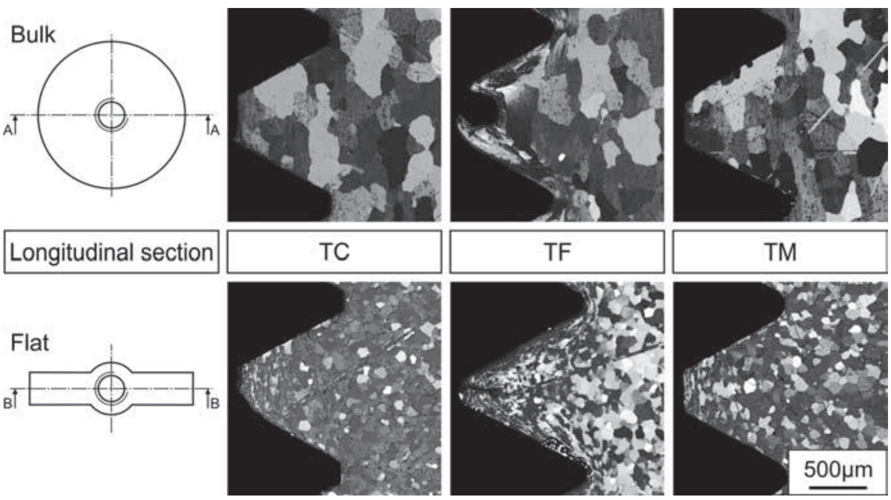

Figure 10: Microstructures of internal threads in bulk material and flat profile specimens at initial condition

The profiles from Vickers micro-hardness tests (Struers, Duramin-5) in thread crests and roots of formed internal threads (TF) in bulk material (a) and flat profile (b) specimens are shown in Figure 11. The basic hardness of bulk material specimens was about 80 HV 0.01 and that of flat profile specimens about 60 HV 0.01. Work hardening was detected at the edge area for formed internal threads in bulk material and flat profile specimens. The increase in hardness was about 20 % in bulk material and about 40 % in flat profiles in contrast to the basic hardness of material. For cut (TC) and milled (TM) internal threads no considerable hardness increases were detected.

Summary

The quasi-static and cyclic deformation behavior of M10 internal threads made by the three different production chains tapping (thread cutting), thread forming and thread milling in aluminum alloy EN AW-6060 was investigated. For the determination of characteristic mechanical parame-

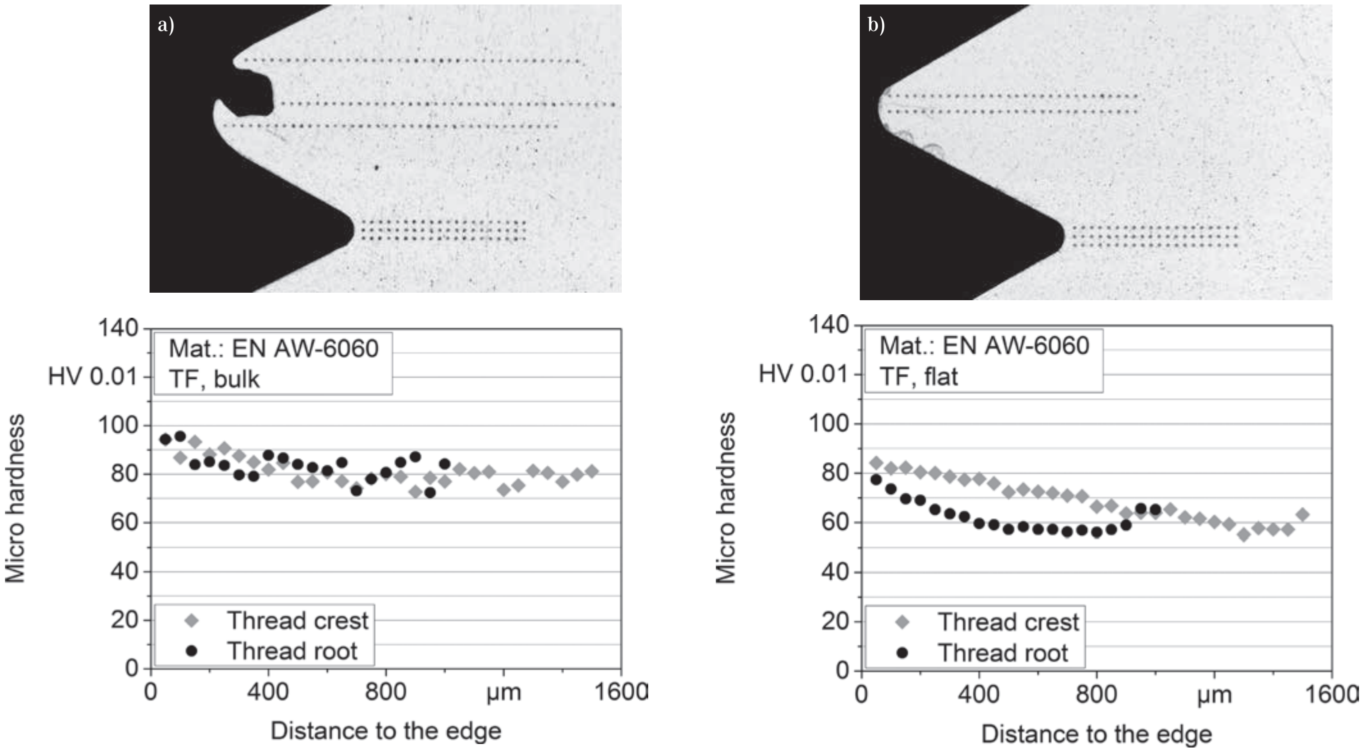

Figure 11: Micro-hardness profiles in thread crests and roots of formed internal threads (TF) a) bulk material, b) flat profile

ters test setups with optimized sensor systems were successfully developed. The total strain in tensile tests was measured using a video extensometer and for plastic strain amplitude measurements in fatigue tests a customized mechanical extensometer was used. Formed internal threads showed the best mechanical properties caused by process related work hardening along the thread flank. The thread quality of formed threads in bulk material and flat profile specimens was the best, followed by milled threads. Cut threads showed poor mechanical properties because of threads cut unevenly. Due to oval forms of the core holes caused by the friction drilling process, flat profile specimens could only tolerate lower maximum loads. The ratio of flat profiles to bulk materials between maximum forces in tensile tests was about 1 : 2 and between failure force amplitudes in load increase tests about 3 : 4. In contrast, flat profile specimens showed higher fracture strains than bulk material specimens. The fatigue limit leading to lifetimes between 10^6 and 10^7 cycles could be reliably estimated in continuous load increase tests by means of plastic strain amplitude. The new time and cost efficient thread machining processes show considerable advantages compared to the standard process and the presented short-time procedure for fatigue assessment allows an process associated application for quality inspection and condition monitoring purposes.

Outlook

The presented results provide the basis for further studies, e. g. to analyze the influence of thread manufacturing parameters on the mechanical properties of internal threads. Moreover, other lightweight materials, like aluminum cast alloys or magnesium alloys, could be investigated to extend the range of applications. For a detailed characterization of the microstructural changes in fatigue tests, additional sensors should be applied, e. g. alternating current (AC) potential probe and thermocouples. To evaluate the influence of different environmental conditions on the mechanical properties of internal threads, investigations at higher temperatures or under corrosive atmospheres would be conceivable.

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Prof. Dr.-Ing. Frank Walther, born in 1970, studied Mechanical Engineering with a focus on Materials Science and Engineering at TU Kaiserslautern University, Germany, from 1992 to 1997. There he finished his PhD on the fatigue assessment of highly-loaded railway ICE wheel steels at Institute of Materials Science and Engineering (WKK) in 2002. From 2002 to 2008, he headed the research group “Fatigue Behavior” at WKK and finished his postdoctoral qualification (habilitation) in Materials Science and Engineering in 2007. Afterwards, he joined Schaeffler AG in Herzogenaurach, Germany, and took responsibility for Public Private Partnership comprising public research funding and materials research projects within Corporate Development. Since 2010, he has been Professor for Materials Test Engineering (WPT) at TU Dortmund University, Germany. His research portfolio includes determination of structure property relationships of metal- and polymer-based construction materials and components taking the influence of manufacturing and joining processes as well as service loading and corrosion deterioration into account. New measurement and destructive/non-destructive testing techniques are applied for the characterization of fatigue behavior from LCF to VHCF range under mechanical, thermal, chemical and mixed influences, as well as new physically based approaches for the calculation of damage development and (remaining) fatigue life. Besides, he is engaged in various committees, e. g., as referee for German Research Foundation (DFG), member of board of German Materials Society (DGM), member of German Association for Materials Research and Testing (DVM), member of Association of German Engineers (VDI) and member of Scientific Association of Materials Engineering (WAW). Prof. Walther published more than 120 reviewed papers and conference proceedings and maintains close scientific contact with institutions and industries in materials science and engineering field worldwide.

Abstract

Einfluss des Fertigungsprozesses auf die Verformungs- und die Ermüdungseigenschaften fließgebohrter Innengewinde in der Aluminiumlegierung 6060. Aluminiumlegierungen werden zur Dynamiksteigerung, Ressourcenschonung und Emissionsminderung in vielen Bereichen der Verkehrstechnik eingesetzt, wobei Aluminiumbauteile mit Hilfe von Schweiß-, Löt-, Klebe- oder Schraubverbindungen hergestellt werden. Das Fließbohren, als umformendes Verfahren in Kombination mit anschließender Gewindefertigung, bietet für Leichtbauprofile die Möglichkeit, durch lokales Aufweiten des Materials, ein Innengewinde mit größerer nutzbarer Gewindetiefe als die eigentliche Profilstärke zu erzeugen. Die direkte Einbringung der Gewinde bietet im Vergleich zur konventionellen Gewindebearbeitung zudem ein enormes Potential hinsichtlich Zeit- und Kostenersparnis. Die mechanischen Eigenschaften von Innengewinden in Profilproben und Vollmaterial aus der Aluminiumlegierung EN AW-6060 wurden in Zug- und Schwingversuchen im Zug-Schwellbereich mikrostrukturell charakterisiert. Verglichen wurden dabei die Fertigungsverfahren wie Gewindebohren, Gewindeformen und Gewindefräsen. Die maximal ertragbaren Belastungen der Profilproben sind im Gegensatz zum Vollmaterial im quasistatischen Bereich um ca. 50 % und im zyklischen Bereich um ca. 25 % geringer. Dabei weisen geformte Gewinde die besten und gebohrte Gewinde die schlechtesten mechanischen Eigenschaften auf, die mit den fertigungsbedingten Profilgüten und Gefügestrukturänderungen korreliert wurden. Mehrstufige Ermüdungsversuche belegen zudem, dass die in Einstufenversuchen bis 10^7 Lastzyklen validierte Ermüdungsfestigkeit der Aluminium-Innengewinde, auf Basis der aus Spannung-Dehnung-Hysteresiskurven ermittelten plastischen Dehnungsamplitude, zuverlässig abgeschätzt werden kann.