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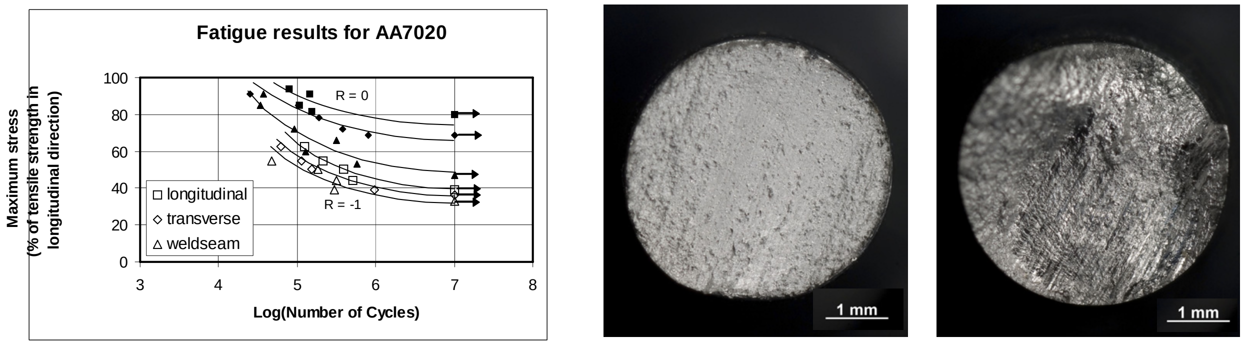
Executive summary

Static and dynamic mechanical properties of longitudinal weld seams in industrial AA6060, AA6082 and AA7020 aluminium extrusions



Fatigue results for AA7020: S-N curves and fracture surfaces of transverse samples (left: with weld seam; right: without weld seam)

Problem area
Complex hollow extrusions contain weld seams where the aluminium streams rejoin in the die. For structural applications the mechanical properties of these weld seams should be comparable to the bulk material properties. The properties of the weld seams are governed by process-related phenomena and the tooling geometry. For different alloys this combination of die shape and process settings needs to be optimised to ensure good performance of the weld seams, especially in fatigue.

The objective of this investigation was to determine weld seam properties of industrially relevant alloys.

Description of work
Full scale extrusion test runs were conducted, in which box-section profiles were produced of a type where weld seam quality of AA6082 and AA7020 parts was known to be a critical factor. The easy-to-extrude alloy AA6060 was included in these experiments as a reference material. Samples were obtained from the extrusions in the longitudinal orientation and the transverse orientation, the latter with and without weld seams. The samples were subjected to static, Charpy and fatigue testing with stress ratios (maximum stress /

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minimum stress) of R = 0 and R = -1.

Results and conclusions

The tensile and yield strengths were (almost) unaffected by the test direction or presence of a weld seam for all three alloys, while the ductility was better in the transverse direction and weld seam samples for AA6060 and AA6082 and worse for AA7020. The Charpy tests showed higher properties for the transverse direction and weld seam samples of AA6060, somewhat lower properties for AA6082 and much lower properties for AA7020 with weld seam. The fatigue strengths for R = 0 were somewhat lower in the transverse direction than in the longitudinal direction for AA6060 and AA6082 and decreased a bit further when a weld seam was present. For AA7020 the fatigue strength was significantly lower for the transverse direction and again lower for the weld seam samples.

For R = -1 (fully reversed fatigue), all three alloys showed similar behaviour, with very small differences in fatigue strength for the different orientations.

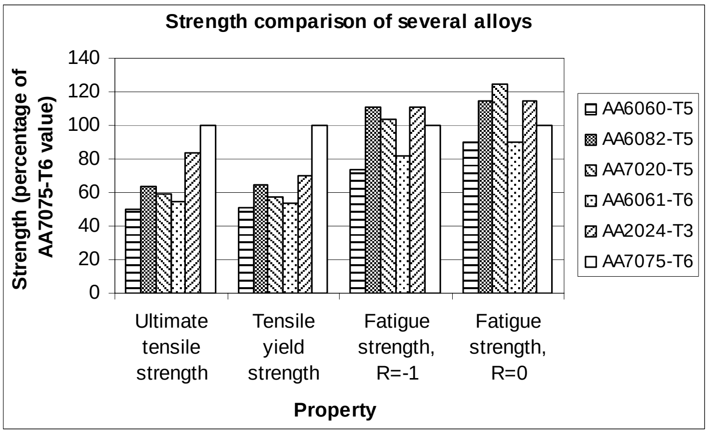
In conclusion, it can be said that the presence of a weld seam reduces the fatigue properties significantly for AA7020 (R = 0) while the reduction in fatigue properties is small for AA6060 and AA6082 (R = 0 and R = -1) and AA7020 with R = -1. The static strengths of all three alloys were almost unaffected by the presence of a weld seam.

Applicability

The differences in fatigue properties are minimal for AA6060 and AA6082 in different orientations and with or without weld seam. Therefore hollow extrusions of these alloys can be readily used for structural components.

For AA7020 the fatigue properties depend on orientation and the presence of a weld seam, even though the static mechanical properties are similar. In structural applications care must be taken that the weld seam is not in a highly (fatigue) stressed location.

With respect to aerospace components, the figure below compares the static and fatigue strengths of the extrusion alloys with those of commonly used aerospace alloys AA2024-T3 and AA7075-T6. The existing alloy static strengths are lower, but the fatigue strength of the AA6082 and AA7020 alloys are equal to those of AA2024-T3 and AA7075-T6.



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Static and dynamic mechanical properties of longitudinal weld seams in industrial AA6060, AA6082 and AA7020 aluminium extrusions

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1 Abstract

Owing to the tooling set up, complex hollow extrusions contain weld seams where the aluminium streams rejoin in the die. For structural applications the mechanical performance of these weld seams is required to be comparable to the longitudinal bulk material properties. The properties of these weld seams are governed by process-related phenomena and the tooling geometry. For different alloys this combination of die shape and process settings needs to be optimised to ensure good performance of the weld seams, especially regarding dynamic mechanical performance (especially fatigue performance).
The objective of this investigation was to determine the weld seam properties of industrially relevant alloys. Full-scale extrusion test runs were conducted, in which box-section profiles were produced of a type where weld seam quality of AA6082 and AA7020 parts was known to be a critical factor. AA6060 was included in these experiments as a reference material. Samples from the extrusions were obtained from various positions and orientations and subsequently subjected to extensive mechanical characterisation by means of tensile, Charpy fracture toughness and fatigue testing. Results are correlated with the processing data, and through microstructural characterisation the particular failure mode of the material was investigated.
It is concluded that the effect of sample orientation and the influence of the weld seams on the mechanical properties is significantly different for the investigated alloys.

2 Introduction

Aluminium extrusions offer an interesting combination of strength properties, light weight and geometrical variation, thus providing a diversity of applications in many fields, including construction and transportation. Especially for those applications where the structural integrity of the extruded parts plays a dominant role, rigorous inspection and testing is required to ensure conformity to the specifications. In the case of (multi-)hollow extrusions produced with porthole dies, the presence of longitudinal weld seams presents an additional challenge regarding the mechanical and structural integrity.
Longitudinal weld seams are formed when aluminium billets are extruded through dies with integrated mandrels. The majority of these tools are of the port-hole type, where the mandrels are suspended in the die orifice by means of bridges. During extrusion the bridges split the billet into a number of metal streams that flow around the core. The metal streams rejoin in the welding chamber of the die, thus forming the inner surface of the hollows in the cross-section of the extrusion. The joining of the aluminium streams occurs through a process of solid bonding under conditions of elevated temperature, deformation and the interfacial pressure acting on the

welding planes. The formation of a sound bond relies upon the fulfilment of a number of critical sub-processes for bond formation: 1) the ´crushing´ of surface asperities due to the interfacial pressure of the contacting surfaces; 2) additional surface stretching of the weld plane after initial bond formation, controlled by the local strain, and 3) subsequent microstructural evolution influenced by temperature, strain and strain rate. These partly interrelated process conditions need to be tailored for specific alloys, since the effect on bond formation will depend on the particular material response to these (local) conditions.
Apart from the obvious case, where the required combination of alloy type and product characteristics (notably cross-sectional geometry) are incompatible in the sense that weld seam integrity cannot be established, a number of factors can have a detrimental effect on the quality of weld seams [Ref. 1]. Inclusions in the form of oxides and/or carbon-based particles can occur on the weld plane. These particles can originate from a number of sources, such as the billet material itself (e.g. contamination of the alloy) or dirt entrapped from the press equipment (oil, grease). These entrapped particles can become situated on the weld plane and may spread out along the weld seam as the profile is formed. This phenomenon can certainly be associated with the transverse weld seam, which is billet-to-billet transition where relatively ´impure´ billet material (shell zone or oxidation of the billet face) enters the extrusion. Voids or porosity may also occur on the weld plane, as a result of entrapped air or other gases [Ref. 2].
The defects described above have been the subject of many investigations. They can be virtually avoided when sound production procedures are followed and clean and well-maintained equipment and extrusion tooling are used. More problematic are defects associated with microstructural phenomena, such as flow patterns, grain size effects, etc. Of particular importance is the ´kissing bond´ defect, where insufficient bonding can hardly be detected by regular inspection routines. In metallographic inspection the microstructure of this faulty bond appears standard, without irregularities, although recent work has shown that novel non-destructive techniques may aid in detecting these defects [Ref. 3]. Bond strengths may achieve adequate values up to the yield point. However instantaneous and catastrophic failure of the bond can occur once (minor) plastic deformation is imposed as the material is loaded statically beyond the yield point. The complete absence of any ductile behaviour constitutes a great risk in any highly loaded construction. This defect has also been studied in conjunction with similar metal bonding techniques such as friction stir welding [Ref. 4], however the associated phenomena (e.g. layer formation, oxide inclusions, etc.) are more akin to transverse weld formation.
To ensure adequate property levels, rigorous quality control measures are commonly implemented. This entails both assessment of the metal structure and destructive testing of samples taken from areas that are expected to be critical. Although these evaluation methods have proven to be effective in intercepting potentially sub-standard material, the mechanical

testing methods only provide information concerning the static properties and thus do not provide any information concerning long term dynamic (fatigue) behaviour, relevant for many transport-related applications. In those cases where fatigue properties were studied, testing was limited to one alloy type for one particular application [Ref. 5]. Furthermore it has been demonstrated that uniaxial tensile testing, employed as a standard test method in industry (in addition to drift expansion testing), is limited in the degree to which suitable information can be gained concerning the weld seam quality: as has been indicated above, only data related to the ductility of the weld seams (i.e. elongation at fracture) provide some degree of information [Ref. 5]. Therefore a test programme was initiated to characterise weld seams based on dynamic (fatigue) testing.

3 Experimental

In order to investigate the relation between static mechanical properties of weld seams and the dynamic properties, full scale extrusion tests were conducted. Since weld seam properties depend on the specific alloy, three alloys were selected: AA6060 as an easy-to-extrude general purpose alloy where adequate weld seam properties are readily achieved; AA6082 as a medium strength alloy where special care is required to ensure sound weld seams; and AA7020, an alloy commonly utilised for solid parts, but whose higher strength may provide an interesting alternative, provided weld seam integrity can be ensured.

3.1 Extrusion Trials

Industrial extrusion experiments were conducted with the 55 MN direct extrusion press at Nedal. Industrial DC cast and homogenised Ø348 mm billet feedstock was processed. The profile used for these experiments was a thick-walled rectangular box section, figure 1, manufactured with a porthole die. The nominal weight of this box section is 33.1 kg/m and the circumscribed circle diameter is 296 mm. The wall thickness ranges from 10 mm to 23 mm. The extrusion ratio for this combination of billet size and profile dimensions is 8.0, a value which may be considered as critical with regard to weld seam formation according to general views regarding the (minimum) required resultant pressure on the weld planes. Earlier extrusion runs with this die showed that weld seam integrity is indeed a critical factor. The die, made from regular H13 hot working tool steel, consists of a core section with a mandrel supported by six bridges, combined with a die plate section forming the outer perimeter of the profile. Corresponding with the bridges in the die, six longitudinal weld seams are present in the profile at positions where the aluminium streams rejoin under the mandrel supports.

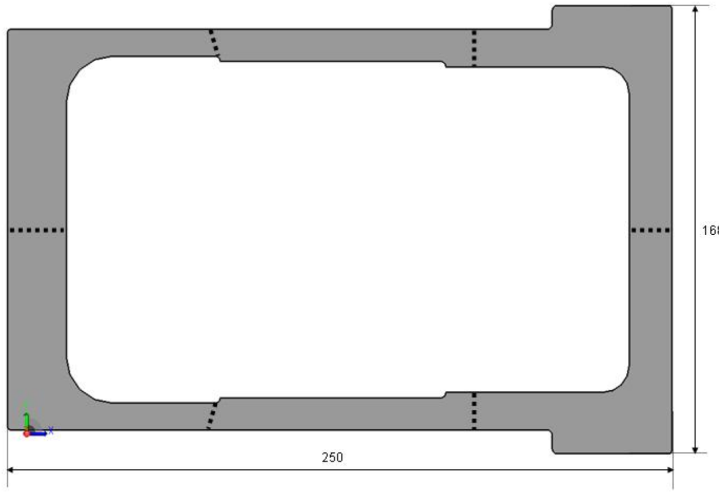


Fig. 1 Test profile geometry. The dashed lines indicate the approximate position of the weld seams

As is customary in industrial practice, the extrusion sequence was initiated with a dummy billet, of which the extruded product was entirely scrapped. For all alloys two billets with a cut length of at least 1000 mm were processed in billet-to-billet extrusion mode. At each billet change a butt discard of approximately 55 mm was sheared from the die face. For each alloy the same cast number was utilised, to avoid any variation in the base metal characteristics. The composition of the alloys is shown in table 1. Care was taken to eliminate the billet-to-billet transition region from the extruded length, since this transition region contained back-end defects preceding the transition and the transverse weld seams after the billet changeover. Process settings are adjusted for each alloy in a manner to achieve optimum extrusion results in terms of product quality (as opposed to productivity goals). High velocity air quenching was performed on all extruded lengths and subsequent ageing was performed to achieve a T5 peak-hardened temper.

Table 1 Alloy compositions of tested materials (values in weight %).

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
AA6060	0.42	0.20	<0.01	0.03	0.46	<0.01	0.02	0.01	<0.01
AA6082	0.99	0.23	0.01	0.51	0.64	0.10	0.01	0.03	<0.01
AA7020	0.14	0.18	0.11	0.23	1.14	0.14	4.39	0.02	0.11

3.2 Mechanical characterisation

From each of the extruded alloys a representative length of approximately 1 m was obtained for further processing into samples. To investigate any relationships between different methods of mechanical testing, the samples were prepared for tensile testing, Charpy fracture toughness testing and fatigue testing. To assess the weld seam properties in relation to the material performance outside the weld seam area, additional samples were taken in the longitudinal and transverse direction from the short sides of the box section with a wall thickness of 16 mm. Figure 2 shows an overview of the relative position and sample type, further detailed in table 2.

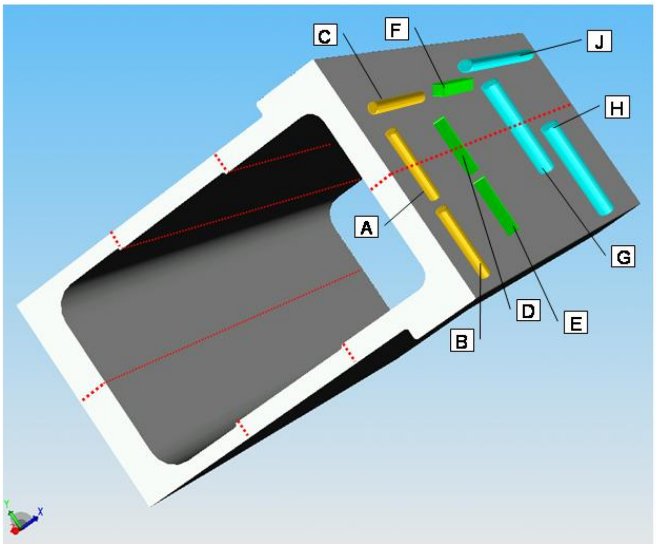
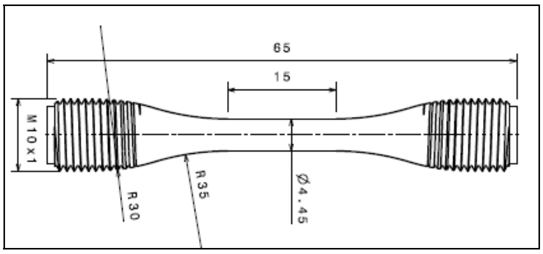


Fig. 2 Sample types and position

Table 2 Sample details

Designation	Sample type	Orientation / position
A	Fatigue	Transverse / weld seam
B	Fatigue	Transverse / non-weld seam
C	Fatigue	Longitudinal
D	Charpy impact (unnotched)	Transverse / weld seam
E	Charpy impact (unnotched)	Transverse / non-weld seam
F	Charpy impact (unnotched)	Longitudinal
G	Tensile	Transverse / weld seam
H	Tensile	Transverse / non-weld seam
J	Tensile	Longitudinal

The geometry of the fatigue and Charpy samples is shown in figure 3. The shape and dimensions of the fatigue samples were developed in earlier exploratory tests executed on reference material collected from regular extrusions. The sample geometry was identical for all orientations and positions to avoid any influences caused by geometrical factors. Care was taken during sampling and machining to ensure that the weld seam was located at the centre position of the test piece. Milling of the samples was performed at appropriately low cutting speeds to avoid excessive heat input during machining of the samples that may cause deterioration of the T5-material properties,



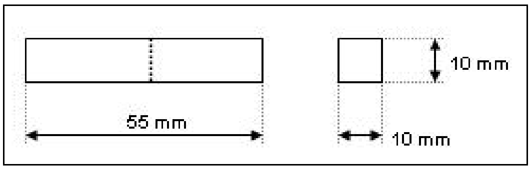


Fig. 3 Sample geometry for fatigue tests (left) and Charpy impact tests (right)

Constant amplitude fatigue testing was performed in accordance with standard practice ASTM E466-96 on an Amsler Vibrophore high frequency resonance machine. The stress ratios applied were $R = S_{min}/S_{max} = 0$ and $R = -1$. The test frequency was 80 Hz. The fatigue strength was assumed to correspond to fatigue lives equal to 10^7 cycles. Owing to the limited number of fatigue specimens, only partial S-N curves could be determined. Following the tests, a number of relevant samples was selected for fractographic examination using optical microscopy and Scanning Electron Microscopy (SEM).
Sample preparation for metallography was done using standard grinding and polishing techniques, finishing with OPS (Struers). Etching was done with Keller's to reveal the grain boundaries. Optical metallography was done using a Zeiss Axioplan 2 microscope. SEM metallography was done with an FEI XL-30S Field Emission Gun Scanning Electron Microscope operating in the secondary electron (SE) detection mode.
The dimensions of the Charpy impact samples were in accordance with the impact testing standard ASTM E23-01. However, the samples were prepared without a notch, in order to focus solely on the effect of the weld seam. At least 6 impact tests were conducted for each combination of alloy and sample location.
Tensile testing was performed in accordance with EN10002-1 on cylindrical test pieces with a diameter of 8 mm and a gauge length of 40 mm. Duplicate samples were tested for each sample type.

4 Results and discussion

The sample material was produced in two extrusion runs, one run in which the AA6060 and AA7020 alloys were extruded, and a separate run for extrusion of the AA6082 alloy. For all alloys, all extrusion trials yielded profiles with no obvious extrusion defects such as hot-shortness cracking and/or die marks, and with a bright appearance and good surface finish. To avoid any anomalies in extrusion, the press speed was fixed at a low setting, appropriate for the most difficult alloy, AA7020. The relevant process data for the extruded alloys is presented in table 3.

Table 3 Extrusion process data

Alloy	Billet temperature [°C]	Initial extrusion pressure [bar]	Pressure at end [bar]	Billet length [mm]	Extrusion speed (avg) [m/min]
AA6060	485	187	117	1100	1.1
AA7020	500	255	136	1500	1.1
AA6082	525	257	131	1550	1.1

Depending on the initial billet length, the extruded profile length varied from approximately 8 m to 11.5 m. After removal of the unsuitable sections (the billet transitions, stretching losses, etc.), sufficient sample material was available for processing into the relevant test pieces.

Metallography of cross-sections perpendicular to the extrusion direction and through the weld seam revealed recrystallised microstructures consisting of elongated grain structures with equiaxed subgrains. The metallographic characteristics of the three alloys are listed in table 4.

Table 4 Metallographic characteristics

Alloy	Extrusion grain structure	Grain structure	Dispersoids	Constituent particles
AA6060	weak	relatively coarse (sub)grains	high density	high density
AA6082	pronounced	relatively fine (sub)grains that refine towards surface and weld seam	very high density	very high density
AA7020	strong	fine (sub)grains that refine towards surface and weld seam	low density, decorating (sub)grain boundaries	(very) low density, aligned in extrusion direction

The weld seam was recognisable at low magnifications as a white etching band in AA6082 and AA7020 (Fig. 4). At higher magnifications the weld seam could not be recognised in AA6082. The weld seam in AA7020 showed clearly as a band of about 100 µm thickness, with somewhat lower hardness. The weld seam was hard to recognise in AA6060 at all magnifications (see Fig. 4).

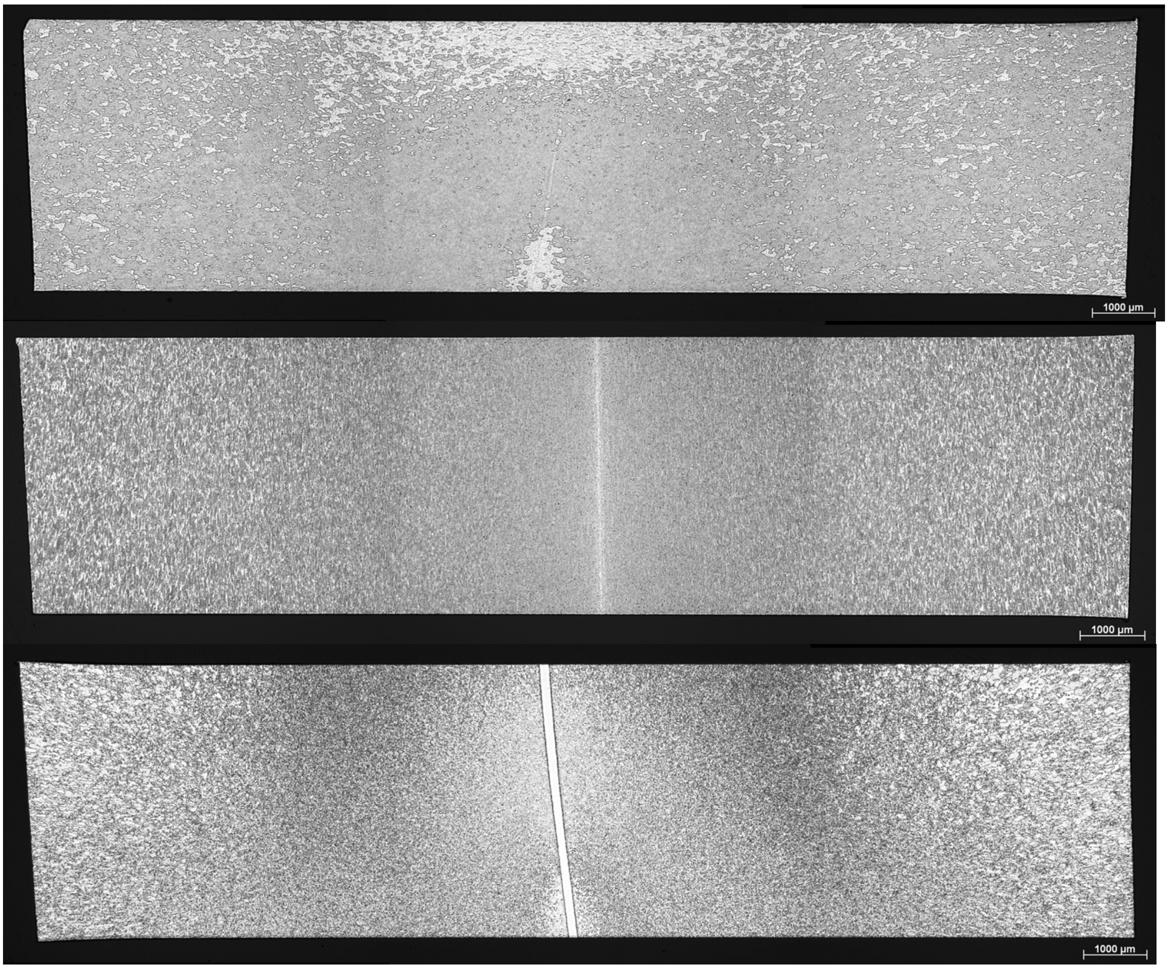


Fig. 4 Metallographic cross sections through weld seam for AA6060 (top image), AA6082 (center image) and AA7020 (bottom image)

4.1 Tensile tests

The results of the tensile tests and the Charpy impact tests are presented in figure 5. The tensile test results for the investigated alloys show only small variations when comparing strength properties: both the yield strength (YS) and the ultimate tensile strength (UTS) levels in the transverse direction with or without weld seam are very similar to the values obtained in the longitudinal direction. From the absolute values of the tensile properties of each alloy it can be

concluded that the exit temperatures and quench rates were sufficient to achieve the desired T5 temper.
With respect to the ductility characteristics, represented by the elongation at fracture (A) and the reduction in area (Z), it can be seen that for all three alloys the elongation at fracture for the transverse sample is lower than the value for the longitudinal direction, and the value for the test pieces with a weld seam is lower still. The magnitude of this change is approximately similar for the 6XXX alloys, whilst alloy 7020 exhibits the most pronounced effect. The trend for the reduction in area (Z) is somewhat different: for all three alloys the value obtained for the non-weld seam transverse samples is approximately similar to or higher than the longitudinal value, whilst for the AA6060 and AA6082 alloys the weld seam samples exhibit the highest value. In the case of the AA7020 alloy the reduction in area drops to a value below that of the longitudinal samples, thus exhibiting a markedly different behaviour. These ductility results show that deformation is more confined in the weld seam samples than in the non-weld seam transverse samples, although the differences are not very large for the 6XXX alloys. For AA7020 the results show that the weld seam material is less ductile than the base material in the transverse direction.

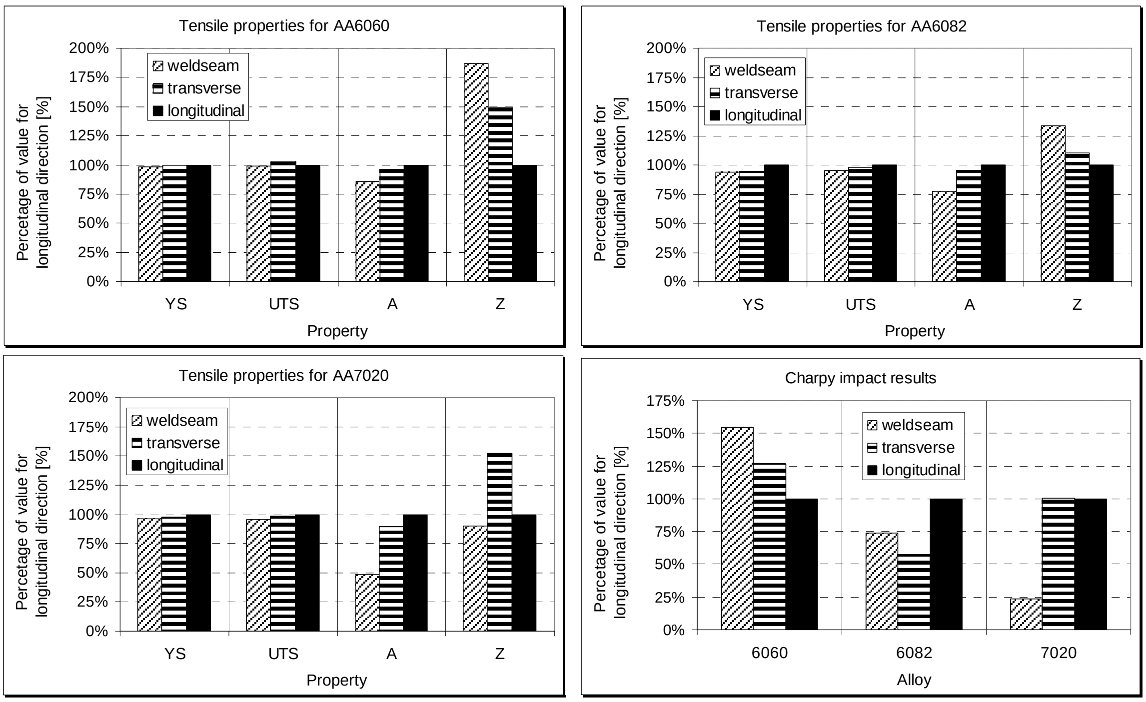


Fig. 5 Tensile test results for AA6060 (top left), AA6082 (top right) and AA7020 (bottom left). Values for each alloy have been scaled to the values obtained in longitudinal direction, as this is the standardised test mode

Only for AA6082 are any data available from the literature for comparison with the results obtained in this project. In tests performed by Dean [Ref. 5] on large extrusions for marine applications, values are presented for yield stress, ultimate tensile strength and elongation, figure 6.

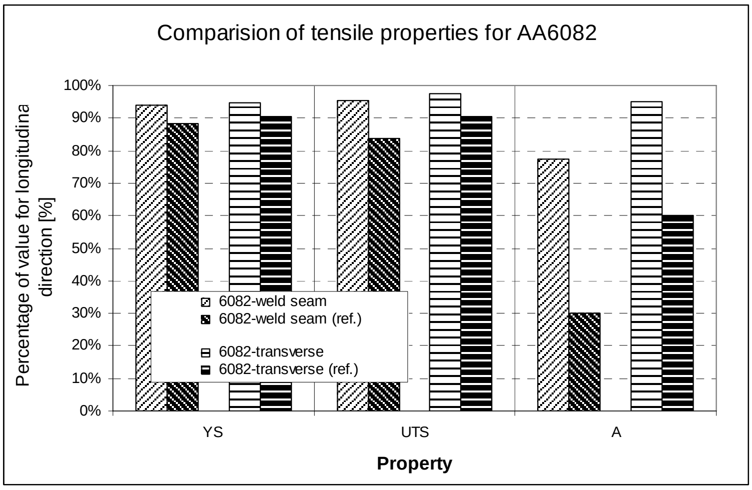


Fig. 6 Comparison of test data with data from literature. Values are scaled to longitudinal values

Although the same trend is observed in both studies, the decrease in properties as observed by Dean is more pronounced. Especially the decrease in elongation for samples with a weld seam is considerably greater for the samples tested by Dean. The relatively small impact of the weld seam on yield stress and ultimate tensile strength and the larger effect on ductility is also in accordance with the results obtained by Donati [Ref. 5].

4.2 Charpy tests

The Charpy impact test results show different trends for the three alloys. For alloy AA6060 the lowest value is obtained in the longitudinal direction and the highest value is measured in the weld seam samples, with an increase of approximately 50% over the longitudinal samples. For the AA6082 alloy the lowest value was found for the transverse, non-weld seam samples at approximately 60% of the value measured in the longitudinal direction. The weld seam material exhibited a slight improvement over the non-weld seam: however, the value was still lower than the longitudinal values at 75%. For the AA7020 material the longitudinal value and the value for the non-weld seam samples are similar, whilst the results for the weld seam samples dropped to very low levels of approximately 25% of the longitudinal value.

4.3 Fatigue tests

The results of the fatigue tests are presented in figure 8. The results for R = -1 show the same trend as for R = 0. It can be seen that the fatigue strength of AA6060 at 10^7 cycles is higher for loading in the longitudinal direction than in the transverse direction. The presence of a weld seam had a small detrimental effect on the fatigue strength. Most specimens containing a weld seam failed in the base material and showed a fatigue life within the scatter band found for the transverse direction. However, some specimens showed crack initiation in the weld seam that led to a shorter fatigue life or failure at stress levels below the fatigue strength in the transverse direction.

For AA6082 the difference in fatigue strength in the longitudinal and transverse directions was small. Like the AA6060 alloy, the presence of a weld seam had a small detrimental effect on the fatigue strength. This observation agrees with results reported by others [Ref. 5], where both for the transverse samples and the weld seam samples a lower fatigue performance was measured. Furthermore, it can be seen that at higher stress levels the fatigue life may be decreased significantly by the presence of a weld seam. In the specimen loaded at 72% of the tensile strength in the longitudinal direction the failure occurred in the weld seam, while the other specimens containing a weld seam failed in the base material.

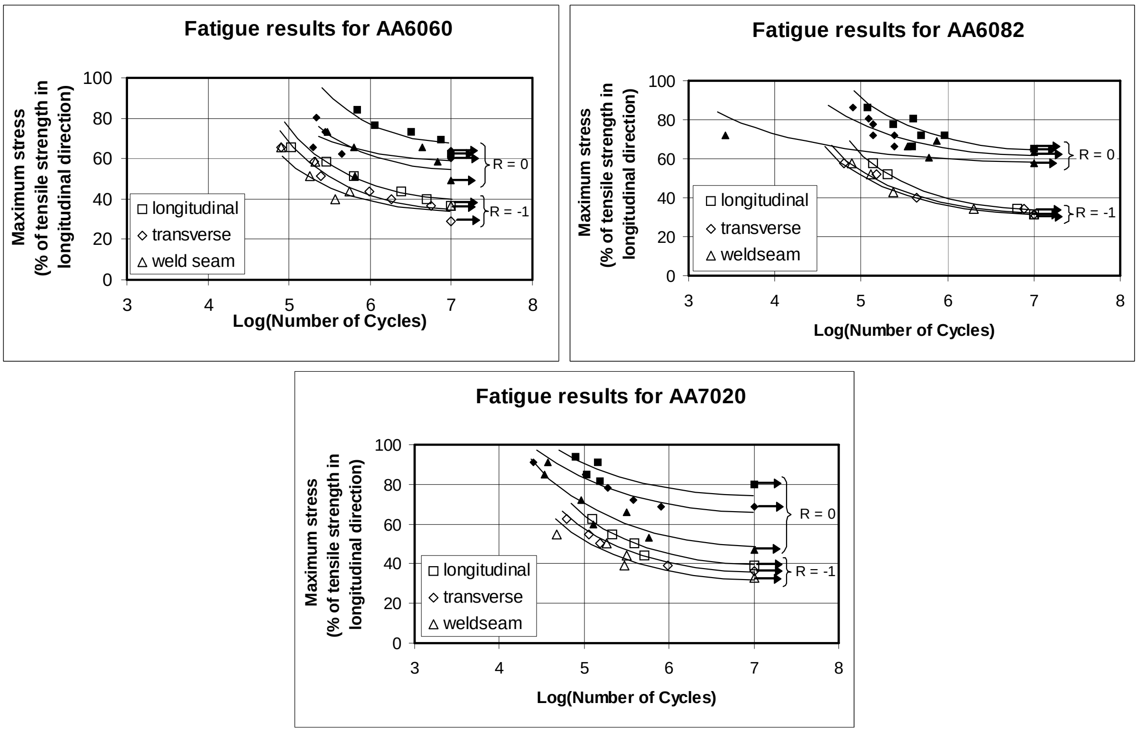


Fig. 7 S-N curves for AA6060, AA6082 and AA7020. For clarity, only the highest loaded unfailed specimens are shown. The curves are to guide the eye

For AA7020 the differences in fatigue strength in the longitudinal and transverse direction were much more pronounced. The presence of a weld seam caused an additional pronounced decrease in fatigue strength. Fractographic investigation of the failed samples showed that failure often occurred along the weld seam in this alloy. Figure 8 illustrates the differences in fracture surfaces found for the three alloys in the transverse direction and with weld seam. The weld seam samples (left) failed along the weld seam, which resulted in a flat, featureless fracture surface for AA7020, whereas the transverse sample fracture surface shows clearly the extrusion grain structure. For AA6082 the weld seam fracture surface showed less structure than the non-weld seam fracture surface, while for AA6060 both fracture surfaces were similar. Note also the difference in extrusion structure between AA6060 on the one hand and AA6082 and AA7020 on the other hand.

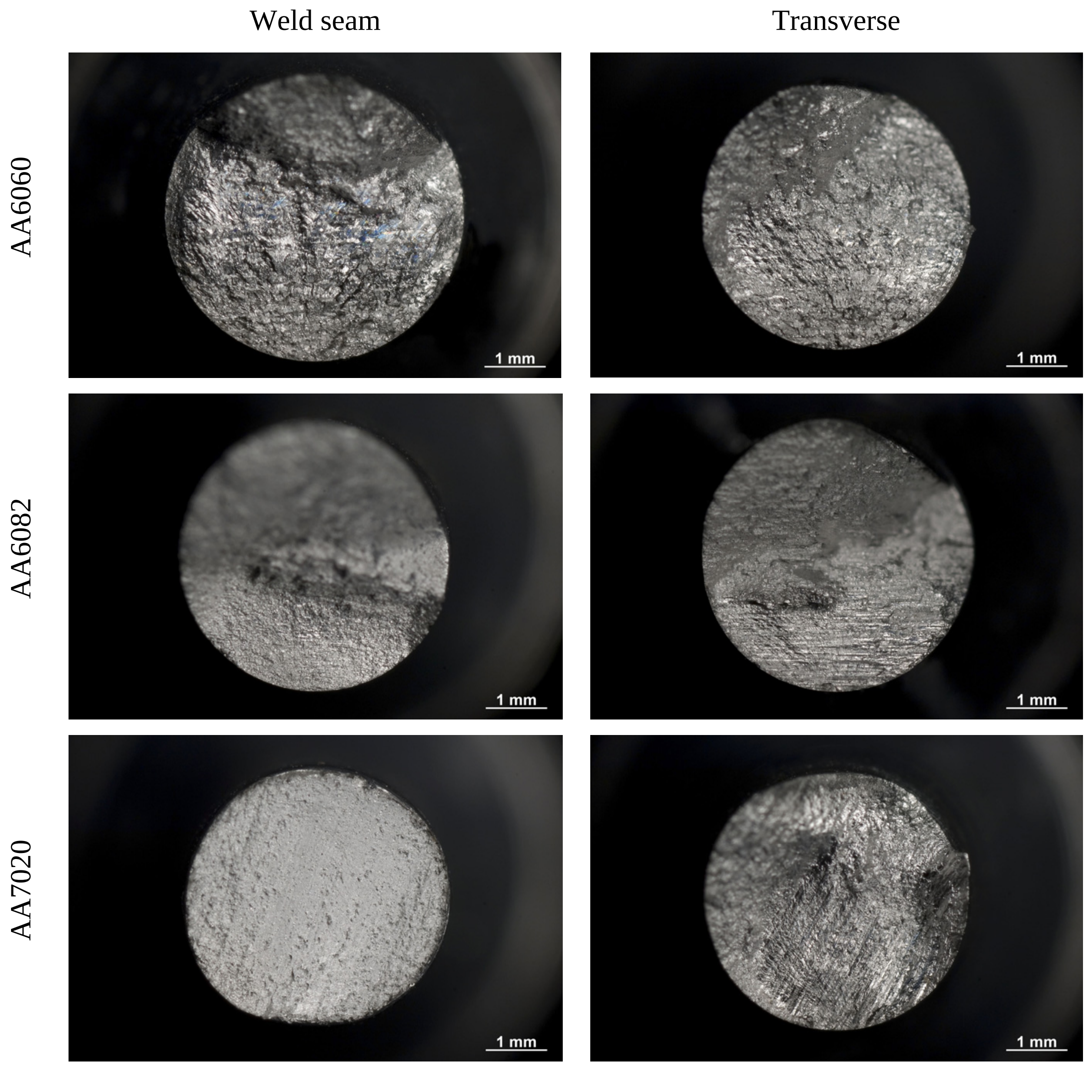


Fig. 8 Macrophotographs of fracture surfaces after fatigue testing. The left hand images show the weld seam samples with fracture along the weld seam, the right hand images show the transverse samples

The reduction in fatigue life, when comparing the longitudinal direction with the transverse direction and weld seam, was small for the 6XXX samples but large for AA7020.

4.4 Comparison with well-known aerospace alloys

Two well-known alloys used extensively in the aerospace industry are AA2024-T3 and AA7075-T6. Depending on the application, the static strength or the fatigue strength may be more important and govern the alloy selection. When evaluating the applicability of the presently investigated extrusion alloys for aerospace applications, their static and fatigue strengths should be compared to the two well-known aerospace alloys. Figure 9 makes this comparison, where all quantities are expressed as percentages of the value for AA7075-T6. (AA6061-T6 is added because it is a weldable alloy that is used in the lower fuselage of Airbus aircraft and has lower strengths than the AA2024-T3 and AA7075-T6.)
It is clear that the tensile strengths are higher for the two well-known aerospace alloys, but the fatigue properties are equal or even better for the extrusion alloys AA7020-T5 and AA6082-T5. The extrusion alloys also have higher static and fatigue strengths than AA6061-T6. AA6060-T5 has (slightly) lower strengths than all the other alloys.

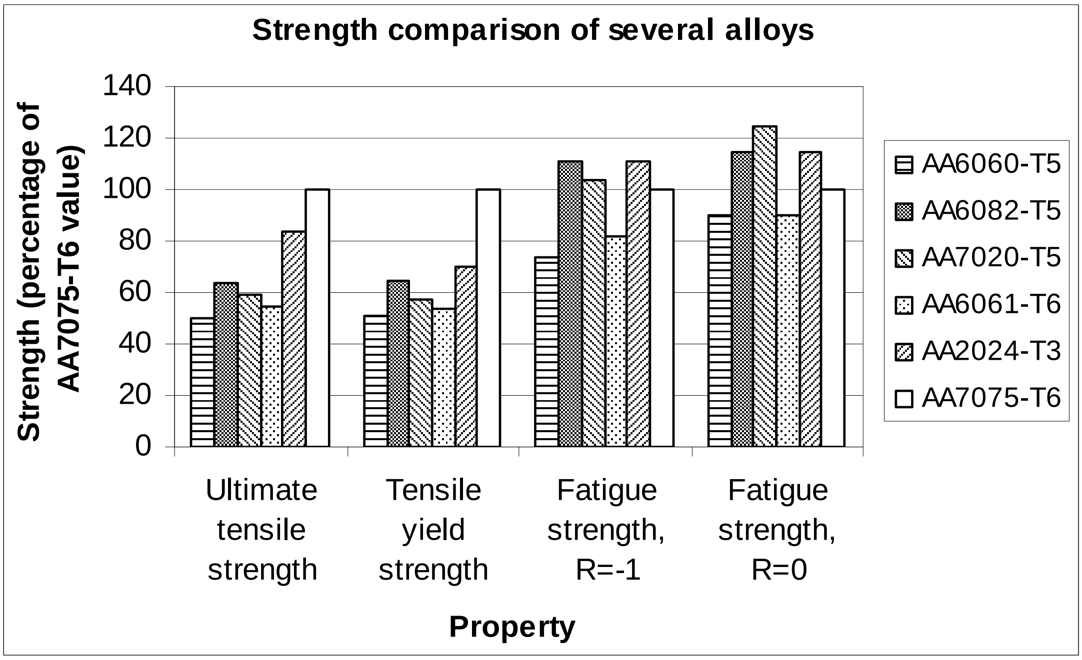


Fig. 9 Strength comparison of the extrusion alloys with two well-known aerospace alloys

5 Conclusions

Extrusion trials were performed on three alloys, AA6060, AA6082 and AA7020. The extrusion speed was kept constant for all trials and a speed appropriate to the most difficult to extrude alloy was chosen. Test samples were prepared from the hollow extrusion in the longitudinal and transverse directions with and without weld seam. Tensile, Charpy and fatigue tests were performed to characterise the properties of the extrusions.

The tensile and yield strengths were (almost) unaffected by the test direction or presence of a weld seam for all three alloys, while the ductility was better in the transverse direction and weld seam samples for the 6XXX alloys and worse for AA7020. The Charpy tests showed increased properties for the transverse direction and weld seam samples for AA6060, somewhat decreased properties for AA6082, and strongly decreased properties for AA7020 with weld seam. The fatigue strengths in the transverse direction were somewhat lower than in the longitudinal direction for the 6XXX alloys, and decreased a bit further when a weld seam was present. For AA7020 the fatigue strength was significantly lower for the transverse direction and again lower for the weld seam samples.
In conclusion, for all three alloys the static strengths were almost unaffected by the presence of a weld seam whereas it reduced the fatigue properties significantly for AA7020, while the reduction in fatigue properties is small for AA6060 and AA6082.
With respect to aerospace components, the static and fatigue strengths of the extrusion alloys is compared with those of well-known aerospace alloys AA2024-T3 and AA7075-T6. The existing alloy static strengths are lower, but the fatigue strength of the AA6082 and AA7020 alloys are equal to those of AA2024-T3 and AA7075-T6.

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